ELECTRIC MOTOR REPAIR

SECOND EDITION

ILLUSTRATIONS

Preface

For many years there has been a need for an intensely practical nontheoretical book on electric motor repair and control that could be used by men with little background of electrical knowledge. This has been only too evident in my contacts with workers over a period of many years in motor repair shops and with learners during my years as an instructor in motor repair and control in the New York City vocational high schools. It is with the hope of satisfying this pressing need that this book has been written. Inclusion of more than 900 illustrative drawings should make it particularly valuable as a direct working guide, not only to the student, but to the repairman at the bench as well.

Because the troubleshooter and repairman must learn to do satisfactory work in the shortest possible time, I have tried to point out the best and quickest methods for testing and repairing. The heading Troubleshooting and Repair at the end of each chapter should be especially helpful.

Both alternating-current and direct-current motors are treated thoroughly, and extensive consideration is given to the connections and troubles in controllers.

Although numerous changes and additions of subject matter and illustrations have been made in this revision, nearly all of the original material in the first edition has been retained. Many parts of the book have been rewritten and rearranged and new information has been added, but every effort has been made to preserve the character and objectives of the first edition. Because s[illegible] state elec[illegible] units are replacing tube-e[illegible] motor [illegible]rollers, a[illegible]ely new chapter has been added devoted [illegible] State Motor Con-

ELECTRIC MOTOR REPAIR

A PRACTICAL BOOK ON
THE WINDING, REPAIR, AND TROUBLESHOOTING OF
A-C AND D-C MOTORS AND CONTROLLERS

SECOND EDITION

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CHAPTER 1

Split-phase Motors

Main Parts of Motor

The split-phase motor is an a-c motor of fractional horsepower size and is used to operate such devices as washing machines, oil burners, and small pumps. This motor has four main parts. These are (1) a rotating part, called the *rotor;* (2) a stationary part, called the *stator;* (3) end plates, or brackets, which are fastened to the frame of the stator by means of screws or bolts; and (4) a centrifugal switch that is located inside the motor. The general appearance of a split-phase motor is shown in Figure 1-1. This motor is generally operated from a single-phase lighting or power circuit and is used where the starting torque requirements are moderate. The National Electrical Manufacturers Association (NEMA) defines a split-phase motor as a single-phase induction motor equipped with an auxiliary winding displaced in magnetic position from, and connected in parallel with, the main winding.

The Rotor

The rotor, one of which is shown in Figure 1-2, consists of three essential elements. One of these elements is a core that is made up of sheets of high-grade electrical sheet steel called *laminations*. Another is a shaft on which the laminated iron core is pressed. The third element is a squirrel-cage winding consisting of heavy copper bars which are placed in slots in the iron core and are connected to each other by means of heavy copper rings located on both ends of the core. In most split-phase motors the rotor has a one-piece cast-aluminum winding. This type is shown in Figure 1-2.

The Stator

The stator of a split-phase motor is composed of a laminated steel core with semiclosed slots, a heavy cast-iron or steel frame into which the core is pressed, and two windings of insulated copper wire that are wound into the slots and are called the *main or running winding* and *auxiliary or starting winding*. A photograph of the stator is reproduced in Figure 1-3, and a schematic diagram of the two windings is shown in Figure 1-4. Both windings are connected to the power line when the motor is started; however, after the motor has reached a predetermined speed, the starting winding is automatically disconnected from the power line by means of a centrifugal switch located inside the motor.

The End Plates (End Shields or Brackets)

The end plates, one of which is illustrated in Figure 1-5, are fastened to the stator frame by means of screws or bolts and serve mainly to keep the rotor in position. The bore of the end plates, in which the rotor shaft rests, is fitted with either ball bearings or sleeve bearings. These sustain the weight of the rotor, keep it precisely centered within the stator, and permit rotation without allowing the rotor to rub on the stator.

The Centrifugal Switch

The centrifugal switch is located inside the motor. Its function is to disconnect the starting winding after the rotor has reached a predetermined speed. The usual type consists of two main parts, namely, a stationary part (shown in Figures 1-5 and 1-6) and a rotating part. The stationary part is usually located on the front end plate of the motor as in Figure 1-5 and has two contacts, so that it is similar in action to a single-pole, single-throw switch. On some of the newer motors, the switch assembly is mounted in the stator shell. The rotating part is located on the rotor, as shown in Figures 1-7 and 1-10.

The action of a centrifugal switch is explained as follows: Reference to Figure 1-8 shows that when the motor is at a standstill, the two contacts on the stationary part of the switch are kept closed by the pressure of the rotating part. At approximately 75 percent of full speed, the rotating part releases its pressure against the contacts and causes them to open, thus automatically disconnecting the starting winding from the circuit. A popular type of centrifugal switch mechanism is shown in Figure 1-9. Here we see the stationary switch and the rotating governor weight mechanism. The rotating part is shown in Figure 1-10 and is attached to the rotor. The operation is similar to that of Figure 1-8, except that the governor weight moves outward as the speed increases, and away from the stationary contact plate, causing the contacts to open, and disconnecting the auxiliary circuit. Figure 1-11 shows the stationary and rotating parts of another centrifugal switch.

In an older type of centrifugal switch the stationary part consists of two copper semicircular segments. These are insulated from each other and mounted on the inside of the front end plate. The rotating part is composed of three copper fingers that ride around the stationary segments while the motor is starting. These parts are illustrated in Figure 1-12. At the start, the segments are shorted by the copper fingers, thus causing the starting winding to be included in the motor circuit. At approximately 75 percent of full speed, the centrifugal force causes the fingers to be lifted from the segments, thereby disconnecting the starting winding from the circuit.

Operation of The Split-phase Motor

Generally there are three separate windings in the split-phase motor. These windings are necessary for the proper operation of the motor. One of these is on the rotor and is known as the *squirrel-cage winding*. The other two windings are on the stator and are placed as shown in Figure 1-13. Each winding of the motor illustrated has four sections or poles.

Squirrel-cage Winding

The squirrel-cage winding consists of a number of heavy copper bars that are fitted into slots in the laminated iron core. The ends of each bar are welded to heavy copper rings that complete the electrical circuit. Most split-phase motors have a cast aluminum winding on the rotor, as shown in Figure 1-2.

Stator Windings

The stator windings consist of (1) a winding of heavy insulated copper wire, which is generally located at the bottom of the stator slots and is known as the *running* or *main winding;* and (2) a winding of fine insulated copper wire, which is usually located on top of the running winding and is known as the *starting* or *auxiliary winding*. These two windings are connected in parallel. When the motor is started, both stator windings are connected to the line, as shown in Figure 1-14(a). Upon reaching approximately 75 percent of full speed, the centrifugal switch opens, as shown in Figure 1-14(b) and disconnects the starting winding from the circuit, thereby causing the motor to operate on the running or main winding only.

At the start, the current flowing through both the running and the starting windings causes a magnetic field to be formed inside the motor. This magnetic field rotates and induces a current in the rotor winding, which in turn causes another magnetic field. These magnetic fields combine in such manner as to cause rotation of the rotor. The starting winding is necessary at the start in order to produce the rotating field. After the motor is running the starting winding is no longer needed and is cut out of the circuit by means of the centrifugal switch.

Procedure for Analyzing Motor Troubles

When a motor fails to run properly, a definite procedure should be followed in determining the repairs necessary to put it into running condition; that is, a series of tests is made on the motor to discover the exact trouble. These tests enable the repairman to tell quickly whether or not the motor needs minor repairs, such as new bearings, new switches, new leads; or whether it needs partial or complete rewinding.

Analysis Procedure

The following steps in analyzing motor troubles are given in the logical order to be followed in determining what repairs are required for reconditioning the motor:

1. Inspect the motor to detect such mechanical troubles as broken or cracked end plates, badly bent shaft, broken or burned leads.

2. Test the motor for bearing troubles. To do this, try to move the shaft up and down in the bearing as in Figure 1-88. Any such movement indicates a worn bearing. Next, turn the rotor by hand to determine whether it rotates freely. A shaft that does not rotate freely indicates bearing trouble, a bent shaft, or an improperly assembled motor as shown in Figures 1-92 and 1-93. In any case, a fuse is likely to burn out should the motor be connected to the power line.

3. Examine the motor to discover whether or not the internal wires are touching the iron cores of the rotor or stator. This is called a *ground test* and is accomplished by using a test lamp as shown in Figure 1-78(a) and (b).

4. After determining that the rotor turns freely, the next test is to run the motor. The power line wires are connected to the terminals of the motor and the switch is closed for a few seconds. If there is something wrong internally, the fuse may blow, the windings may smoke, or the motor may rotate slowly or noisily or may not turn at all. Such symptoms always indicate trouble inside the motor, usually a burned-out winding. The end plates and rotor are then removed, and the windings tested more carefully. Should the trouble be a badly burned winding, the winding itself will look burned and will also feel and smell burned.

Rewinding the Split-phase Motor

After previous tests have shown that the windings of the motor are burned out or are severely shorted, rewinding is required in order to recondition it. Before the motor is taken apart, the end plates and frame are marked with a center punch so that it may be reassembled properly. One center-punch mark is made on the front end plate and the adjacent frame, and two marks are made on the back end plate and also at a corresponding point on the frame as shown in Figure 1-15. The motor is then disassembled and made ready for repair.

Repair of a split-phase motor with a damaged winding consists of several separate operations, the most important of which are (1) taking data, (2) stripping the windings, (3) insulating the slots, (4) rewinding, (5) connecting the winding, (6) testing, and (7) baking and varnishing.

Taking Data

Taking data is one of the most important of the above operations. It consists of noting certain specific information concerning the old winding, so that no difficulty will be encountered when the motor is rewound. The information is recorded before and during the process of stripping the stator core of its windings. The best procedure is to obtain as much data as possible before the stripping operation. The information that should be obtained for both the running and starting windings includes (1) name-plate data, (2) the number of poles, (3) the pitch of the coil (the number of slots that each coil spans), (4) the number of turns in each coil, (5) the size of the wire on each winding, (6) the kind of connection (that is, series or parallel), (7) the position of each winding in relation to the other winding, (8) the type of winding (whether hand, form, or skein), (9) slot insulation, both size and kind, and (10) number of slots.

The information listed above must be recorded in such manner as to enable any motor repairman to rewind the motor without loss of time because of inadequate data regarding the original winding. To explain the workmanlike manner of obtaining the desired information, it will be assumed that a 32-slot, four-pole motor requires rewinding. The well-trained repairman would proceed as follows to gather the necessary data.

Record the name-plate data on a data sheet such as shown on page 8. The information contained on the name plate is very important. It tells at a glance the make of the motor, the horsepower, the voltage on which it must be operated, and the speed at full load. Among other things it indicates whether it is an a-c or d-c motor, the current it draws at full load, the type, and serial number. The last is especially important if it is necessary to order new parts. The minimum amount of information on a name plate of a single-phase motor should be (1) manufacturer's type and frame designation, (2) horsepower output, (3) time rating, (4) temperature, (5) r.p.m. at full load, (6) frequency, cycles per second-(Hertz)*, (7) number of phases, (8) voltage, (9) full load amperes, (10) code, (11) design letter for integral horsepower motors, (12) for motors equipped with thermal protection, the words "thermally protected," and for motors rated more than 1 h.p. a type number, and (13) service factor. For explanation, p. 122.

Figure 1-13 shows a 32-slot, four-pole stator of a split-phase motor as it would look if viewed from one end. Each winding consists of four sections. These sections are known as *poles,* or *groups.*

* Hertz = cycles per second.

To determine the number of poles in the motor, count the number of sections in the running winding. In Figure 1-13 the four sections of the running winding indicate a four-pole motor. If there were six sections in the running winding, it would indicate a six-pole motor. The number of poles in an induction motor governs the speed of the motor, and it is therefore essential that the correct number be recorded. A two-pole motor will rotate just below 3,600 r.p.m.; a four-pole motor about 1,750 r.p.m.; a six-pole motor just under 1,200 r.p.m., and an eight-pole motor slightly under 900 r.p.m. These speeds apply only when the motor is supplied with 60-cycle alternating current; different speeds will prevail for other frequencies.

Should the winding assembly be cut at one point and rolled flat, the winding would appear as in Figure 1-16. Notice the location of the running winding with respect to the starting winding. The starting winding overlaps two poles of the running winding. This is always true in split-phase motors, regardless of the number of poles or the number of slots in the motor. *Noting and recording the location of the running winding with respect to the starting winding is highly important.* If they are placed in any different location in rewinding, the motor may not start properly. Actually, the running and starting windings are separated by 90 electrical degrees. This is true no matter how many poles the motor has. However, the number of mechanical degrees between windings will differ with the number of poles in the motor. In the four-pole motor the windings are 45 mechanical degrees apart, and in a six-pole motor they are 30 mechanical degrees apart.

If a pole of either the running or starting winding of the motor is examined closely, it will be found to consist of three separate coils that have been wound one at a time, as illustrated in Figure 1-17. Also, each coil is wound in two slots that are separated by one or more other slots. The number of slots separating the sides of a coil, including the slots in which the winding lies, is called the *pitch*, or *span*, of a coil and is recorded as "1 and 4," or "1 and 6," or "1 and 8," as the case may be. This is shown in Figure 1-18. These coils protrude a certain distance from the ends of the slots. This is called the *end room*. This distance should be measured and recorded. It is important that the new coils do not extend beyond the slots any farther than this distance; otherwise the end plates may press against the coils and cause a ground.

The next step is to record the information thus far obtained regarding the positions of the windings and the pitch of the coils. It may be recorded by showing all the slots and the windings in the manner that most repairmen use, as illustrated in Figure 1-19. This shows a motor with 32 slots. In this method, the spans of all the coils are recorded merely by drawing curved lines in the proper slots. This is recorded first for the starting winding because it is on top and more visible than the running winding. The pitch of the running winding coils can be seen more easily if the ends of the starting winding are lifted. Each of the curved lines represents one coil of a pole. A complete data sheet for listing the information to be taken follows.

DATA SHEET FOR SPLIT-PHASE MOTOR

Make

H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	S.F.
Temp. Rise	Model	Serial #	Phase
No. of Poles	Code	No. of Slots	Time Rating

Winding	Size Wire	No. of Circuits	Pitch	Turns
Running				
Starting				

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	1
Running																																					
Starting																																					

Rotation Clockwise Counter Clockwise

All motors do not have 32 slots. Most split-phase motors have 36 slots; some have 24. A recording for a 36-slot, four-pole motor is shown in Figure 1-20 and one for a 24-slot, four-pole motor in Figure 1-21. Note in Figure 1-21 that the outer coils of each pole in this motor overlap each other and are placed in the same slot. This condition exists in many motors. Note also in Figure 1-20 that the poles of the starting winding have three and four coils in adjacent poles.

Another item of the data that should be recorded is the location of the running-winding poles with respect to the frame itself. In some motors the center of each main pole is identified by a change in the slot size. This is sufficient for properly locating the poles in rewinding. However, in the absence of the odd-sized slot, the position must be clearly indicated by punch-marking the center slot or slots.

The type of connection is the next item to be recorded. This can only be obtained if one is familiar with methods of winding and connecting the poles to each other.

Split-phase motors are connected in a variety of ways, such as single voltage, dual voltage, externally reversible, two speed, etc. In order to be able to record the kind of connection in the motor, the repairman must have a knowledge of the various connections to be found in this type of motor. It is best, therefore, to read and study the section Connecting the Winding on page 16 and How to Recognize a Connection on page 18 before attempting to record the connection.

Information regarding the number of turns of wire in each coil must be obtained and recorded. This is done by counting the turns as they are unwound or by cutting the coils on one end and counting the ends. It is important to note also whether or not there is more than one strand per conductor. Sometimes two strands of a smaller wire are used instead of one strand of a larger size. The size of wire, as determined by a wire gauge or micrometer, must also be recorded. These data are noted as the windings are removed from the stator.

When only the top, or starting, winding is burned out or shorted, it is necessary to record only the data pertaining to that winding.

Stripping the Stator

If only the starting winding needs replacing, its coils can usually be removed easily by cutting the wires on one side of the stator and then pulling them out from the other side. Sometimes the wires can be lifted from the slots after removing the wedges that hold them in place. The wedges can be removed by using a power hacksaw blade, as shown in Figure 1-22. The blade *1* is first tapped with a hammer *2* so that the teeth are embedded in the wedge; then it is driven out in the direction in which the teeth point.

If the entire stator must be rewound, it would be very difficult and time consuming to remove the windings from the core without first softening or charring the varnish and insulation. The windings are usually extremely hard because of the varnish, and to attempt to remove the wires before charring would require considerable time.

The procedure in many shops is to place the stator in a burn-off oven for several hours at approximately 400°F and then permit it to cool off. The burn-off oven may be gas fired or electric. It is important that the heating be controlled to prevent warping of the frames and damage to the lamination plating. Usually the coils on the back side of the stator are cut off flush with an air chisel or electric chisel before being placed in the oven, (Figure 1-23). Removing the rest of the coils after charring is relatively simple because the remaining coils may be pushed through the slots from the other side of the winding.

It is important to remember that the old windings should not ignite, that the temperature does not increase too rapidly, and that the stator should be allowed to cool off gradually. This applies to all types of motors.

Stator coil insulation may also be softened by placing the stator between two banks of infrared lamps. Usually the coils are first cut off at one end of the stator close to the laminations. Oil is often poured around the cut ends and insulation and allowed to penetrate before the stator is set between the lamps. Generally, 15 minutes is enough to heat the coils so that they can be removed easily.

During the process of stripping, the number of turns in each of the coils of one or two poles of the starting and running windings must be counted. This information is then recorded on the data sheet beside the curved lines that represent the pitch of the coils. At this time, also, the size of the wire of both the running and the starting windings is measured, usually by means of an American Wire Gauge or micrometer after it is stripped clean of its insulation. It is then recorded on the data sheet. The insulation on the wire is noted also.

Magnet Wire

Copper magnet wires differ mainly in the type of insulation covering the wires. It is important that this coating occupy little space and that it be able to withstand considerable and continuous heat. The thickness of the insulation depends on the application.

Insulating materials, whether on wire, in slots, or other parts of the motor, are classified according to thermal endurance. Four classes of insulation systems are used in motors and generators.

There are Class A (105°C), Class B (130°C), Class F (155°C), and Class H (180°C). Abnormally high temperatures shorten the life of motors or generators unless the proper class of insulation is used. Thus, Class A (105°C) insulation can be used on motors where the total temperature will not exceed 105°C. This rating is the total of the ambient temperature and the temperature rise. Class A motors are usually wound for continuous duty at 40 to 50°C rated rise at 40°C ambient temperature. Class B, F, and H motors must use insulation that will withstand higher temperature.

A number of companies manufacture and market magnet wires for all classes of insulation systems. These are marketed under a variety of trade names, some of which follow.

Formvar (single or heavy) wire is insulated with a film of polyvinyl resin and is one of the most widely used magnet wires. It has excellent properties such as high abrasion resistance and flexibility and can be used in essentially all Class A applications. Some of the applications are stators, armatures, transformers, electromagnets, etc. Some of the magnet wires with Formvar have an outer covering of nylon for high resistance to strong solvents used in common varnishes. Other trade names are Formex, Nyform, and Nyclad. Magnet wire manufacturers publish handbooks describing their products.

Class B 130°C magnet wires usually have a polyurethane film with an outer covering of nylon. Some of these wires can be soldered directly without prior film removal. Some of the trade names for Class B are Nylac, Beldsol, Heavy Alkanex, and Formvar with glass covering.

Other types of wire coverings are used on Class F and H. Generally these are used on motors where extreme heat prevails; glass fibers bonded with silicone or other materials are used for this application.

Motors are rewound, to a lesser degree, with enameled wire covered with a layer of cotton, silk, or glass fiber. These are abbreviated S.C.E., S.S.E., and S.G.E. If a No. 18 wire has a single layer of cotton over enamel it is recorded as No. 18 S.C.E. In recording a Formvar insulated wire, use the designation No. 18 Single Formvar. It should be remembered that most of the coated films are either single or heavy coated and should be recorded as such. When in doubt, use the heavy coated film. Wire with a heavy coated film is approximately 0.001 in. larger in diameter than a single coated wire.

After the winding is removed, the slot insulation should be cleaned out. If the insulation is charred, its removal is comparatively simple, because it will fall out as the wires are removed. But if the insulation sticks to the sides of the slots, a knife or other sharp instrument may be used to loosen it.

The usual procedure after the winding and the insulation are removed is to blow out whatever dirt, grit, or foreign material may be lodged in the stator. This is done by means of an air compressor. The pressure of the air flowing through a small nozzle will clean the stator thoroughly. If the stator is greasy, it should be washed clean with a cleaning fluid, preferably nonflammable.

Slot Insulation

With the completion of the procedure described above, the motor has been disassembled. Preparations for rewinding may now be started. Before placing the winding in the slot, some form of insulation must be installed so that the wires do not touch any part of the iron core. Different types of material are available for this purpose. Some of the more common materials used are (1) ragstock paper, highly refined to insure chemical purity and physical strength (manufactured in various thicknesses and cuffed; this is a Class A insulation); (2) Mylar combination or sandwich slot insulation for Class A; (3) Dacron-Mylar combinations for Classes B and F; (4) nylon paper for Classes B through H; it is particularly resistant to high temperatures, has high tensile strength and high standards of electrical performance.

There are many other types of insulating materials. The best procedure to follow when reinsulating a core is to replace it with the same type and thickness of insulation as was employed in the original winding.

The insulation is cut [as shown in Figure 1-24(a)] so that it is about ¼ in. longer than the slot and is then shaped to fit the walls of the slot. The ends of the insulation are often cuffed, as shown in Figure 1-24(b) to prevent it from sliding in the slot and possibly being the cause of a grounded coil. This insulation paper is manufactured and sold in rolls in assorted widths and thicknesses and is available in many motor supply houses. Cuffed insulation is cut to a length to fit the slots; an insulation cutter is used for this purpose. For the average size of fractional-horsepower motors, insulation paper approximately 0.007 to 0.015 in. thick is suitable for slot insulation, and varnished cambric 0.007 in. thick is generally placed between the running and starting windings. Figure 1-24(a) also shows the manner of installing a feeder strip of insulation that covers the edges of the slot while winding. This feeder may be removed after winding the coil, or its ends may be folded over and left in the slot.

Rewinding

There are three methods of winding a split-phase motor. These are (1) hand winding, (2) form winding, and (3) skein winding. Each of these methods is used in practice, and each has certain advantages. In all cases, the entire running winding is placed in the slots first, then the starting winding is wound on top of it. Suitable insulation should be used between the running and starting windings. After the starting winding is wound on top of the running winding, place pre-formed wedges (wood, fiber, or other standard material) over the winding in each slot to keep the wires in the slot compact and to guard against vibration. These wedges (Figure 1-25) usually come in 36 in. lengths and various widths and are cut to fit the length of the slot.

Hand Winding Hand winding may be employed for both the running and the starting windings. There are two main advantages to this type of winding: (1) a tighter winding is possible, especially where end room is limited, and (2) a winding form is unnecessary. In this method, the wires are placed in the slots, one turn at a time, starting with the inner coil and continuing until all the coils of the pole are wound. In the explanations that are to follow, it will be assumed that a 32-slot stator is being wound.

1. The stator and spool of wire are arranged as shown in Figure 1-26, and the end of the wire is placed in the bottom of the slot. If the stator has no base, use supports, vise, or stator holder as shown in Figure 1-27. The inner coil, pitch 1 and 4, is wound with the required number of turns.
2. After all the turns have been put on the inner coil, the next coil, pitch 1 and 6, is wound in the same direction, as illustrated in Figure 1-28. Continue in this manner until all the coils of the pole are installed. The wire should not be cut until the entire pole is finished. It is desirable before starting the winding to place dowel pins (or wooden wedges) in the center empty slots of the pole, as shown in Figure 1-29, and wind the turns of wire under the ends of the pins.

This prevents the coils from coming out of the slots while winding.

3. After the pole is finished, wooden or fiber wedges are placed in the slots above the wires so that they will not slip out, and the dowel pins are removed.

4. The other poles are wound in the same manner as the first pole.

5. The starting winding is wound on top of the running winding halfway between the running winding poles, using suitable insulation (varnished cambric) between windings. Even though a hand winding was used for the running winding, the practice has been to use either the form winding or skein winding for the starting winding. As each pole of the starting winding is finished, wedges are placed in each slot to keep the wires in place. Figure 1-30 shows several poles of the completed winding.

Form Winding In form winding, the coils are first made on a wooden or metal form and then removed from the form and placed in the slots. This is the most common method of winding a split-phase motor.

1. The first step is to obtain the size for the form from the core of the stator. A single pieces of heavy wire is shaped for the inner coil, pitch 1 and 4, as shown in Figure 1-31, allowing at least ¼ in. extension at each end of the slot. The same procedure is repeated for the next larger coil, with extensions beyond the slot ends sufficient to provide spacing of about $\frac{3}{16}$ in. between the first and second coils. The size of the additional coil or coils is obtained in the same manner.

Blocks of wood having a thickness about three-quarters of the depth of slot are cut and shaped for each size and bolted together as illustrated in Figure 1-32(a).

2. The required number of turns of wire are wound on the blocks, starting with the smallest. The coils are tied with cord to keep the turns in position and are then removed from the form. If the coils are made by means of a manufactured adjustable concentric winding form as shown in Figure 1-32(b), the coils may be wound quickly and accurately for many makes of motors. The advantage of this type of form lies in the fact that considerable time is saved in winding the motor. It is unnecessary to construct new forms for each motor. Figure 1-33 shows the procedure of inserting these coils into the stator.

3. The coils are now placed in the slots and firmly pressed down to the bottom.

4. The wires are made fast in the slots with wedges of Class A, B, F, or H material, depending on the class of insulation in the motor.

Skein Winding The skein-winding method is used mainly for the starting winding. This type of winding uses one long coil for each pole. The coil is made large enough to be wound into all the slots necessary to complete the individual sections of a pole. The advantage of this method lies in the fact that many conductors may be placed in the slot at one time. However, some motor shops convert from skein to form coils, especially if an adjustable winding head is available.

1. The size of the skein coil is usually obtained from the old one at the time the motor is disassembled. A skein winding is easily recognizable because the entire pole may be removed as one coil. However, if the size of the skein cannot be found in this manner, it can be ascertained by winding a single piece of wire in the slots, as shown in Figure 1-34(a). Enough room should be allowed so that the winding to be put on will not be crowded. The two ends are twisted together and the wire removed from the slots.

2. The wire is shaped into a rectangular or oblong form, as shown in Figure 1-34(b). A form is then used for winding the skein coil. Actually the shape of the coil does not matter too much as long as the circumference is the same. A form is shown in Figure 1-35(a).

3. The required number of turns of the skein is then wound around the form with the ends of the wire being left free. Before removing the coil from the form, tie it at several places to prevent unraveling.

Another method of winding makes use of two small empty spools which can be nailed to the side or top of the workbench. The turns are wound around the spools, as shown in Figure 1-35(b).

Still another method employs the use of an adjustable winding head shown in Chapter 4, page 98. Although used for three-phase coils, it can be modified for skein coils. The advantage of this head is that it is adjustable and can be used for any type of skein coil merely by moving the form to the proper length.

4. The coil is now removed from the form and placed in the slots of the smallest pitch in the manner illustrated in Figure 1-36(a). After this, the coil is twisted and placed in the slots of the next larger pitch, then continued, as shown in Figure 1-36(b), until the pole is complete. In many motors the coil is placed in the same slots two or three times, depending upon the manner in which the original coil was wound. Figure 1-37 shows a coil wound twice in the same slots.

Changing Hand Winding to Skein Winding Very often it is desirable to change a stator from hand winding to skein winding, especially when the wire is not heavier than No. 21 A.W.G. However, this is not advisable if the wire is heavier, since difficulty will be encountered in making the twists.

In order to show how this is accomplished, an explanation will be given for a pole which originally had a total of 85 hand-wound turns, of which 20 turns were in pitch 1 and 4, 38 turns in pitch 1 and 6, and 27 turns in pitch 1 and 8. The total number of turns in the pole after being installed in the slots should be as near 85 as possible, and there should be approximately the same number of turns in each slot as in the original winding. The skein is wound with 21 turns and placed in pitch 1 and 4 one time, in pitch 1 and 6 two times, and in pitch 1 and 8 one time, as illustrated in Figure 1-37. There will be, then, 21 turns in pitch 1 and 4, 42 in pitch 1 and 6, and 21 in pitch 1 and 8, with a total of 84 turns for the pole. This number is near enough the original total of 85 turns; also, the number of turns in each slot approximates the original closely enough for satisfactory performance of the motor. To obtain the size of the skein, proceed in the manner illustrated in Figure 1-34(a) except that the wire must be wound in the middle pitch two times.

Connecting the Windings—Single Voltage

After all the poles of the motor have been wound, the next step is to connect the windings. Regardless of the number of poles, it is essential that adjacent ones be of opposite polarity. This is accomplished by connecting them in such manner that the current will flow through the first pole in a clockwise direction and through the second pole in a counterclockwise direction, (Figure 1-38) and likewise in alternate directions through the remaining poles.

Four-pole motors connected in series are by far the most common in use today. Therefore, this connection will be explained. It should be remembered that if the running winding is connected in series, the starting winding is connected in this same manner. There are exceptions to this, but they are not often encountered.

Series Connection for Four Poles of the Running Winding Refer to Figure 1-38 and connect the wires as illustrated, namely, the end lead of pole *1* to the end lead of pole *2*. Next, connect the beginning lead of pole *2* to the beginning lead of pole *3*, as shown in Figure 1-39. Continue, as illustrated in Figure 1-40, by joining the end lead of pole *3* to the end lead of pole *4*. The power-line leads are then connected to the beginning lead of pole *1* and the beginning lead of pole *4*.

For the sake of simplicity, the above noted connections may be shown by representing each pole as a rectangular block, as in Figures 1-41 to 1-43.

For comparison, the entire running winding of a 36-slot, four-pole motor is illustrated in Figure 1-44, showing both the detailed winding and the simplified form. Notice that each pole is wound in the same manner, but that the poles are connected so that alternate polarity is maintained in adjacent poles.

After experience has been gained in winding the running poles, the student will be able to wind all the poles without cutting the wire after one is finished. Care must be taken to alternate the direction of winding for each pole; thus, the first pole should be wound clockwise; the second counterclockwise; and third, clockwise; and so on.

In order to determine whether the polarity of the poles is correct after the connections have been completed, a low-voltage direct current is connected to the winding, and a compass is moved inside the stator from one pole to the next. If the connections are correct, the compass needle will reverse itself at each pole.

Series Connection for the Starting Winding The poles of the starting winding are connected so that they too alternate in polarity. The method of connecting them to each other is the same as that described above for the running winding. The only difference is that the centrifugal switch is placed either in series with the lead from pole *4*, or between pole *2* and pole *3*. Figures 1-45 and 1-46 show the proper connections for both the running and starting windings, Figure 1-45 having the centrifugal switch at the end of the starting winding and Figure 1-46 having it in the center of the winding. Figure 1-47 represents both windings placed in circular form as they would actually be inside the stator.

The connection drawing can be shown in simpler form by making a schematic diagram, like that in Figure 1-48(a). Such a diagram does not indicate the number of poles, but it does show how the lead wires from the windings are connected to the power line. It is seen that two wires are brought out directly from the running, and likewise, two wires are brought out from the starting winding. The direction of rotation of the motor can easily be changed by reversing the lead wires of either the running or the starting winding. The running winding leads are marked T_1 and T_4.

The starting winding leads are marked T_5 and T_8. Figure 1-48(b) shows the method of connecting the leads for clockwise and counterclockwise rotation.

A six-pole motor is connected in the same manner as a four-pole motor, except that two more poles must be added. Figure 1-49 shows a connection diagram of a six-pole, split-phase motor.

Parallel Connections Although the majority of split-phase motors are series connected, there are some that are parallel connected by manufacturers. These are known as *two-parallel* (or *two-circuit*) connections. A two-parallel connection is one in which there are two circuits for each winding, as shown in Figures 1-50 and 1-51. However, regardless of the number of circuits in the running winding, the connections must be such that the adjacent poles have opposite polarity.

How to Recognize the Connection

Before attempting to record the type of connection on the split-phase or other a-c motors, read and study the name-plate information. This will tell you whether it is a single or dual voltage motor, single- or two-speed motor, and the exact speed of the motor, among other data. If the frequency is 60 cycles, a four-pole motor will run at approximately 1725, a six-pole motor about 1150, a two-pole motor about 3450. These poles are easily visible on the stator, both for the starting winding and running winding.

Leads connected to the terminal board or centrifugal switch or brought out should be left intact. Make a drawing of where these leads are connected, bearing in mind that those leads connected to the bottom heavy wire winding are those of the running winding, while lighter wires are those of the starting winding. It may be necessary to cut the binding cord holding the windings together to separate the leads. For a single-voltage, externally-reversible motor there will be four leads, two from each winding. One lead of the starting winding will usually connect to the centrifugal switch.

In most single-voltage, split-phase motors, the poles of the winding are connected in series for alternate polarity.

The procedure in many shops, especially if the winding is hard baked, is to disconnect the wires from the terminal board, first marking them. The stator is then placed in a burn-off oven to char the winding. This not only permits easy stripping, but also enables the winder to check on the connection. This will also make it easier to count the number of turns.

Split-phase and other motors of this type may have some complicated connections. Experience and a good knowledge of connections will enable the winder to recognize these connections without much difficulty. Generally, however, most of the connections are simple and should give the student very little trouble.

Methods of Splicing and Taping Leads

One method of splicing the wires that connect the poles is to remove the insulation from about 2 in. of the ends of the two wires, twist the two ends securely together, and solder. After this, the splice is taped. This method is illustrated in Figure 1-52, where the end lead of pole *1* is spliced to the end lead of pole *2*.

Another method utilizes fiber glass or varnished sleeving instead of tape. The detailed procedure of making this kind of splice is illustrated in Figure 1-53, which shows the five steps involved in the operation. First, remove the insulation from about 1 in. of the end lead of pole *1* and the end lead of pole *2;* second, place about 1 in. of sleeving, or as much as is necessary, on each lead; third, place about 2 in. of a larger sleeving over one of the smaller sleevings; fourth, splice the two wires, using a straight splice, then solder; fifth, slide the small sleeving toward the splice and slide the larger sleeving over the soldered splice so that it is entirely covered. The entire operation requires less time than taping and produces a neater splice.

Still another method uses a torch to weld the wires together. A short piece of sleeving is slipped over the joint and then tied to the winding. See Figure 1-54.

One of these methods should be used in splicing the coils of both the running and starting windings. After all the coils have been properly connected, flexible leads are spliced to the wires of both the running and the starting windings that are to be connected to the power line. Again, the preferred splicing is that in which the fiber glass sleeving is used. In addition, care must be taken to tie the leads to the windings with twine, as shown in Figure 1-55, so that if the leads for any reason are pulled, they will not be torn from the winding. The entire winding is then tied together with a suitable cord or tape, such as nylon, linen, or cotton. This keeps the winding from unraveling, makes it compact, and prevents, to a certain extent, the wires from vibrating and moving.

Testing the New Winding

After the rewinding and connections have been completed, it is important that the windings and connections be thoroughly tested for shorts, grounds, open circuits, and incorrect connections. This must be done before varnishing and baking so that any trouble that is discovered may be corrected more readily. Detailed instructions for these tests will be found later in this chapter under Troubleshooting and Repairs.

Baking and Varnishing

When all the connections between poles of the windings have been completed and tested and the flexible leads to the power line attached and tied, the stator should be placed in a baking oven at a temperature of approximately 250°F and preheated for a short period of time, approximately 1 hour. This removes moisture from the windings and increases the penetration of the varnish. The stator is then dipped into a container of insulation varnish compatible with the type of magnet wire used. It is important to remember that the varnish must be thin enough to penetrate the winding and thick enough to leave an adequate film when baked. The varnish may become thickened due to evaporation of the thinning fluid. If this happens, use a thinner recommended by the manufacturer.

After the winding has soaked in the varnish for approximately one-half hour or until all bubbling has ceased, it is removed from the container and allowed to drip. After it has stopped dripping it is again placed into the baking oven and baked for several hours. In using any type of varnish, make certain the manufacturer's recommendations and directions are followed. When the stator is removed from the oven, the inner surface of the core should be scraped to remove the adhering varnish, so that there will be sufficient space for the rotor to turn freely.

Dipping and baking bonds the entire winding into a solid mass that is not subject to movement. It seals the windings against moisture and foreign material and increases the mechanical and dielectric strength of magnet wires.

There are other types of varnishes that do not require baking and are called *air drying varnishes*. Many shops use this varnish for fractional horsepower stators of the thermal Class A type. Here again the manufacturer's recommendations should be followed.

Many shops use a solventless epoxy resin or polyester varnish that can be applied to windings in less than 20 minutes. These varnishes are completely solventless and give the same protection that ordinary varnishes provide. The winding is heated first by applying approximately half voltage. The resin is then poured through the heated windings while the stator is kept in a horizontal position. The resin is permitted to trickle through the slots. After the pouring has been completed, the winding is kept heated by sending current through the coils for about five minutes. This permits the resin to cure and gel quickly. The entire process should take less than one-half hour. Figure 1-56 shows how the varnish is applied to a three-phase motor. The same method is used for single-phase motors.

Reversing a Split-phase Motor

Since the direction of rotation of a split-phase motor may be changed by reversing the wires of either the running or the starting winding, the process is a simple one. Figure 1-57 shows the wires of the starting winding reversed as compared with those in the connection shown in Figure 1-48(a).

Most split-phase motors have terminal plates (or blocks) attached to the end bracket. Instead of all the lead wires being brought outside the motor, these leads are brought to the terminal plate, as illustrated in Figure 1-58. On motors of this type, the stationary part of the centrifugal switch is usually on the same plate. To reverse a single-voltage motor with a terminal plate, interchange the starting or running winding leads.

It is sometimes necessary to connect the motor for a definite direction of rotation, usually counterclockwise as viewed from the end opposite the drive. This can be easily accomplished if it is understood that the rotation is from a starting winding pole toward a running pole of the same polarity. The reason for this is that the starting winding magnetic field will build up before the magnetic field of the running winding. This causes the magnetic field to rotate from the starting winding pole to running winding pole of the same magnetic polarity, in turn causing the rotor to spin in the same direction.

Consequently, it is a simple matter to connect the main and auxiliary windings in such a manner as to cause definite direction of rotation. Figure 1-47 shows a four-pole motor connected for clockwise rotation, Figure 1-49 a six-pole motor connected for counterclockwise rotation. Note the current flow in the main and auxiliary windings. It is necessary at times to make certain of the direction of rotation of a burnt-out motor prior to stripping. Try to trace out the leads of the main and auxiliary windings, keeping in mind the principle outlined above. Remember, also, that: (1) the running winding has heavier wire than the starting wire; (2) one wire of starting winding is usually connected to the centrifugal switch; (3) the starting winding is usually wound on top of the running winding.

Connecting Dual-voltage, Split-phase Motors

Most split-phase motors are made for single-voltage operation. However, some split-phase motors, usually motors made for a specific application, are made so that they can be connected for either of two voltages, usually 115 and 230 volts. Such a motor generally has a main winding of two sections and a starting winding of one section. A sufficient number of leads are brought out to permit a changeover from one voltage to another. An externally reversible motor must have the two starting winding leads brought out also.

If the motor is to operate on 115 volts, the two sections of the running or main winding are connected in parallel, as shown in Figure 1-59. If operation on 230 volts is desired, the two sections are connected in series, as shown by the terminal markings in the same figure. In either case, the starting winding generally operates on the lower voltage only and is connected across one of the sections of the running winding. This means that the starting or auxiliary winding is intended for only one voltage.

In the dual-voltage motor, one section of the running winding is wound first, just as in a single-voltage motor. The second section is wound directly over the first with the same number of turns, the size wire, and in the same slots. Two wires are brought out of each section. The leads of the first section are marked T_1 and T_2. The leads of the second section are marked T_3 and T_4. The usual starting winding is wound last. Its leads are marked T_5 and T_8. This is shown in Figure 1-60. Sometimes the starting winding is also wound in two sections. These would be marked T_5 and T_6 for one section and T_7 and T_8 for the other section.

Another method consists of winding both sections at the same time using two separate wires. This saves considerable time.

In still another method, used in many shops, each section consists of half the number of poles. For example, in a four-pole motor, two poles are wound and connected in series as one section and its leads marked T_1 and T_2. The other two poles are wound, and its leads marked T_3 and T_4. For the lower voltage the sections are connected in parallel, and for the higher voltage the two sections are connected in series. In either case, the starting winding is connected across one section of the running winding. This is shown in Figure 1-61.

It is very important that the sections be connected for alternate polarity, otherwise the motor will not run.

Figure 1-62 shows a four-pole, two-voltage reversible motor using a long jumper or top-to-bottom or finish-to-start connection. Figure 1-61, on the other hand, uses the short jumper or top-to-top or finish-to-finish connection. The long jumper connection produces a quieter starting motor.

Motor Overload Protective Devices

Most overload devices used on single-phase motors are thermally operated and serve as protection against dangerous overheating due to overload, failure to start, and dangerous temperatures. The protector is mounted in any convenient location inside the motor housing, usually on the centrifugal switch terminal block. Essentially, this device consists of a bimetallic element that is connected in series with the line. This element is made of two metals that expand at different rates when heated. These are bonded together, so that when the entire element is heated, it will bend and open the circuit to the motor. See Figure 1-63(a) and (b). The heat causing the element to bend may come from the motor windings, excessive motor temperatures, or from an auxiliary heater coil placed under the bimetallic strip and connected in series with the motor windings.

A popular type of thermal device consists of a round dishshaped, bimetallic disc, with two contacts on diametrically opposite sides bearing against two stationary contacts, marked 1 and 2 (Figure 1-64).

Another type consists of the previously explained disc, but mounted directly underneath the bimetallic strip and in close proximity to it, is an auxiliary heater. Figure 1-65(a) and (b) show the closed and open position of the disc. These devices usually have three terminals numbered *1, 2,* and *3,* as shown. Terminals *1* and *2* are stationary contact points, and *2* and *3* are the heater connections. When an overload occurs, the current flows through the heater and will produce sufficient heat to cause the disc to snap quickly and open the contacts and thereby open the circuit, stopping the motor.

On some types, the contacts automatically close when the bimetallic element cools. On other units, a reset button must be operated manually to restore the motor to operation.

This type of thermal unit can be used for single- and dual-voltage motors. In the single-voltage motor, terminal *2* is not used. The heating element and disc are connected in series with the entire motor winding. This is illustrated in Figure 1-66. In a dual-voltage motor, the heating element is connected in series with half the main winding for lower voltage and the entire winding for high voltage. This is because the current on high voltage is half that on low voltage. An illustration of the connections is shown in Figure 1-67.

There are other types of thermal devices in use today. One of these utilizes a bimetallic unit which is heated by current flow through the unit itself. This type uses a toggle link to open the contacts. This unit is mounted on the terminal plate, which also serves as a connection block for the winding leads. The operation is as follows. When a condition of excessive temperature or current occurs, the bimetal arm is heated and deflects in a direction tending to open the contacts. The contacts will remain closed, however, until the downward force of the bimetal arm overcomes the opposing force of the toggle link and snaps open the contacts. This type is shown in Figure 1-68.

Thermal protectors of special construction can be imbedded in stator windings to protect the motor from excessive winding temperatures. These protectors have a snap-acting disc with normally closed contacts. The disc is operated both by the current passing through it and by heat received from the windings. When the temperature of the disc reaches a predetermined calibration point corresponding to the maximum safe limit of the winding, the disc snaps open to interrupt the circuit. When the winding temperature returns to a normal safe limit, the protector resets automatically. Thermal protectors are frequently used with hermetic motors, and, in such cases, the protectors are installed in the end windings and located so that the best possible heat transfer between the winding and thermal unit can be afforded without abusing the insulation on the motor winding. It is important to exercise care in assembly, since additional forming of the winding for location of the protector may injure or weaken the insulation on the winding.

Terminal Markings for Single-phase Motors

The following standards for terminal markings have been reproduced from the National Electrical Manufacturers Association Standards Publication M.G.1, 1968. The connection diagrams of split-phase motors—single voltage—reversible will be found in the illustration section of Chapter 1, Figure 1-69.

MG1—2.40 General

A. DUAL VOLTAGE

Regardless of types, when a single-phase motor is reconnectible series-parallel for dual voltage, the terminal marking shall be determined as follows: *

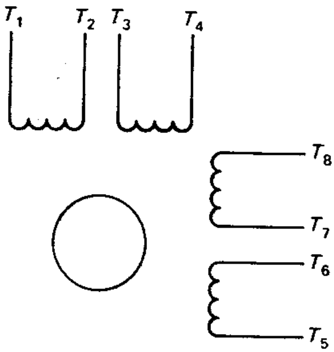
For the purpose of assigning terminal markings, the main winding is assumed to be divided into two halves, and T_1 and T_2 should be assigned to one half and T_3 and T_4 to the other half.

For the purpose of assigning terminal markings, the auxiliary winding (if present) is assumed to be divided into two halves, and T_5 and T_6 should be assigned to one half and T_7 and T_8 to the other half.*

Polarities shall be established so that standard direction of rotation (counterclockwise facing the end opposite drive) is obtained when the main winding terminal T_4 and the auxiliary winding terminal T_5 are joined, or when an equivalent circuit connection is made between the main and auxiliary winding.*

The terminal marking arrangement is shown diagrammatically in the following figure.*

* Approved as NEMA Standard 11-16-1967.



Dual Voltage

NOTE I—It has been found to be impracticable to follow this standard for the terminal markings of some definite-purpose motors. †

NOTE II—No general standards have been developed for terminal markings of multispeed motors because of the great variety of methods employed to obtain multiple speeds. †

B. SINGLE VOLTAGE

If a single-phase motor is single voltage or if either winding is intended for only one voltage, the terminal marking shall be determined as follows: *

T_1 and T_4 shall be assigned to the main winding and T_5 and T_8 to the auxiliary winding (if present), with the polarity arrangement such that standard direction of rotation is obtained if T_4 and T_5 are joined to one line and T_1 and T_8 to the other. *

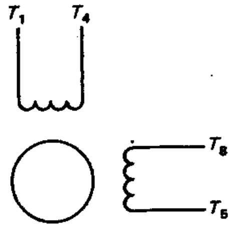
The terminal marking arrangement is shown diagrammatically in the figure to follow. *

MG1—2.41 Terminal Markings Identified by Color

When single-phase motors use lead colors instead of letter and number markings to identify the leads, the color assignment shall be determined from the following: *

T_1 – Blue	T_5 – Black
T_2 – White	T_8 – Red
T_3 – Orange	P_1 – No color assigned
T_4 – Yellow	P_2 – Brown

* Approved as NEMA Standard 11-16-1967.
† Approved as Authorized Engineering Information 11-16-1967.



Single Voltage

MG1—2.42 Auxiliary Devices within Motor

The presence of an auxiliary device or devices such as a capacitor, starting switch, thermal protector, and so on, permanently connected in series between the motor terminal and the part of the winding to which it ultimately connects shall not affect the marking unless a terminal is provided at the junction.*

Where a terminal is provided at the junction, the terminal marking of this junction shall be determined by the part of the winding to which it is connected. Any other terminals connected to this auxiliary device shall be identified by a letter indicating the auxiliary device within the motor to which the terminal is connected.*

MG1—2.43 Auxiliary Devices External to Motor

Where the capacitors, resistors, inductors, transformers, or other auxiliary devices are housed separately from the motor, the terminal markings shall be those established for the device.*

MG1—2.44 Marking of Rigidly-mounted Terminals

On a terminal board, the identification of rigidly-mounted terminals shall be either by marking on the terminal board or by means of a diagram attached to the machine. When all windings are permanently connected to the rigidly-mounted terminals, these

*Approved as NEMA Standard 11-16-1967.

terminals may be identified in accordance with the terminal markings specified in this publication. When windings are not permanently attached to rigidly-mounted terminals on a terminal board, the rigidly mounted terminals shall be identified by numbers only, and the identification need not concide with that of the terminal leads connected to the rigidly mounted terminals.*

MG1—2.45 Internal Auxiliary Devices Permanently Connected to Rigidly-mounted Terminals

If the motor design is such that the starting switch thermal protector or other auxiliary device is permanently connected to a rigidly-mounted terminal, some variation from the illustrated connection arrangements of MG1—2.47 (through MG1—2.53) will be required. However, any variations shall be based on the provisions of MG1—2.46.*

MG1—2.46 General Principles for Terminal Markings for Single-phase Motors

The terminal marking and connection procedure given in MG1—2.40 through MG1—2.45 and in the schematic diagrams MG1—2.47 through MG1—2.53 are based on the following principles: †

A. First Principle

The main winding of a single-phase motor is designated by T_1, T_2, T_3, and T_4 and the auxiliary winding T_5, T_6, T_7, and T_8 to distinguish it from a quarter-phase motor which uses odd numbers for one phase and even numbers for the other phase.†

B. Second Principle

By following the first principle, it follows that odd-to-odd numbered terminals of each winding are joined for lower voltage (parallel) connection and odd-to-even numbered terminals are joined for high voltage (series) connection.†

* Approved as NEMA Standard 11-16-1967.
†Approved as Authorized Engineering Information 11-16-1967.

C. THIRD PRINCIPLE

The rotor of a single-phase motor is represented by a circle, even though there are no external connections to it. It also serves to distinguish the single-phase motor schematic diagram from that of the quarter-phase motor in which the rotor is never represented.†

Author's note: On dual-voltage motors, the auxiliary winding is usually designed for the lower voltage and should have two leads marked T_5 and T_8.

Two-speed, Split-phase Motors

Since the speed of an induction motor is governed by the number of its poles (for a given line frequency), to change the speed of a split-phase motor, it is necessary to change the number of poles. This may be accomplished in several ways. One method requires the use of an additional running winding, but not an extra starting winding; another method requires two running windings and two starting windings; and a third method makes use of special connections, known as *consequent-pole connections,* without requiring additional running or starting windings.

Two Running Windings, One Starting Winding

In this type of variable-speed motor, three windings are needed, namely, two running and one starting. Usually these motors are wound for six and eight poles and run at speeds of approximately 1150 and and 875 r.p.m., respectively. Their most common use is in electric fans.

The coils must be placed in the correct slots when rewinding this motor; therefore, careful note should be made of the exact position of the original coils at the time the motor is stripped. A diagram of the position of the windings in relation to each other is shown in Figure 1-70.

The wiring of a two-speed, split-phase motor is illustrated in Figure 1-71. A schematic connection diagram for such a motor is shown in Figure 1-72. A double-contact centrifugal switch, whose action is similar to that of a double-throw hand switch, is necessary to connect the eight-pole running winding to the power line when it is desired to run on low speed. The circuit in Figure 1-72 shows

† Approved as Authorized Engineering Information 11-16-1967.

that this type of motor must always start on high speed, regardless of whether the switch is set for high or low speed. When set for low speed, however, the centrifugal switch disconnects the high-speed running winding and connects the low-speed running winding after the motor has reached a predetermined speed.

Two Running Windings, Two Starting Windings

In rewinding a motor having four windings, the coils of the different windings must be placed in the proper slots with respect to each other. A typical layout of a combination six- and eight-pole motor is illustrated in Figure 1-73 and the wiring diagram of the starting and running windings of the six-pole portion is shown in Figure 1-74. The starting winding has only three poles, and these are connected to give the same polarity. When current is applied, a pole of opposite polarity will be formed in the stator frame between each pair of these poles. This produces twice as many magnetic poles as there are wound poles, and the result is that, in effect, the starting winding has six poles. When poles are connected in this manner, they are said to be *consequent poles*.

In the eight-pole part of the motor, the four wound poles of the starting winding are connected so as to give the same polarity, and the number of magnetic poles in the starting winding is doubled for the reason just mentioned.

A schematic diagram showing the line connections and the centrifugal-switch connections for this type of two-speed motor is represented in Figure 1-75. This diagram reveals that the centrifugal switch serves only to disconnect the starting windings when the motor reaches the predetermined speed, and that the motor may be started and operated in low speed without first starting in high speed.

One Running Winding, One Starting Winding—Consequent-pole Connections

As explained above, when poles are connected so that adjacent ones have the same polarity, the magnetic effect is to produce twice as many magnetic poles as there are wound poles. The way in which this is accomplished is illustrated in Figure 1-76. This makes it possible to provide a two-speed motor by arranging the connections between the poles in such manner that when a speed switch is thrown in one direction it will connect the poles so that they have alternate polarity and the motor operates as a four-pole motor. When it is thrown in the opposite direction, it will connect the poles so that they have the same polarity and the motor operates as an eight-pole motor by means of the consequent-pole method. [See Figure 1-77(a) and (b).] For high speed, leads *B* and *D* are connected together to one line wire, and leads *A* and *C* are connected together to the other line wire. Note that for this speed the running winding is connected two-parallel. For low speed, lead *A* is connected to one line wire and leads *C* and *D* are connected to the other line wire. For this connection the running winding is connected series consequent. For both speeds, the starting winding is connected series consequent.

Calculations for Rewinding and Reconnecting

Before any rewinding or reconnecting calculations are made, it is best to understand some facts about wire size and its measurements. The size of copper magnet wire is designated by its diameter and identified by a gauge number. The diameter may be measured in thousands of an inch by a micrometer and its gauge number by means of an American Wire Gauge (A.W.G.).

Refer to Table I in the Appendix and note that the first column of this table for bare copper wire lists the various sizes of wire. The second column lists the diameter of each wire in inches. For size No. 18 in the first column, the diameter is 0.0403 in. The figure can be read as 40.3 thousands of an inch or 40.3 mils just by moving the decimal point three numerals to the right. A mil, therefore, is one thousandth (1/1000) of an inch.

Since we are primarily interested in the safe ampere carrying capacity of a wire, all computations involving round copper wire are based on a term called *circular mil area.* This area is arrived at by multiplying the diameter in mils by itself. In other words, the diameter squared is the circular mil area. Looking at column 3 in the table alongside No. 18 wire, we find the area in circular mils to be 1624. This is found by multiplying 40.3 by 40.3, the diameter in mils squared.

From Table I a number of basic facts can be deduced:

1. The larger the gauge number, the smaller the wire; for example, No. 20 is smaller than No. 17. This is shown in the wire table.

Number 20 wire has an area of approximately 1000 c.m. (circular mils), whereas No. 17 has an area of 2,000 c.m.

2. By examining the wire table, it can be seen that the area in circular mils doubles or halves every three numbers. By adding three gauge numbers, the circular mil area is halved. By subtracting three gauge numbers, the circular mil area is doubled. Thus, No. 17 is twice the circular mil area than No. 20, and No. 18 is half the circular mil area of No. 15. Two No. 18 wires are the equivalent in area to one No. 15.

3. A No. 10 wire is approximately 100 mils in diameter and has approximately an area of 10,000 circular mils.

4. Every ten sizes the circular mil area is divided or multiplied by ten. For example, a No. 10 wire has a circular mil area ten times that of No. 20 wire. From this and the previous fact, the circular mil area of nearly all wires can be approximated.

5. Adding three wire sizes doubles the resistance. Subtracting three wire sizes halves the resistance.

6. Adding three wire sizes halves the weight of the wire. Subtracting three wire sizes doubles the weight of the wire.

Rewinding for a Change of Voltage

One of the simplest types of changes is that involving just a voltage change. The only change necessary for this type of conversion is in the wire size and number of turns per coil. The coil spans and connection are not changed.

RULE 1.

$$\text{New turns} = \frac{\text{new voltage}}{\text{orig. voltage}} \times \text{orig. turns per coil}$$

RULE 2.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

The following example will illustrate the above rules. A 115-volt, ⅓-hp., 1725-r.p.m. 60-cycle, split-phase motor having 32 slots is to be rewound for 230 volts, same speed. Find new turns per coil and wire size for both windings.

Data: Running winding,	span	1-8	2-7	3-6	#17
	turns	35	18	14	
Starting winding,	span	1-8	2-7		#22
	turns	75	42		

Use Rule 1 for new turns.

Since the new voltage is twice the original voltage, the turns per coil will be doubled.

Running winding, new turns	70	36	28
Starting winding, new turns	150	84	

Use Rule 2 for new circular mil area.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

$$= \frac{115}{230} = \frac{1}{2} \text{ c.m. area}$$

R.W. { c.m. area of #17 = 2,048 c.m.
½ of 2,048 = 1,024 c.m.
1,024 c.m. = #20

S.W. { c.m. area of #22 = 642 c.m.
½ of 642 = 321
321 c.m. area = #25

The starting winding could also be replaced with the original turns and size wire if it is connected across one-half of the running winding. In this case, the running winding will also act as an autotransformer. Since the voltage across two poles of a four-pole running winding is one-half the line voltage and since the starting winding is connected across two poles, it is apparent that the starting winding will receive one-half the line voltage.

Assume the above motor is to be rewound for dual-voltage operation on 115 or 230 volts. Proceed as follows:

1. Rewind the running winding as before for 230 volts. However, bring out six leads for dual-voltage, externally reversible operation as shown in Figure 1-62.

2. Use the same turns in the running winding as calculated in the previous example.

3. Since the starting winding is connected to one section of the running winding, no change is necessary.

4. The two sections of the running winding are connected in series for 230 volts and in parallel for 115 volts.

Reconnecting for a Change in Voltage

The principle involved in all reconnections for voltage change is that the original pole voltage remains the same in spite of the line voltage change. Thus, a four-pole, 230-volt, series-connected, split-phase motor may be converted to operate on 115 volts merely by reconnecting it two-parallel or two-circuit, as shown in Chapter 4, Figures 4-65 and 4-66. Note that in either connection the voltage across each pole remains the same.

Voltage changes by means of reconnections are not always possible. For example a four-pole, series-connected motor cannot be reconnected for a higher voltage operation because if a higher voltage is impressed on the series connection, the voltage across each pole will be greater than they were designed for and they will, therefore, burn out. Likewise, a two-pole, two-parallel motor cannot be reconnected for a lower voltage because there can be no more than two parallels in a two-pole motor.

Rewinding Split-phase Motors for a Change in Speed

Before developing specific rules for rewinding a split-phase motor for a change in speed, it is necessary to explain and define two terms essential in the calculations effecting this type of conversion. These terms are *effective turns* and *chord factor*. Effective turns in a coil are usually different from the actual turns in a coil. This is because the effective turns depend on the span of the coil. Full span will make the coil 100 percent effective. A lesser span will make the coil less effective. For example, a full span coil having 20 actual turns will also have 20 effective turns, whereas, a lesser span coil of 20 turns may have only 10 effective turns. By examining Figure 1-20, note that each pole of this particular motor consists of four coils, each having different spans. From the above it can readily be seen that the outer coil will be more effective than the other coils since it has a greater span. The amount of effectiveness will depend on the number of electrical degrees spanned. It is well to know at this time that each pole covers a distance of 180 electrical degrees.

To compute the effectiveness of each pole, examine the four-pole, 36-slot motor of Figure 1-20. Each pole has nine slots and since this is equivalent to 180 electrical degrees, it follows that there are

20 electrical degrees between adjacent slots. The pitch of the outer coil in each pole is 1-9 or 8 slots. This has a value of 8 × 20 or 160 electrical degrees. In order to compute the effectiveness of this coil, it is necessary to use a formula for determining the trigonometric value of angles. Rather than do this, a table has been set up giving these values for some of the more common motors. See Table VIII in the Appendix. These values are called *chord factors* and are equal to the sine of half the angle spanned by the coil.

For the above motor, the chord factor of the outer coil would be 0.98 and the effective turns would be equal to the actual turns multiplied by 0.98. The next coil in the pole spans six slots and is equivalent to 6 × 20 or 120 electrical degrees. Its chord factor is 0.87, and the effective turns are equal to the actual turns in the coil multiplied by 0.87.

From the above, we develop the following formula:

$$\text{Effective turns} = \text{actual turns} \times \text{chord factor}$$

To calculate the effective turns in one pole of a motor, we will assume a four-pole, 36-slot motor, as in Figure 1-20. This motor has nine slots per pole and four coils in each pole of the running winding. Use chord factor from Table VIII in the Appendix.

Span	Actual Turns	Chord Factor		Eff. Turns
1-9	30	0.98	=	29
1-7	30	0.87	=	26
1-5	18	0.64	=	12
1-3	20	0.34	=	7
				74

The effective turns in the starting winding can be found in exactly the same manner.

It was mentioned at the beginning of this section that it would be necessary to compute the effective turns for a conversion in speed.

As an example, assume that the four-pole, 36-slot, 1750-r.p.m. motor of Figure 1-20 is to be rewound for six-pole, 1150 r.p.m.

STEP 1. Compute the total number of effective turns in the entire running winding. For a four-pole motor, this would be the number of effective turns for one pole multiplied by four, or 74 × 4 = 296 effective turns.

STEP 2. Rewinding for six pole, use the formula:

$$\text{New eff. turns} = \frac{\text{orig. r.p.m.}}{\text{new r.p.m.}} \times \text{orig. eff. turns}$$

$$= \frac{1800}{1200} \times 296 = 444 \text{ turns for entire running winding}$$

STEP 3. Determine eff. turns per pole:

$$\text{Eff. turns per pole} = \frac{\text{total turns}}{\text{poles}} = \frac{444}{6} = 74 \text{ eff. turns}$$

Since this will be a six-pole motor, each pole will occupy six slots. Three coils per pole will be used having pitches 1-7, 1-5, and 1-3, as in the six-pole layout of Figure 1-73. Note that the outer coils of each pole overlap each other.

STEP 4. It has been found in practice that the actual turns are approximately 1.25 the effective turns. To obtain the actual turns from the effective turns, multiply by 1.25. This will be $74 \times 1.25 = 92$ actual turns.

STEP 5. Since the outer coils of adjacent poles overlap, use half the turns in coil 1-7 as for 1-5 pitch. Use the same turns for pitch 1-3.

Span	Turns	Chord Factor	Eff. Turns
1-7	23	1.0	23.0
1-5	46	0.87	40.0
1-3	23	0.50	11.5
	92		74.5

The sum 74.5 checks with 74 effective turns originally computed for each pole of this six-pole motor.

Compute the starting winding in the same manner.

To determine the size wire necessary in this conversion, compute in the following manner:

$$\text{New c.m. area} = \frac{\text{new speed}}{\text{orig. speed}} \times \text{c.m. of orig. wire}$$

$$= \frac{1{,}200}{1{,}800} \times \text{c.m.} = \frac{2}{3} \text{ c.m. of orig. wire}$$

If the original wire was No. 17 = 2048 c.m., then

$$\tfrac{2}{3} \times 2048 = 1365 \text{ c.m.}$$
$$1365 = \text{No. } 19$$

It should be remembered that it is important to take into consideration the centrifugal switch in making a speed change. It is essential that the centrifugal switch open at the proper speed (approximately 75 percent of normal speed). Therefore, in changing, for example, from a four-pole to a six-pole motor, it must be ascertained beforehand whether or not the centrifugal switch will open at approximately 900 r.p.m.

Troubleshooting and Repair

Testing

To detect defects in a split-phase motor, both the running and the starting windings should be tested for (1) grounds, (2) opens, (3) shorts, and (4) reverses.

Grounds A winding is said to be grounded when it makes an electrical contact with the iron of the motor. Grounds may be caused by a number of conditions, the most common of which are the following: (1) the bolts that fasten the end plates to the frame may make contact with the winding as a result of the coils of the winding protruding too far from the ends of the slots; (2) the wires press against the laminations at the corners of the slots, which is likely to occur if the slot insulation shifts during the winding process or if the insulation tears or cracks during winding; and (3) the centrifugal switch may be grounded to the end plate.

To determine whether the winding is grounded, a test lamp may be used. One test lead to the lamp is connected to the winding and the other lead to the stator core or motor frame as shown in Figure 1-78(a) and (b). If the lamp lights, the winding is grounded.

Should the winding prove to be grounded, try first to locate the ground by visual inspection; in other words, examine the winding closely to see whether any wires are touching the core. Try moving the turns of the winding back and forth while the test leads are connected to see whether the light flickers. A flicker under these conditions indicates that the grounded point has been temporarily removed, and usually a spark may be observed at the point of the ground.

If this test does not disclose the ground, it will be necessary to disconnect the splices between poles and test each pole. After the poles have been disconnected, test each one individually as described above until the fault is found. When the grounded pole is located, determine the point of the ground and remove it by reinsulating or by rewinding. It may be necessary to unwind the entire pole and rewind it more carefully.

Open Circuits The usual cause of an open circuit in a split-phase motor is a loose or dirty connection or broken wire, which may be in either the running or the starting winding or in the centrifugal switch.

To determine whether the running winding is open, the leads of the test lamp are connected to the ends of the winding, as shown in Figure 1-79. If the lamp lights, the circuit is complete. If the lamp does not light, an open circuit is indicated, as illustrated in Figure 1-80. The open circuit may be located by connecting one test lead of the lamp to one end of the winding and placing the other lead to the end of each pole separately, as indicated by points *1*, *2*, *3*, and *4* in Figure 1-81. If the lamp does not light at point *1*, the coil of the first pole is open. If the lamp lights at point *1* but does not light at point *2*, the second coil is at fault. If it lights at *1* and *2* but not at *3*, the third coil is at fault. Such a condition is shown in Figure 1-81. Note that the lamp would also not light at point *4*. After repair of the open circuit of coil *3*, the lamp should light at point *4*. If it does not light, coil *4* is also open and requires repair. By continuing in this manner the open circuit can be found.

An open circuit in the starting winding may be difficult to locate, since not only is the winding itself involved but the centrifugal switch as well. The centrifugal switch is probably the worst offender in producing open circuits. The parts become worn, defective, and dirty; also, insufficient pressure of the rotating part of the switch against the stationary part will prevent the contacts from closing and thereby produce an open circuit.

If the starting winding is connected to the centrifugal switch and the motor is disassembled, the tests for an open circuit are as follows: The test leads of the lamp are connected to the leads of the starting-winding circuit. The lamp should not light until the two contacts on the centrifugal switch are pressed together. If the lamp does not light, the open may be in either the switch or the winding. By next connecting the test lamp directly across the winding it can be determined whether this is at fault. If it is not, the trouble is in the switch, which should then be examined carefully, all contacts cleaned, and the pressure of the rotating part adjusted.

If the motor has been assembled and the starting winding is to be tested for an open circuit, connect the test leads of the lamp to the starting-winding circuit, as shown in Figure 1-82. The lamp should light, but if it does not, it is possible that the centrifugal switch contacts are not closed. The rotor is then pushed lengthwise toward the front end. This may cause the contacts to close; if so, the lamp will light. To correct this trouble, add several fiber washers to the pulley end of the rotor shaft to keep the rotor pushed forward. It may be necessary to remove washers from the front end to accomplish this. In all cases be certain that the rotor core is aligned with the stator core.

If tests show that the trouble is not in the centrifugal switch, then the open circuit is in the starting winding. If this is true, the starting winding must be tested and repaired in the manner described for the running winding.

Shorts Two or more turns that contact each other electrically will cause a short circuit. This condition may develop in a new winding if the winding is tight and much pounding is necessary to place the wires in position. In other cases, excessive heat developed from overloads will make the insulation defective and will cause shorts. Usually a short circuit exists when the winding smokes while the motor is running or when it draws excessive current at no load.

Several methods may be employed in general practice to find shorted coils in a split-phase motor. Among these are the following:

1. Run the motor for a short time and then locate the hottest coil by feeling the poles. This coil is generally the one that is shorted.
2. Use an internal growler. The growler is a coil of wire wound on a laminated iron core and connected to a 115-volt a-c outlet. After the motor is disassembled, the growler is placed on the core of the stator and moved from slot to slot. A shorted coil will be indicated by the rapid vibration of a metal blade, such as a hacksaw blade, held at the other end of the coil, as illustrated in Figure 1-83(a) and (b).
3. Use the voltage-drop test. The winding is connected to a source of low d-c voltage, and a voltage reading is taken across each pole. The pole that has the least voltage drop is the shorted coil.
4. Use the strength-of field test. A piece of iron is held against the core of each pole while the current from a low d-c source is

passing through the winding. The pole that has the weakest pull is the one that is shorted.

5. Use an ammeter. This method is used when the motor can be operated without a load.

Measurement of the current can be made without removing any leads by use of a clip-on type of ammeter. This instrument is clipped over one line lead, and its pointer indicates the current flowing through the circuit. If the reading is higher than the current value shown on the name plate of the motor, the windings can be assumed to be shorted.

To repair a shorted pole, it is necessary to remove the coil and rewind it, unless the short can be located by inspection and thoroughly insulated without rewinding.

Reverses Reverses result from wrong connections between poles and are best discovered by means of a polarity test. Two methods are used, namely, the compass method and the nail method.

In using the compass method, the stator is placed in a horizontal position, and a low d-c voltage is applied to the winding. The compass is then held inside the stator and moved slowly from one pole to another. The compass needle will reverse itself at each pole, as shown in Figure 1-84, if the winding is correctly connected. If the same end of the needle is attracted to two adjacent poles, a reverse pole is indicated.

In using the nail method, the stator is placed on its side, and a low voltage of either alternating or direct current is applied to the winding. A nail is placed on the core so that it extends from the center of one pole to the center of the next pole. If the adjacent polarity is correct, the nail will be attracted to both poles; but if the polarity is incorrect, one end of the nail will be repelled from its pole.

Should it be found that one pole has the wrong polarity, this error can be corrected by reversing the two lead connections to this pole. In the event that more than one pole has the wrong polarity, reference should be made again to Figure 1-44, and the poles connected as shown therein.

Repairs

It is now in order to consider the various troubles that develop in split-phase motors and to note how they may be repaired. These troubles and their remedies will be grouped for explanation into four classes, as follows: (1) motor fails to start; (2) motor runs slower than normal speed; (3) motor runs very hot; (4) motor runs noisily.

Motor Fails to Start Failure of the motor to start when it is connected to a power line of the correct voltage may be due to (1) open running winding, (2) open starting winding, (3) grounded winding, (4) burned or shorted winding, (5) open-circuited overload device, (6) excessive overload, (7) worn or tight bearing, (8) end plates improperly mounted, or (9) bent rotor shaft. Each one of these will be considered in their order named.

1. OPEN RUNNING WINDING. An open running winding may be discovered by testing the winding with a test lamp. If the lamp fails to light, the winding has an open circuit. The exact location of the open is determined by the method previously explained under Testing the Split-phase Motor and repaired by rewinding if necessary.

2. OPEN STARTING WINDING. Three practical tests show whether the starting winding has an open circuit. One method is to connect the motor to the power line. An open circuit in the starting winding will cause the motor to hum.

A second test is to turn the rotor manually. This may be done by winding a cord around the rotor shaft, as in Figure 1-85, and pulling the cord so that the rotor turns. While the rotor is thus turning, the power-line switch is turned on. If the motor continues to run, the trouble is in the starting-winding circuit.

The third test for discovering an open circuit in the starting winding is to use the test lamp. If the circuit is found to be open, the trouble is in either the centrifugal switch or the starting winding.

The centrifugal switch should be examined first, since it is most likely to be the cause of the trouble. Moving the rotor shaft toward the front end plate may close the contacts of the switch, in case the trouble is at this point, and cause a test lamp in the circuit to light. The rotor may also have too much end play, which can be determined by moving it back and forth. There should be a maximum end play of not more than $\frac{1}{64}$ in. If more end play is observed, fiber washers should be put on the shaft so that the rotor core lines up with the stator core. If too much end play is allowed to exist, the rotor may come to a stop in such position that the centrifugal switch contacts will remain open. If these tests have been made and the circuit still remains open, the motor is disassembled and a test lamp is used to check the operation of the switch. If found to be defective, the centrifugal switch is carefully cleaned and all parts adjusted.

The starting winding is next tested, if the centrifugal switch is found to be in good order. The flexible leads to the power line that are spliced to the wires of the coils are examined first and replaced if they are at fault. If the starting winding is defective, the open may be located by the method described earlier in this chapter for open circuits. Although the break in the coil may be repaired by splicing if it is readily accessible, rewinding is necessary if the coil is burned or otherwise severely damaged. Should it be necessary to rewind the starting winding, it is advisable to test the running winding thoroughly for any defects before replacing the new starting winding over it.

3. GROUNDED WINDING. One ground in a motor may not be noticeable as far as running conditions are concerned; but two or more grounds in a winding are equivalent to a short circuit. This may cause a fuse to blow, or it may cause the winding to smoke, depending on the extent of the grounds. The grounds are located by the method previously explained, and are then repaired by reinsulating or by rewinding. A grounded winding may cause a shock if touched and is therefore dangerous. It is recommended that motor frames be grounded under certain conditions.

4. BURNED OR SHORTED WINDING. A burned or short-circuited winding usually causes a fuse to be blown when the motor is connected to the line. If the fuse does not blow, the winding will smoke. In either event the motor must be disassembled. A burned winding is easily recognizable by its smell and its burned appearance. The only remedy is to replace the burned winding. In many cases, only the starting winding will be burned. Should this be true, only the starting winding will need to be rewound; however, the running winding should be tested for any defects before installing the new starting winding. If the winding is not burned and only a short circuit exists, the short may be located and repaired as explained earlier in this chapter.

5. OPEN-CIRCUITED OVERLOAD DEVICE. Some motors are equipped with an overload device consisting of a bimetal element that will expand when heated and cause associated contacts to open. This device is connected in series with the motor, as shown in Figure 1-86, and its contacts will open if the motor is overloaded or if for any other reason too much current flows through the wind-

ing. However, the contacts must close after the motor has cooled somewhat or when the overload is withdrawn. The contacts are examined for dirty, defective, or burned points. If the points are in bad condition, they should be replaced with new ones.

6. EXCESSIVE OVERLOAD. When too much load is placed on a motor not having an overload device, the motor will hum and stall. An overload condition may be readily determined by connecting an ammeter in the circuit, as shown in Figure 1-87, and noticing whether the ammeter registers a higher current reading than the ones recorded on the name plate of the motor. A snap-around volt ammeter-ohmmeter can be used for this reading. This instrument is shown in Chapter 4, Figure 4-134. A shorted winding will likewise cause a large reading. It is assumed, however, that previous tests have shown that the windings are neither shorted nor grounded.

7. WORN OR TIGHT BEARING. Bearing troubles frequently develop in motors after they have been in use for a considerable time. A worn sleeve bearing may be discovered by attempting to move the shaft up and down by hand, in the manner illustrated in Figure 1-88. If the shaft moves, it indicates a worn bearing or possibly a worn rotor shaft, as shown in Figure 1-89. In either event, new bearings are required. A small amount of play in the bearings will allow the rotor to touch the stator, as shown in Figure 1-90, and thus prevent the motor from starting. Quite often, sludge will accumulate in the worn part of the bearing and may prevent an up-and-down motion of the shaft. In this case the motor is disassembled so that the rotor is resting in one end plate. If the end plate can be wobbled back and forth, the bearing or shaft is worn.

A sleeve bearing is removed by placing a piece of round stock on the bearing in the end-plate housing and pressing it out by means of an arbor or some other type of press. A convenient tool for this purpose is a piece of round stock that has been turned down in a lathe to fit different sizes of bearings, as shown in Figure 1-91. Care should be exercised to press out the old bearing through the side of the end plate having the larger opening and to remove any screws or oil wick that may prevent the bearing from coming out easily.

The new sleeve bearing is set in place by using the round stock as before and pressing the bearing into the end plate. The bearing is pressed in to the proper distance from the side of the end plate having the larger opening. The oil holes must be lined up with those in the end plates, and the bearing must not be burred while being replaced.

New sleeve bearings are usually made a few thousandths of an inch undersize, and need to be reamed to the proper size. This is done by placing the end plates on the stator after the new bearings have been pressed in, but before the rotor is replaced, and using a through reamer to ream the holes. The reamer is first passed through the bearing in one end plate, then continued through the stator to the other end plate. In this manner, the bearings are reamed to the same size and also properly aligned. Separate reamers of the proper sizes will need to be used, however, when the rotor shaft requires different sized bearings at the two ends. In such cases, care must be exercised to align the bearings correctly.

If the shaft is worn, it may be reconditioned to its original roundness and smoothness by turning it in a lathe. Then it must be fitted with a smaller sized new bearing. Or, the shaft may be built up to its original size by forcing molten metal on it, in a process called *metallizing*. If this process is used, the metallized shaft is turned in a lathe to the correct size, and a standard-sized bearing is used to replace the old one.

When a bearing is allowed to become dry from lack of oil, the motor shaft may heat and expand to such a degree that it welds itself to the bearing. Such a condition is known as a *frozen* bearing. To repair a frozen bearing, the end plate and bearing must be knocked loose from the shaft or loosened with a blow torch. The shaft is then smoothed up, and a new bearing is installed.

8. End Plates Improperly Mounted. When an end plate is not fastened securely around the entire edge, as shown in Figure 1-92, the bearings are out of alignment, and the rotor can be turned by hand only with difficulty or not at all. The end plate should sound "solid" when tapped gently with a mallet or lead hammer and should fit the stator perfectly at all points. If it does not fit, all screws should be loosened and each one tightened a little at a time, thus drawing the plate evenly and securely to the stator. In assembling a motor, do not tighten the first screw on the end plate, then the next adjacent one, and so on. If tightened this way, the opposite side of the end plate will not contact the stator tightly.

9. Bent Rotor Shaft. A bent shaft, shown in Figure 1-93, may be suspected if the rotor does not turn easily by hand after it has been determined that the end plates are on properly. To determine whether the shaft is bent, the rotor is removed from the motor and

placed in a lathe. With the lathe turning slowly, it is usually possible to see the rotor bobbing up and down if the shaft is bent. To locate the bend, a special gauge made for this purpose is held close to the shaft while it is rotating in the lathe. If no such gauge is available, a piece of chalk can be held near the shaft. The bent portion of the shaft will touch the chalk during rotation and thus be marked.

A bent shaft may be repaired by securely mounting the rotor between centers in a lathe. A pry bar or a long section of pipe is inserted under the bent portion to obtain the necessary leverage. The pressure exerted in bending the shaft back into position must be carefully controlled. Usually, the bending should be done a little at a time, until the shaft is straight. This method should be employed only for small rotors; otherwise, the lathe centers may be damaged.

Motor Runs Slower than Normal Speed A motor that does not attain normal running speed is likely to have one or more of the following defects: (1) short circuit in running winding, (2) starting winding remaining in circuit, (3) reversed running-winding poles, (4) other incorrect stator connections, (5) worn bearings, or (6) loose rotor bars.

1. SHORT CIRCUIT IN RUNNING WINDING. A short circuit in the running winding will cause the motor to run at a lower speed than that for which it is rated, and will produce a humming or growling noise. The pole that contains the short, as shown in Figure 1-94, will usually become excessively hot; it may also smoke if the motor is allowed to run for many minutes.

To locate the shorted pole, an internal growler is used. Or, the pole may be located by merely feeling for the hot coil. The remedy for a short-circuited coil is to find the short and, after it is found, insulate it if possible. If it cannot be insulated, rewind the coil or the entire winding.

2. STARTING WINDING REMAINING IN THE CIRCUIT. The symptoms of this defect are the same as those for a shorted running winding. To determine conclusively that the starting winding remains in the circuit, disconnect one lead of this winding and start the motor manually, as illustrated in Figure 1-85, and connect the power line after the rotor is turning. If the motor then runs properly, the centrifugal switch does not disconnect the starting winding at the proper time.

The contact points of the centrifugal switch may be welded or stuck together, other faulty parts may be causing the contact points to remain closed, or the rotating part of the switch may not release the contacts on the stationary part because fiber washers are improperly placed on the rotor shaft. In any of these cases, the switch is repaired as previously explained, a new switch is installed, or fiber washers are placed on the rotor shaft so that the switch will open and close in the proper manner.

3. Reversed Running-winding Poles. If the poles are connected in such manner as to produce incorrect polarity, the motor will rotate slowly, if at all, and rotation will be accompanied by a growling noise. More definite analysis requires that the motor be disassembled and each pole tested for correct polarity by the compass or nail tests previously described. When the pole of improper polarity is located, the lead wires of the pole are disconnected, reversed, and reconnected.

4. Other Incorrect Stator Connections. Incorrect connections between the poles of either the running or starting winding may cause induced currents to flow in the pole coils, with the result that the coils will become over-heated, smoke, and perhaps burn out. When this condition exists, the motor must be disassembled and the connections carefully remade as explained earlier in this chapter under Connecting the Split-phase Motor. The amateur repairman often makes mistakes in connecting the windings of this type of motor, one of the most common being that he connects two of the poles in series and the remainder in a closed circuit, in the manner shown in Figure 1-95. Extreme care should be exercised to connect all the poles exactly as required by the data.

5. Worn Bearings. A motor with worn bearings or worn shaft is noisy in operation and sluggish in rotation. The cause is that the rotor rubs against the stator while running, as shown in Figure 1-90. A worn bearing or worn shaft diagnosis may be confirmed by noting whether the shaft can be moved up and down while the motor is still assembled. In either case, repair should be made as explained earlier in this chapter.

6. Loose Rotor Bars. An indication that the rotor bars are open is shown when the motor runs with reduced power and produces a growling noise. The rotor must be removed from the motor for further testing. The open bars may be located by a visual inspection, particularly if it is possible to move them at the end rings. Failing this, the rotor is tested on an armature growler. This type

of growler consists of a U-shaped laminated iron core having a coil or wire wound around it. The rotor is placed in the open end of the core, as shown in Figure 1-96, and rotated. Flickering of a lamp connected in series with the growler indicates open bars. The open bars, when located, must be soldered or welded to the end rings. Rotors with a die cast aluminum squirrel cage do not have this defect.

Motor Runs Hot A motor may become excessively hot after running a short time for one of the following reasons: (1) shorted winding, (2) grounded winding, (3) short circuit between running and starting windings, (4) worn bearings, or (5) overloading.

1. SHORTED WINDING. If either the running or the starting winding has a short circuit, the shorted pole will become excessively hot when the motor is running. In addition, the motor operates with a growling noise. The winding will eventually become so hot that the entire motor will be damaged if it is allowed to run in this condition. The procedure for determining whether a short circuit exists and for locating it has been explained under Testing the Split-phase Motor. Unless the short, after having been located, can be repaired and insulated, the pole or the entire winding must be rewound.

2. GROUNDED WINDING. A winding grounded in two or more places is equivalent to a shorted winding and will cause the motor to run very hot and will eventually produce severe damage. The grounded points are located by methods previously explained and are repaired by reinsulating, if possible. If reinsulating is impossible or seems inadvisable, the grounded pole must be rewound.

Should the motor be grounded at one point only, it is likely that a shock will be felt if the motor is touched when running. This condition is dangerous to workmen, and therefore immediate repair is essential.

3. SHORT CIRCUIT BETWEEN RUNNING AND STARTING WINDINGS. A short circuit between these two windings will permit a current to flow through a part of the starting winding continuously while the motor is in operation, and in time will burn out the starting winding. To locate the shorted point, the windings are disconnected from the terminals and one of the leads of a test lamp (connected to the line) is connected to the running winding, and the other lead is connected to the starting winding. The lamp will light, since current flows from the running winding through the shorted point to the starting winding. The starting winding is then moved away from the running winding at various places in the stator. If the

shorted point is moved, the lamp will flicker or go out. If the shorted point cannot be determined in this manner, it will be necessary to remove the coils of the starting winding one at a time until it is located.

The short circuit can usually be repaired by inserting a strip of varnished cambric or Armo paper in the slot between the two windings.

4. Worn Bearings. When the bearings are worn sufficiently to permit the rotor to touch the stator, the motor will become overheated after running for a short time. Worn bearings may be readily detected by trying to move the rotor shaft up and down while the motor is assembled. If such movement is possible, the bearings are worn. If the rotor is removed from the motor and found to have polished surfaces on it, this is an indication that the rotor is probably rubbing against the stator. This condition is repaired by replacing the bearings.

5. Overload. An overload on the motor will cause it to draw more than the rated current and thereby produce excessive heat. An ammeter is placed in the circuit to test for overload. Should the meter show a larger reading than that listed on the name plate of the motor, the load should be reduced or the motor replaced with a larger one. This test assumes that the motor is externally overloaded.

Motor Runs Noisily There are several reasons why a split-phase motor may operate with an unusual amount of noise. The most common of these are (1) shorted winding, (2) improperly connected poles, (3) loose rotor bar, (4) worn bearing, (5) worn centrifugal switch, (6) too much end play, and (7) foreign material in the motor.

The first three conditions just named will all produce a magnetic hum when the motor is running. When such a hum is noticeable, the repairman can be certain that one of these defects exists. More positive tests for locating these troubles and the methods of repairing them have already been explained.

Bearings that are excessively worn allow the rotor to rub against the stator when the motor is running and thus produce a loud noise. Specific tests for this trouble and repairs should be made in the manner already described.

A worn centrifugal switch is likely to cause a noticeable noise when the motor is in operation. Since part of the switch is located on the rotor, it revolves at high speed. A loose member of the rotating part may hit or rub against some other part of the motor, and thus make the noise. When such a defect is suspected, the rotor should be removed from the stator and the switch carefully inspected. It may be found that the faulty parts can be repaired; if not, a new switch must be installed.

Should the rotor have end play of more than $1/64$ in., it may produce a noise during operation. The remedy for this trouble is to place fiber washers on the rotor shaft at the proper places.

Sometimes foreign material, such as a piece of insulation or wire, becomes embedded in a winding or a slot and protrudes sufficiently for the rotor to rub against it. This will cause an undesirable noise. The foreign material can be located by dismantling the motor and inspecting all windings and slots carefully. After it is found, the foreign matter usually can be removed with a pair of pliers or a screwdriver. In removing it, care must be exercised not to damage the insulation on the wires or between the windings.

Miscellaneous Diagrams

Figure 1-97 shows connection diagrams of single- and dual-voltage split-phase motors, also single- and two-speed split-phase motors. These motor and live wiring diagrams are the type received from motor manufacturers when a request is made for the connection diagrams for specific motors.

CHAPTER 2

Capacitor Motors

The capacitor motor operates on alternating current and is made in sizes ranging from 1/20 h.p. to 10 h.p. It is widely used to operate such machines as refrigerators, compressors, oil burners, washing machines, pumps, and air conditioners.

The construction of the capacitor motor is similar to that of the split-phase motor, but an additional unit, called a *capacitor,* is connected in series with the starting, or auxiliary, winding. The capacitor is usually mounted on top of the motor, as shown in Figure 2-1, but it may be mounted in other external positions or inside the motor housing. Figure 2-2 is an illustration of a-c capacitors with mounting hardware and accessories.

According to NEMA Standards Publication of January 1968, a capacitor motor is defined as follows: A capacitor motor is a single-phase induction motor with a main winding arranged for direct connection to a source of power and an auxiliary winding connected in series with a capacitor. There are three types of capacitor motors, as follows:

1. CAPACITOR-START MOTOR. A capacitor-start motor is a capacitor motor in which the capacitor phase is in the circuit only during the starting period.

2. PERMANENT-SPLIT CAPACITOR MOTOR. A permanent-split capacitor motor is a capacitor motor having the same value of capacitance for both starting and running conditions.

3. TWO-VALUE CAPACITOR MOTOR. A two-value capacitor motor is a capacitor motor using different values of effective capacitance for the starting and running conditions.

The Capacitor

A capacitor is formed when two conductors, usually of aluminum, are separated by an insulator such as paper or gauze. For use in motors the strips are rolled together into a compact unit and placed into a sealed metal or plastic container. This may be either cylindrical or rectangular in shape and may be mounted on, in, or away from the motor. Two terminals or leads are provided for connection. The name *capacitor* is descriptive of the operation of the device. The capacitor acts essentially as a storage unit; that is, it has capacity to store electricity and provides a leading current to the auxiliary or starting winding. All capacitors have this quality and all are electrically the same; they differ only in mechanical construction.

The Oil-filled Capacitor

This capacitor is used mainly in the permanent-split capacitor motor and for the two-value capacitor motor. These capacitors use an oil-impregnated paper as the dielectric and are permanently connected in the circuit. They are capable of constant duty and are substantially larger than an equivalent microfarad value in an electrolytic type. Different manufacturers use various types of oil or synthetic liquids as the impregnating medium. Capacities range from 2 microfarads to 50 microfarads (abbreviated μf). Figure 2-3 illustrates a capacitor that uses a synthetic askarel liquid for impregnating purposes.

The Electrolytic Capacitor

Electrolytic capacitors are used mainly in capacitor-start and two-value capacitor motors. This type consists of two sheets of aluminum foil that are separated by one or more layers of gauze. The gauze has previously been saturated with a chemical solution called an *electrolyte*. The electrolyte forms a film which acts as the insulating medium of the electrolytic capacitor. These layers are rolled together and fitted into an aluminum or plastic container. An electrolytic capacitor is shown in Figure 2-4. Motor-starting electrolytic capacitors should not be kept in a circuit more than a few seconds at a time because they are designed for only intermittent duty.

Capacity

Capacitors are rated in microfarads. A capacitor for motor starting may have a capacity ranging from 2 to 800 μf or more, depending on its use, size, and type. Capacitors may lose some capacity because of excessive use, overheating, or other conditions. In such a case, it must be replaced with one of approximately the original value of capacity and voltage; otherwise the motor may not have the required starting torque.

When replacing a defective capacitor on a capacitor motor, be certain to use a replacement with a voltage rating at least as high as the original. Wherever any question exists, it is always safer to use a capacitor of higher voltage rating.

There are three types of capacitor motors, and each employs capacitors in conjunction with the windings. These are the capacitor-start motor, the permanent-split capacitor motor, and the two-value capacitor motor. Capacitor-start motors have a relatively high starting torque and use the electrolytic capacitor. The capacitor must not be used for continuous duty and must be switched out of the circuit when the motor attains a predetermined speed. The permanent-split capacitor motor has a relatively low starting torque and uses an oil-impregnated paper as the dielectric. These capacitors remain in the circuit at all times. The two-value capacitor motor has a high starting torque and uses the electrolytic and oil capacitors in parallel at start. When the motor reaches the required speed, the electrolytic capacitor is cut out of the circuit, permitting the motor to operate as a permanent-split motor.

The Capacitor-start Motor

Construction

Except for the capacitor, this motor is similar in construction to the split-phase motor. The main parts of the capacitor-start motor are (1) a slotted stator, having a running winding and a starting winding; (2) a squirrel-cage rotor; (3) two end plates; (4) a switch, usually of the centrifugal type, consisting of a stationary part attached to the front end plate or stator shell and a rotating part attached to the rotor; and (5) a capacitor, generally electrolytic. The capacitor-start motor provides higher starting torque with a lower starting current than the split-phase motor and is generally operated from a single-phase lighting or power circuit.

Operation

The circuit of the capacitor-start motor is shown in Figure 2-5. During the starting period, both the running (main) and starting (auxiliary) windings are connected across the line since the centrifugal switch is closed. The starting winding, however, is connected in series with the capacitor and the centrifugal switch.

When the motor reaches approximately 75 percent of full speed, the centrifugal switch opens. This action cuts out both the starting winding and the capacitor from the line circuit and leaves only the running winding across the line.

To produce a starting torque in a capacitor motor, a revolving magnetic field must be established inside the motor. This is accomplished by placing the starting winding 90 electrical degrees out of phase with the running winding. The capacitor is used to permit the current in the starting winding to reach its maximum value before the current in the running winding becomes maximum. In other words, the capacitor causes the current in the starting winding to lead the current in the running winding. This condition produces a revolving magnetic field in the stator, which in turn induces a current in the rotor winding. As a result, the magnetic field acts in such a manner as to produce rotation of the rotor.

Procedure for Analyzing Motor Troubles

Since the capacitor motor is similar in construction to the split-phase motor, the steps outlined in Chapter 1 should be followed in determining what repairs are required for reconditioning the motor. Briefly, they are: (1) inspect the motor for mechanical defects; (2) test the motor for bearing troubles; (3) test for grounds, shorts, and so on; (4) running test for noise, speed, and so on. In addition to the above, the capacitor must be tested.

Rewinding

The most common type of capacitor-start motor has two windings on the stator, a running winding and a starting winding, as the split-phase motor has. The running winding is always placed at the bottom of the slots. The starting winding is placed above this in the slots but is displaced 90 electrical degrees; in other words, the starting poles are placed midway between the running-winding poles. An examination of the starting winding of a capacitor-start motor will reveal that it is usually wound with wire of slightly smaller size than that of the main winding.

The capacitor-start motor windings are placed in the slots in the same manner as the windings of the split-phase motor. Hand winding, form winding, or skein winding may be used, depending on the individual motor.

Rewinding a capacitor motor having a damaged winding consists of a number of separate operations similar to those of the split-phase motor. These are: (1) taking data; (2) stripping the windings; (3) insulating the slots; (4) rewinding; (5) connecting the winding; (6) testing; and (7) baking and varnishing.

All of these operations are explained fully in the chapter on split-phase motors and are similar except for the connections of the capacitors.

Connections of the Capacitor-start Motor

Some of the many types of capacitor motors are listed below. Each has its own characteristic connections of the windings. Some of these types are designed to operate on one voltage, some on two voltages. Many of them are externally reversible, and others are reversed internally. Each of the following motors is described, and a wiring diagram is given to illustrate its operation:

1. Single-voltage, externally reversible
2. Single-voltage, nonreversible
3. Single-voltage, reversible, with overload protector

3a. Terminal-block

4. Single-voltage, with current or potential relay
5. Two-voltage
6. Two-voltage, reversible
7. Two-voltage, with overload protector
8. Single-voltage, three-lead, reversible
9. Single-voltage, instantly reversible
10. Two-speed
11. Two-speed, with two capacitors

In the wiring diagrams of these motors, the leads will be shown coming out of the motor. This is not the case in the actual motor, because the leads are usually connected to terminals inside the front end bracket. Many motors have the terminals mounted on the stationary part of the centrifugal switch. In all of the following capacitor-start motors, electrolytic capacitors are used. In all single-voltage capacitor motors, the main or running winding terminals are marked T_1 and T_4. All auxiliary or starting winding terminals are marked T_5 and T_8. Standard terminal markings are described on page 25 of the text and illustrated in Figure 2-48.

1. *The Single-voltage, Externally Reversible Capacitor-start Motor* This motor has four leads brought outside the housing, two from the running-winding and two from the starting-winding circuit. These four wires are necessary if external reversing is desired. Internally, the starting winding is connected in series with the centrifugal switch and capacitor. Figure 2-6 shows the windings connected for clockwise rotation, and Figure 2-7 shows the same windings connected for counterclockwise rotation, or rotation in the opposite direction. As the illustrations show, to reverse this or any other type of capacitor motor, it is necessary only to reverse the starting-winding leads with respect to the running-winding leads, or vice versa.

Just as in other types of motors, the number of poles in this motor determines its speed: The more poles, the lower the speed; the fewer poles, the greater the speed. As in the split-phase motor, the poles are connected in series or in parallel, and care must be taken to produce alternate polarity in connecting the poles. The four-pole motor is most common, and therefore diagrams of a four-pole, series-connected motor and a four-pole, parallel-connected motor will be shown first. Figures 2-8 and 2-9 illustrate a four-pole, series-connected capacitor-start motor, and Figures 2-10 and 2-11 show a four-pole, two-circuit capacitor-start motor. In Figure 2-9 terminals T_1 and T_8 are connected together to line lead L_1 for counterclockwise rotation. Terminals T_4 and T_5 are connected together to line lead L_2. In Figure 2-11 terminals T_1 and T_5 are connected together to L_1 for clockwise rotation.

2. *Single-voltage, Nonreversible Capacitor-start Motor* If the starting-winding leads are connected internally to the leads of the running winding, the direction of rotation of the motor cannot be reversed unless the motor is taken apart and the leads reversed. Some motors are made in this manner because their application requires just one direction of rotation. Figure 2-12 shows the

circuit of this type of motor with two external leads. Most modern motors, however, permit easy reversal by making the running- and starting-winding leads readily accessible.

3. *Single-voltage, Reversible Capacitor-start Motor with Overload Protector* Very often capacitor-start motors are equipped with a device called an *overload protector* which serves as protection against overload, overheating, short circuits, and so on. Essentially, this device consists of a bimetallic element that is connected in series with the line and is generally mounted inside the motor. Many definite-purpose motors have the overload device mounted outside the motor. The bimetallic element is made of two metals that expand at different rates when heated. These are welded together, so that when the entire element is heated, it will bend. Usually, one end of the element is fixed and the other end serves as the contact point.

The circuit of a motor with a bimetallic overload device is shown in Figures 2-13(a) and (b). When excessive current flows through the motor for a short period of time, it causes abnormal heating of the element with the result that the element bends sufficiently to open the contact points and thereby open the circuit. On some types of thermal units, the contacts automatically close when the bimetallic element cools. On other units, a reset button must be operated manually to restore the motor to operation. In some types of thermal units, a heating unit supplies heat to the bimetallic element. In this type, the heating unit is connected in series with the line. When excessive current due to overload flows through the heating unit, the bimetallic element opens the circuit.

On all motors which are thermally protected, care must be taken to insert the bimetal unit in series with the line. A diagram of a two-pole, thermally-protected capacitor motor is shown in Figure 2-14.

3a. TERMINAL-BLOCK CAPACITOR. Some older refrigerator motors have a terminal block attached to the capacitor. Three of the terminals are marked *T, TL,* and *L,* as shown in Figure 2-15. The line wires L_1 and L_2 are connected to terminals *L* and *TL*. Wires leading to the thermostat inside the refrigerator are connected to *TL* and *T*. The unmarked terminal has one side of the capacitor connected to it. The other side of the capacitor is connected to terminal *L*. This capacitor connected to a capacitor-start motor is shown in Figure 2-16.

4. *Single-voltage, Nonreversible Capacitor-start Motor with Current Relay* Motor starting relays are used instead of centrifugal switches for many split-phase and capacitor motors. These relays are standard equipment for hermetically sealed motors in refrigerators, air conditioners, some office machinery, pumps, and many other definite purpose machines. It is impractical to use a centrifugal switch on hermetically sealed types, since servicing or replacing the switch is practically impossible. For this reason, an external magnetic relay is used. The relay may be located on or near the motor and may be a current- or potential-operated type. In either case, it is used to disconnect the starting winding from the circuit when the motor reaches approximately 75 percent of full speed.

The current relay operates on the principle that the initial inrush of current in the main winding at start is two to three times greater than at full speed. The relay mechanism consists of a magnetic coil and two normally open contacts. The coil is connected in series with the running winding, the contacts in series with the starting winding. Two types are shown in Figures 2-17(a) and (b). When line current is applied, the coil becomes sufficiently energized to cause the contacts to close. Consequently, when the motor is thrown across the line, both the starting and running windings will be excited and the motor will run; but as soon as the high starting current drops to normal with increased motor speed, the current flowing through the magnet coil will be insufficient to keep the contacts closed. When the contacts open, the auxiliary circuit is disconnected, allowing the motor to run on the main winding only.

The wiring of a capacitor-start motor connected to a current relay is shown in Figures 2-18(a) and (b) and 2-19(a) and (b). These motors are not usually connected for reversing. To reverse them it would be necessary to bring four wires out of the motor.

A disadvantage of this type of relay lies in the possibility that overloads may cause the magnet coil to operate and connect the starting winding across the line. Since the starting winding normally operates for only a few seconds, it may burn. However, this can be prevented by the use of overload protectors.

Figure 2-20 shows a capacitor-start motor connected to a current relay and a two-terminal overload protector (similar to the three-terminal protector, except that terminal *2* is not used).

4a. Single-voltage Capacitor-start Motor with Potential Relay. The function of the potential relay, as with the current relay, is to disconnect the starting winding from the line when the motor reaches a predetermined speed. The relay consists of a magnet coil which is continuously connected across the starting winding, and two normally closed contacts in series with the starting winding. When line current is applied to the motor, both windings will receive current and the motor will run. As the motor increases in speed, the voltage across the starting winding will increase, and at a predetermined speed (approximately 75 percent of normal speed) the voltage across the starting winding will be high enough to energize the relay coil. This in turn opens the relay contacts, disconnecting the starting winding. The contacts will remain open during normal operation due to an induced starting-winding voltage. Figure 2-21 shows the connection of a thermally protected capacitor-start motor using a potential relay. Note that the thermal protector uses two terminals. Figures 2-22 and 2-23 are similar to Figure 2-21 with the exception that a three-terminal protector is used. In this motor, the current enters terminal *1*, passes through the bimetal disc and splits at terminal *2*. The running-winding current goes directly to the motor, and the starting-winding current passes through the heater when the relay contacts are closed. Therefore, on overload, the additional heat provided by the heater, opens the overload contacts more quickly than if just the disc alone were used.

It may be well to add at this point that a small resistor is sometimes found connected across the electrolytic capacitor when a voltage relay is used. This may be in the form of a resistive compound deposited between the terminals. The resistance is used to prevent the relay from fluttering, to prevent relay contacts from welding together, and to discharge the capacitor.

5. *Two-voltage, Capacitor-start Motor* A two-voltage or dual-voltage capacitor-start motor can be operated on either of two voltages, usually 115 or 230 volts. This type of motor generally has a main or running winding of two sections and a starting winding of one section. To permit a changeover from one voltage to another, it is necessary to bring out four leads from the running winding, two from each section. These sections are marked T_1, T_2 and T_3, T_4. If the motor is to operate on 115 volts, the two sections of the running winding are connected in parallel. The starting

winding is connected across one section of the running winding. This is shown in Figures 2-24 and 2-25. Note that the sections of the running winding are marked Run. Sec. *1* and Run. Sec. *2*. In most two-voltage capacitor motors the starting winding leads are brought to a terminal board for easy reversal and are marked T_5 and T_8.

If operation on 230 volts is desired, the two sections of the running winding are connected in series. The starting winding is connected across one section of the running or main winding, thereby receiving 115 volts or one-half of the line voltage. This is illustrated in Figures 2-26 and 2-27. Note that even though the line voltage is 230 volts, the voltage across the starting winding is 115 volts. Therefore, in a dual-voltage motor the potential across the starting winding will always be the lower voltage, regardless of the line voltage, and will always be connected across one section of the main winding.

Rewinding the Two-voltage Capacitor-start Motor

The auxiliary winding on a dual-voltage, capacitor-start motor is identical to that of a single-voltage motor and is wound in exactly the same manner. The running winding, however, consists of two sections and may be wound in any of three different ways. One method consists of winding each section separately as a complete running winding. First one section is wound for all the poles as in a single-voltage motor. Then the second section is wound over the first in the same slots, with the same number of turns and same size wire. The starting winding is wound last, 90 electrical degrees removed. Actually, the entire motor winding will consist of three layers appropriately insulated from each other. A layout and stator connection diagrams for a four-pole, dual-voltage capacitor-start motor are shown in Figures 2-28 and 2-29.

Data taken on a typical rewound motor follow. This was a ¾-h.p., two-voltage, capacitor-start motor. Inspection revealed a 36-slot, three-layer winding. The layers consisted of two running-winding sections placed in the same slots and insulated from each other and a starting winding 90 electrical degrees displaced from the running windings. Each running-winding section was connected two-parallel, and the starting winding was series connected. Five leads were brought out of the motor to provide operation on either 115 or 230 volts. To reverse the direction of rotation, the starting-winding leads are reversed on the centrifugal-switch terminal plate.

Figure 2-30 shows the connections of the windings for 115-volt operation. The internal connections of the poles of this motor are given in Figure 2-31. Figure 2-32 shows all leads of a reversible two-voltage motor with thermal protection. Other methods of connecting this type of motor are shown in Figure 2-48.

The pitch of the coils, the number of turns, and the wire size were recorded upon stripping. These data are shown in Figure 2-33.

Another method of winding consists of placing both sections of the running winding into the slots at the same time by using two separate wires. This method saves valuable winding time. It should be remembered that since there cannot be an insulation barrier between sections, a high quality covering on the magnet wires is a necessity. A third method consists of winding the poles as in a single-voltage motor and connecting half the poles for one section and the other half for another section. Regardless of the method, the starting winding is connected across one section of the running winding. This is shown in Figure 2-34.

For the third method of winding dual-voltage motors, a long jumper or end-to-beginning connection is preferable to that of the short jumper connection. Diagrams for a four-pole, dual-voltage motor short jumper connection are shown in Figures 2-35 and 2-37. Long jumper connections are shown in Figures 2-36 and 2-38.

6. *Two-voltage, Reversible Capacitor-start Motor* This motor provides for external reversing by means of two additional leads that are brought out from the starting-winding circuit. Figures 2-39 and 2-40 show the connections for clockwise and counterclockwise rotation, respectively, on 115 volts. Figures 2-41 and 2-42 show the connections for 230-volt operation.

7. *Two-voltage Capacitor-start Motor with Overload Protection* The two-voltage, capacitor-start motor described in Section 5 (page 59) contained a thermostatic device for overload protection. This consisted of a three-terminal, bimetallic disc type of relay with auxiliary heater and is connected as shown in Figure 2-30.

8. *Single-voltage, Three-lead, Reversible Capacitor-start Motor* External reversing is impossible in the ordinary capacitor-start motor if only three leads are provided. However, reversing is

easily accomplished if a two-section running winding is used, as on the two-voltage motor. To make this possible, the two sections are internally connected in series, as in the 230-volt connection of the two-voltage motor. The two remaining leads are brought out for connection to the power line (Figure 2-43). One lead of the starting winding is internally connected to the midpoint of the two-section running winding. The other lead of the starting-winding circuit is brought out of the motor. This arrangement permits the starting-winding circuit to be connected across running section *1* in Figure 2-43 for one direction of rotation.

For reversed rotation, the external lead of the starting-winding circuit is changed to the position shown in Figure 2-44, where it is connected across running section *2*. This changes the direction of current through the starting winding.

A schematic diagram showing the windings with three leads brought out for reversing purposes is shown in Figure 2-45.

9. *Single-voltage, Instantly Reversible Capacitor-start Motor.* Under normal operating conditions, a capacitor-start motor must be brought to a complete stop before it can be started in the reverse direction, because the centrifugal switch cannot close until the motor has almost stopped. Since the starting winding is out of the circuit when the switch is in the OPEN position, the reversal of the starting-winding leads while the motor is running has no effect on the operation of the motor.

Some capacitor-start motors have a reversing switch, which is connected as shown in Figure 2-46. This switch has three blades, or poles, that move as one unit to either of the two positions. In one position, clockwise rotation of the motor is provided as shown in the illustration; in the other position, the leads of the starting winding are reversed for counterclockwise rotation. Push button manual, magnetic reversing starters or drum starters are utilized for reversing purposes.

To reverse this type of motor, it is necessary to wait until the motor slows down to a point where the centrifugal switch closes and connects the starting winding to the line.

INSTANT REVERSAL. For certain types of work, considerable time would be lost waiting for the rotor to slow down before it could be reversed. To permit instant reversal while the motor is operating at full speed, a relay is placed in the circuit to short-circuit the centrifugal switch and connect the starting winding in the circuit in the opposite polarity.

Figure 2-47 shows such an instantly reversible capacitor-start motor with a reversing switch. At rest, the double-contact centrifugal switch is in the START position, which places the starting winding and the capacitor in series across the line. At the same time, the coil of the normally closed relay is connected across the capacitor. With the manual switch in the FORWARD position, the running winding is connected across the line, the starting winding and capacitor are in series across the line, and the relay coil is connected across the capacitor.

The voltage developed across the capacitor is applied to the relay coil, causing the normally closed relay contacts to open. As the motor starts and its speed increases, the centrifugal switch is thrown into the running position. This disconnects the capacitor from the circuit and leaves the starting winding in series with the relay coil. This coil has high resistance and permits only enough current to flow through the starting winding to keep the relay contacts open.

During the split-second interval while the switch is being thrown from FORWARD to REVERSE, no current flows through the relay coil; consequently, the relay contacts close. Then, when the switch reaches the REVERSE position, current flows through the now-closed relay contacts to the starting winding but in the opposite direction. This creates a torque in the direction opposite to rotation. As a result the rotor is immediately brought to a stop and the centrifugal switch returns to its starting position. This places the capacitor in series with the starting winding, and the rotor starts turning in the opposite direction. The windings and rotor on this type of motor are designed to withstand the strain of quick reversal.

Schematic Diagrams of Capacitor-start Motors

The schematic diagrams in Figure 2-48 of the illustrations are reproduced through the courtesy of NEMA and show the terminal markings of single- and dual-voltage capacitor-start motors with and without a thermal protector. These diagrams are part of the NEMA Standards Publication MGI of April 1968. Data on terminal connections will be found in Chapter 1, page 25.

10. *Two-speed Capacitor-start Motor.* One method of changing the speed on a capacitor-start motor is to change the number of poles in the winding. To accomplish this, two separate running windings are placed in the slots. Usually these consist of a six-pole winding and an eight-pole winding. One starting winding is used, which acts in conjunction with the higher-speed running winding. The centrifugal switch is of the double-action, or transfer, type, having two contact points on the start side of the switch and one contact point on the run side of the switch. An external switch is used to change the speed of the motor. Figure 2-49 shows a schematic diagram of a two-speed capacitor-start motor.

This motor always starts on high speed, regardless of whether the speed switch is on HIGH or LOW. If this switch is set on LOW, the starting winding and high-speed running winding are cut out of the circuit by the centrifugal switch as soon as the motor comes up to speed; at the same time, the centrifugal switch cuts in the low-speed winding.

The three windings used on this motor are placed in the slots in a definite relationship to one another, as shown in Figure 2-50. This is a typical layout of the pitch of the coils in a 36-slot motor.

11. *Two-speed Capacitor-start Motor with Two Capacitors* This motor has two running windings, two starting windings, and two capacitors. One capacitor is used for high-speed operation and the other for low-speed operation. A double centrifugal switch disconnects the starting windings from the circuit after start. Figure 2-51 shows a diagram of this type of motor.

Permanent-split Capacitor Motor

A permanent-split capacitor motor is a capacitor motor having the same value of capacitance for both starting and running conditions. This motor is similar to the capacitor-start motor except for the following:

1. The capacitor and starting winding are connected in the circuit at all times.
2. The capacitor is generally of the oil-impregnated type.
3. No centrifugal switch or other disconnecting mechanism is necessary.

This motor is quiet and smooth running and of comparatively low torque. These motors are very often called single-value *capacitor-run* motors.

Some of the types of permanent-split capacitor motors are

1. Single-voltage
2. Two-voltage
3. Single-voltage, reversible
4. Two-speed, single-voltage
5. Three-speed, single-voltage

These motors and their connections are described in the following paragraphs.

1. *Single-voltage, Permanent-split Capicitor Motor* This motor is similar in all respects to the capacitor-start motor, except that it does not contain a centrifugal switch. It has two windings, one running (main) and one starting (auxiliary), and these are placed 90 electrical degrees from each other. A capacitor may be mounted on top of the motor or set up separately. The capacity is generally low, the value ranging from approximately 3 to 25μf. The capacitor is usually a paper-insulated type and impregnated with oil or synthetic liquid.

The low value of the capacitor results in a motor of low starting torque. Consequently, this motor can be used only on applications that are satisfied by this condition. Such applications include oil burners, voltage regulators, and fans. Permanent-split capacitor motors are quiet and smooth running in operation.

The connections of the windings are identical with those of the capacitor-start motor, except that the centrifugal switch is omitted. A wiring diagram of the single-value capacitor motor is shown in Figure 2-52.

To reverse the motor shown in Figure 2-52, it is necessary to remove the end bracket and reverse the leads of the starting winding in respect to the running winding. To avoid the necessity for removing the bracket, four leads are brought out of the motor or to the terminal board on the motor as illustrated in Figure 2-53.

2. *Dual-voltage, Permanent-split Capacitor Motor* This motor, illustrated in Figure 2-54, differs from the dual-voltage, capacitor-start motor only in that it has no centrifugal switch. A two-section running winding and one starting winding are used. The sections are connected in series for high-voltage and in parallel for low-voltage operation. With either connection, the starting winding is always connected across one running-winding section. As in the two-voltage capacitor-start motor, both sections of the running winding are identical and can be wound one at a time or with

two wires by the hand-winding method or by using half the poles for one section and the other half for the second section.

3. *Single-voltage, Reversible Permanent-split Capacitor Motor* This motor has low starting torque and is used for control of valves and rheostats. It has two main windings, placed 90 electrical degrees from each other. These windings are identical. One serves as the running winding and the other as a starting winding for one direction of rotation. During the reverse rotation, the one that formerly served as the running becomes the starting winding, while the former starting winding serves as the running winding. These windings may be formed in the same manner as those in the capacitor-start motor.

The principal of operation of this motor depends upon the fact that the direction of rotation of the rotor is always from a starting-winding pole to an adjacent running-winding pole of the same polarity. Tracing the circuit shown in Figure 2-55 shows that when the switch is in the forward position, current travels through winding *b* to the other side of the power line. The current also takes a path through the capacitor and winding *a* back to the line. Thus, winding *a* acts as the starting winding, and winding *b* acts as the running winding, causing rotation in one direction.

If the switch is in the REVERSE position, winding *a* becomes the running winding, and winding *b* acts as the starting winding. The motor then rotates in the opposite direction.

4. *Two-speed, Single-voltage Permanent-split Capacitor Motor* Unlike the two-speed capacitor-start motor, this single-voltage motor does not require a change in the number of poles in order to produce a decrease in speed. Instead, advantage is taken of the fact that the speed of rotation of the rotor is never as fast as the speed of the rotating magnetic field set up by the stator. The difference between these two speeds is called *slip*. A decrease in the strength of the magnetic field increases the slip and therefore causes a decrease in the speed of the rotor.

To obtain a lowered voltage for the running winding, an auxiliary running winding is connected in series with the main running winding. The auxiliary winding is wound in the same slots as the main running winding. The starting winding is placed 90 electrical degrees from the running winding.

In Figure 2-56, with the speed switch on LOW, running and auxiliary windings are in series across the line. Thus the line voltage divides between the two windings, and only a portion of the line voltage is applied to the running winding. Consequently, this lowered voltage decreases the field strength of the running winding and causes a decrease in speed. The starting winding for the low-speed connection is in series with the capacitor and across the line.

With the speed switch set on HIGH, the main running winding is across the line, while the auxiliary winding is in series with the starting winding and the capacitor. The main winding now has full voltage and, consequently, a greater field strength. This reduces the slip and causes the rotor to run faster. Figure 2-57 shows a wiring diagram of this motor.

The auxiliary winding may be wound with a different size of wire than that employed in the main running winding but is always placed in the same slots as the main winding. The procedure in winding is to put the main winding in the slots first, next the auxiliary winding, and then the starting winding, which is placed 90 electrical degrees from the other windings. Suitable insulation should be used between windings.

To reverse this motor, reverse the starting-winding leads. Figure 2-58 shows a winding diagram of a two-speed, single-value capacitor-run motor connected for high speed.

5. *Three-speed, Single-voltage Permanent-split Capacitor Motor* This motor is similar to the one just described, except that it has a tap at the center of the auxiliary winding as shown in Figure 2-59. There is thus formed one running winding, one auxiliary winding having two sections, 1 and 2, and one starting winding.

The schematic diagram of Figure 2-59 also shows how the windings are connected for the three speeds. On high speed, the running winding is across the line, and auxiliary windings *1* and *2* and the starting-winding circuit are in series across the line. For medium speed, the running winding and half the auxiliary winding (section 1) are connected in series, and the other half of the auxiliary winding (section 2) is connected in series with the starting-winding circuit across the line. For low speed, the running winding is connected in series with both auxiliary sections across the line. The starting winding circuit is also across the line. In all three connections, the capacitor remains in series with the starting winding.

Figure 2-60 shows a winding diagram of this motor, and Figure 2-61 shows a typical layout of the poles for a motor of this type.

Terminal Markings for Multispeed, Single-voltage, Permanent-split Capacitor Motors

Figure 2-62 shows the identification of the terminal leads of multispeed permanent-split capacitor motors for fractional horsepower air-conditioning condensers and evaporator fans. These illustrations are reproduced through the courtesy of the National Electrical Manufacturers Association.

Two-value Capacitor Motor

The two-value capacitor motor starts with a high capacity in series with the starting (auxiliary) winding. This creates high starting torque which is required by furnace stokers and compressors, and so on. For running, a lower capacity is substituted by the centrifugal switch. Both the running and starting windings remain in the circuit at all times.

The two values of capacity can be obtained by using two capacitors in parallel at the start and then disconnecting one for low-value run or by using a transformer in conjunction with one capacitor so that the effective capacity value is increased for starting.

Use of Transformer-capacitor Unit Instead of using two capacitors, some older motors utilize an autotransformer and one capacitor to provide the high value of capacity required for starting. The transformer steps up the voltage applied to the capacitor, then the centrifugal switch transfers the circuit, so that the voltage is reduced for running. The higher voltage can be placed across the capacitor for only a few seconds; otherwise, it will cause a breakdown in the capacitor insulation and thus a short circuit.

The autotransformer consists of a laminated iron core on which is wound a coil of copper wire having several taps as shown in Figure 2-63. The capacitor is usually connected to points *a* and *d*, the ends of the transformer winding, as shown in Figure 2-64. If point *b* is the center tap and power line is connected to taps *a* and *b*, twice the line voltage is applied to the capacitor.

When approximately twice normal voltage is applied to the capacitor, the effective capacity increases as the square of the transformer voltage ratio, which is 2 to 1. Therefore, the effect of the capacity will be increased 2 $\times$ 2, or four times. If the value of the capacitor is 4 μf, then its effective capacity with the transformer added to the circuit is 4 $\times$ 4 or 16 μf.

If tap *b* is one-quarter of the total number of turns between point *a* and point *d*, the ratio of the capacitor voltage to line voltage will be 4 to 1. The effective capacity will therefore be sixteen times the normal capacity of 4 μf, or $16 \times 4 = 64$ μf.

If the transformer is tapped so that the ratio of capacitor voltage to line voltage is 4 to 1, then a 6-μf capacitor would have an effective capacity of 96 μf, which may be sufficient to produce a high starting torque. The ratio is changed by the centrifugal switch moving to another tap when the motor reaches approximately 75 percent of full speed. The motor then operates with a normal capacitor value. The switching circuit is shown in Figure 2-65.

Usually oil-impregnated capacitors of approximately 4 to 16 μf are used in this type of motor. The capacitor and transformer are sealed in a rectangular steel box and mounted on top of the motor. Figure 2-66 illustrates a stator-connection diagram for this motor. This motor was rather popular in the 1940s, and many are still in existence.

Both two-capacitor types and capacitor-transformer types will be found in the following two-value capacitor-run motors:

1. Single-voltage
2. Single-voltage, reversible
3. Two-voltage
4. Two-voltage, reversible, with capacitor transformer
5. Two-voltage, with overload protector

1. *Single-voltage, Two-value Motor* This motor has two windings, one running and one starting, placed 90 electrical degrees from each other. The capacitors are mounted on top of the motor; one is a high-capacity, electrolytic type and the other is a low-capacity, oil-insulated type. On start, the capacitors are connected in parallel with each other and in series with the starting winding, as shown in Figure 2-67. After the motor has reached approximately 75 percent of full speed, the electrolytic capacitor is disconnected from the circuit by the centrifugal switch, leaving only the paper-oil capacitor in the circuit. The running winding is connected across the line.

2. *Single-voltage, reversible Two-value Motor* This motor is similar to the motor just described, except that a capacitor-transformer unit is used. Four leads are brought out of the motor to

make it externally reversible, two from the running-winding circuit and two from the starting-winding circuit. To reverse the motor, it is necessary only to interchange leads T_5 and T_8 as shown in Figure 2-68.

3. *Two-voltage, Two-value Motor* This motor is similar to the two-voltage capacitor-start motor, except that two capacitors are used at starting. A two-section running winding and one starting winding are used. The starting winding is always connected across one section of the running main winding. Figure 2-69 shows the connections of the windings of this motor for 115 volts; Figure 2-70 shows 230-volt operation.

On start, the capacitors are connected in parallel and are in series with the starting winding. The electrolytic capacitor is connected in series with the centrifugal switch. When the motor reaches approximately 75 percent of full speed, the centrifugal switch opens and disconnects this capacitor from the circuit. The oil-filled capacitor remains in the circuit, as does the starting winding. For external reversing, the two starting-winding leads must be brought out, as shown in Figure 2-71.

One type of two-value motor uses two capacitors, which are constructed to fit one inside the other. The electrolytic capacitor is shaped like a hollow cylinder, and the running capacitor is cylindrical and fits inside the electrolytic capacitor, as shown in Figure 2-72(a). The two units are sealed into one container. A diagram of a motor having the double-unit capacitor mounted on the top is shown in Figure 2-72(b).

4. *Two-voltage, Two-value Capacitor Motor with Capacitor Transformer* This motor contains windings that are similar to those of the previous motor, the only difference being in the type of capacitor unit used. On start, the double-contact centrifugal switch permits a step-up of voltage in the capacitor which produces high effective capacity. After the motor reaches proper speed, the centrifugal switch transfers contact to the run position, and a normal voltage is applied to the capacitor. The capacitor-transformer unit remains in the circuit. Figure 2-73 shows a diagram of this motor. The motor is reversed by interchanging the leads of the starting winding.

5. *Two-voltage, Two-value Capacitor Motor with Overload Protector* This motor has a two-section running winding, a starting winding, two capacitors (oil and electrolytic), and a

three-terminal overload protector. Note that this motor, shown in Figure 2-74, is externally reversible and uses the conventional centrifugal switch to disconnect the electrolytic capacitor when the motor attains a predetermined speed. The current enters terminal *1* of the thermal unit, and flows through the bimetal element to terminal *2*. Here the current splits, part going to one section of the running winding and part going through the heater to terminal *3* and then to section *2* of the running winding. The starting winding, as customary on dual-voltage motors, is connected across one section of the running winding.

Note that the starting winding will remain in the circuit at all times. The centrifugal switch in this motor just disconnects the electrolytic capacitor.

This motor may be wound as described earlier in this chapter under the heading of Rewinding the Two-voltage Capacitor-start Motor.

Single-voltage, Two-value Capacitor Motor Using a Voltage Relay and Overload Protector Figure 2-75 shows a single-voltage, nonreversible two-value capacitor motor connected to a voltage relay and a two-terminal thermal overload protector. Note the following:

1. The relay coil is connected directly across the starting winding only.
2. Two capacitors are used (oil and electrolytic).
3. The oil capacitor is permanently connected in series with the starting winding.
4. The electrolytic capacitor is connected in parallel with the oil capacitor through the relay contacts.
5. The thermal unit is connected in series with the common terminal of the running and starting windings; that is, line *1* is connected to terminal *1*, terminal *3* to common. It was previously explained that as the motor attains a predetermined speed the relay coil will be sufficiently energized to open the normally closed relay contacts, disconnecting the electrolytic capacitor and permitting the motor to operate with the oil capacitor in the starting-winding circuit.

The motor shown in Figure 2-76 is identical to the previous motor, except that a three-terminal overload protector is used. Line *1* enters the protector at terminal *1*. At terminal *2*, the current flows through the running winding to L_2, also through the starting winding and oil capacitor to L_2. At terminal 3, the current flows to the electrolytic capacitor which is connected through the relay contacts to the starting-winding circuit. When the motor attains normal speed the relay contacts open, disconnecting the electrolytic capacitor and current flow from terminal *3*. Note that the relay coil is connected across the starting winding.

If a two-terminal overload is used, remove the wire from terminal *2* and connect it to terminal *3*. There are several ways of connecting the relays and protectors to the motor. Replacement of overloads and relays should always be made with exact type number.

Schematic Diagrams of Two-value and Permanent-split Capacitor Motors These schematics on page 64, Figure 2-77 of the illustrations are reproduced through the courtesy of NEMA and show the markings of leads as recommended by NEMA.

Calculations for Rewinding and Reconnecting

Rewinding for a Change in Voltage

It would help the reader considerably to review the comparable section applied to split-phase motors (page 32). As before, a voltage change is rather simple. This type of conversion requires a wire size change, turns per coil change and in some instances a capacitor value change. The coil span and connection are not changed.

RULE 1.

$$\text{New turns} = \frac{\text{new voltage}}{\text{orig. voltage}} \times \text{orig. turns}$$

RULE 2.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

RULE 3.

$$\text{New capacitance in } \mu\text{f} = \frac{(\text{orig. voltage})^2}{(\text{new voltage})^2} \times \text{orig. } \mu\text{f}$$

Rules 1, 2, and 3 will be applied in the following example. A 115-volt capacitor-start motor is to be rewound for 230 volts at the same frequency and speed. Compute the new turns, wire size and capacitor size. The wire size and number of turns are computed as for the split-phase motor.

Determining the size of the capacitor requires use of Rule 3.

$$\text{New capacitance in } \mu\text{f} = \frac{(\text{orig. voltage})^2}{(\text{new voltage})^2} \times \text{orig. } \mu\text{f}$$

$$\text{New } \mu\text{f} = \frac{(115)^2}{(230)^2} \times \text{orig. } \mu\text{f}$$

$$= \frac{13{,}225}{52{,}900} \times \mu\text{f} = \frac{1}{4}\text{orig. } \mu\text{f}$$

Therefore the new capacity will be 25 percent of the original capacity. If the 115-volt motor had a 120-μf capacitor, the new capacitor needed for the 230-volt rewind would be 30-μf. When a new capacitor is ordered, the new voltage must be specified.

It was mentioned in the chapter on split-phase motors that the starting winding need not be changed in a 115 to 230-volt conversion if the starting winding is connected across half the running winding. This is also true for a capacitor-start motor.

Since the capacitor is part of the starting-winding circuit, its value need not be changed. In rewinding the running winding a tap is brought out from the center of the running winding. The starting winding is connected to this tap and line wire, depending on rotation desired.

Assume the above motor is to be rewound for dual-voltage operation on 115 and 230 volts. Use the same procedure as outlined for the split-phase motor in Chapter 1. No change will be required in the starting winding or capacitor.

Reconnecting for a Change in Voltage

In a voltage reconnection change, the original pole voltage should remain the same regardless of the line voltage. A four-pole, 230-volt series-connected capacitor motor may be converted to 115 volts by reconnecting it two-circuit. The pole voltage will remain the same. The capacitor value, however, will have to be changed using Rule 3 above, unless the starting winding was originally connected across half the poles.

Rewinding for a Change in Speed

The procedure in making this change in capacitor motors is similar to that described in the split-phase motor section. Make certain that the centrifugal switch is changed or adjusted for the new speed.

Common Reasons for Capacitor Failures

1. *Stuck or fused contacts on the switch or relay* This results in continuous application of voltage to the capacitor. Should this be the problem, wire a 15,000-ohm, 2-watt resistor across the replacement capacitor terminals to discharge stored energy when the relay switches the capacitor out of the circuit. This also prevents contact fusing when the relay switches the capacitor back into the circuit.

2. *Worn or frozen bearings on the motor*

3. *Excessive load on the motor* This prevents the motor from starting or from reaching full speed.

4. *Incorrect capacitance rating* A capacitor-start motor is designed so that a particular value of capacitance will induce the right current to supply the maximum starting torque. The value of capacitance for maximum torque is not extremely critical—but too large or too small a capacitor will produce a decrease in the starting torque. It is essential to use the rating called for by the motor manufacturer. The capacitance and voltage is usually stamped on the capacitor supplied with the motor.

5. *Incorrect voltage rating of the capacitor* Always replace defective capacitors with units having the capacitor voltage rating specified by the motor manufacturer. (A higher voltage rating can be used if space permits.) Frequently, the voltage rating of the capacitor is much higher than the voltage rating of the motor. *This higher rating is not a safety factor;* it is the real operating voltage of the capacitor. The capacitor is across both the main winding and the starting winding simulating the full winding of an autotransformer. Therefore, by design, the voltage applied to a capacitor on a 110-volt motor can be, in some cases, as high as 330 volts. As previously mentioned, higher voltage capacitors can be used to replace units with lower voltage ratings. For example, a 110-volt capacitor can be replaced with a unit rated at 330 volts without any sacrifice in efficiency as long as there is

room for the bigger physical size of the higher voltage unit.

6. *Low line voltage* Low line voltage input to the motor may cause the motor to continue running on the starting winding, or may cause frequent cycling of the starting switch or relay. This would keep the capacitor in the circuit longer than permitted by its maximum duty cycle. Low voltage is often due to undersized or overloaded lines to the motor.

7. *Shorted capacitor case* When the capacitor is housed in a metal case, the case must be insulated from ground. This is the reason why metal cases are always covered with outer cardboard tubes. The preceding seven reasons for capacitor failure were reproduced with permission from Sprague Electric Company.

Troubleshooting and Repair

Testing

Defective capacitors are a frequent source of trouble in capacitor motors. They may short-circuit, open-circuit, or deteriorate with resulting change in capacity. If they short-circuit, the motor windings may burn out. Poor starting or improper operation may result from an open-circuited capacitor or one that has changed capacity.

While both electrolytic and oil capacitors are used on capacitor motors, the electrolytic condenser is the type most frequently used. Both types of capacitors are tested in the same manner in the field. The procedure is outlined below. All motor leads must first be removed from the capacitor terminals before tests are made. The capacitor is connected in series with a 10-amp fuse across a 115-volt, 60-cycle power line, as shown in Figure 2-78. If the fuse burns out, the capacitor is short-circuited and must be replaced by a new unit. If the fuse does not burn out, the capacitor will "charge" in a few seconds, after which the line leads are removed. The terminals must not be touched after the charging process, as serious injury may result.

After the line leads are removed, the capacitor terminals are short-circuited with a screwdriver, and care must be taken to hold only the wooden handle when doing this. Figure 2-79 shows the method. A snappy spark should be visible. If the capacitor does not show a spark, it has probably seriously decreased in capacity or is open. This test should be tried several times to make certain that the capacitor has been properly charged by the a-c power supply.

A visible spark when the capacitor is short-circuited is not always an indication that it is in good condition, since a unit that has decreased in capacity may also produce a small spark. This is especially true of the electrolytic capacitor, which, because of its chemical content, may deteriorate and therefore decrease in capacity.

When, as a result of these simple tests in the field, a capacitor is suspected of being defective, it is advisable to replace it. Spare capacitors are usually carried by the serviceman for just this purpose. If on replacement the motor starts and has proper torque, it may be concluded that the capacitor was at fault. Several manufacturers have emergency capacitors or capacitor selectors which provide capacities ranging from 0.20 to 600 μf, merely by changing a switching arrangement.

The same procedure is applied in the shop. However, if it is desired to determine the fault, four tests can be made which will determine the effectiveness of the capacitor. These tests are for capacity, shorts, opens, and grounds.

Capacity Test To determine the strength of a capacitor in microfarads, it is necessary to employ an a-c voltmeter and an a-c ammeter. If the capacitor is mounted on the motor, remove all wires from the terminals before testing. Connect the capacitor across a properly fused, 115-volt, 60-cycle line. Place an ammeter in series with the capacitor and a voltmeter across it, as shown in Figure 2-80. In the following tests, the electrolytic capacitor should be kept in circuit for a very short period.

From the meter readings, the rating of the capacitor in microfarads can be obtained from the formula

$$\text{Capacity in } \mu\text{f} = 2{,}650 \times \frac{\text{amperes}}{\text{volts}}$$

This formula is used when the test is performed with 60-cycle current. The capacity as determined from the formula should be approximately equal to the rated capacity. If it is more than 20 percent below, the capacitor must be replaced. To obtain the capacity in microfarads of motor capacitors of any frequency and any voltage, use the following formula

$$\text{Capacity in } \mu\text{f} = \frac{159{,}300}{\text{frequency}} \times \frac{\text{amperes}}{\text{volts}}$$

For 110 volts, 60 cycles, this would be 24.1 $\times$ I; for 220 volts, 60 cycles, this would be 12.05 $\times$ I. For a given voltage, the capacitor ratings increase as the horsepower increases. For example, a 1/6-h.p. capacitor-start motor would require a capacity rating somewhere between 88 and 108 μf, whereas the rating for a 1/3-h.p. motor would be between 160 and 180 μf at 110 volts.

Test for Opens This test may be made by using the same procedure as above. If the ammeter does not register, an open exists in the capacitor, which must be replaced.

Test for Shorts If a fuse burned out in the previous test, it would indicate a shorted capacitor. However, an ordinary test lamp in series with a 115-volt d-c line can be used for short tests. The capacitor is connected to the test leads, as shown in Figure 2-81. If the lamp lights, a short is indicated. This test cannot be applied with alternating current, since the lamp would light even when the capacitor was in good condition.

Test for Grounds A capacitor in a metal container can be tested for a ground with the test lamp, and either alternating current or direct current can be used. One test lead is held to one terminal of the capacitor, while the other test lead is held on the aluminum container, as shown in Figure 2-82. If the lamp lights, a ground is indicated. If it does not light, this test should be repeated, using the other terminal of the capacitor.

In all these tests, indication of even a slight defect calls for replacement of the capacitor; otherwise, operation of the motor may be faulty.

Test of the Windings If the capacitor is replaced and the motor still does not run, or if it does not run properly, it will be necessary to test the motor windings. Windings on the capacitor motor are similar in nearly all respects to those on the split-phase motor, and therefore the same tests should be given. The tests include those for grounds, shorts, opens, and reverses and are usually made in the shop, rather than on the job. Refer to the chapter on split-phase motors for the procedure used in testing windings.

Repairs

A good rule to follow in testing capacitor-start and two-value, two-capacitor motors is to replace the capacitor and see if the motor runs. Always try this test if inspection reveals no other faults.

If the capacitor-start motor fails to start, the trouble may be a defective capacitor or a burned-out fuse. In addition, the trouble may be due to open windings or centrifugal switch, shorted windings, worn bearings, or overload. Since these troubles and their remedies also apply to the split-phase motor, they are discussed in detail in Chapter 1.

If the motor hums and then blows a fuse shortly after current is applied, a defective capacitor should be suspected. The defect may be either a short, an open, or loss of capacity. In any case, the starting-winding circuit will be inoperative and therefore prevent the motor from starting.

To determine definitely that the capacitor is the cause of the trouble, replace it with another of equal rating, as shown in Figure 2-83. If the motor then starts with proper torque, there is no need to look further for trouble.

If no capacitor is available for substitution, the rotor may be turned by mechanical means and the switch thrown to the ON position. If the motor continues to rotate, the trouble is in the starting-winding circuit, which includes the capacitor. This does not conclusively prove a defect in the capacitor, but it is a fairly reliable sign of such trouble.

As in the case of the split-phase motor, troubles in a capacitor motor may be due to a defective starting winding or centrifugal switch. All of these must be checked in order to determine the exact cause of the troubles. Detailed information on these defects is given in Chapter 1.

Permanent-split Capacitor Motor The tests just described are applicable to this type of motor also, except that centrifugal switch trouble will not be encountered, since such a switch is not employed.

Two-value Capacitor Motor In the two-capacitor type of motor, the electrolytic capacitor may become defective and prevent the motor from starting. If it runs perfectly once it is started mechanically, the starting capacitor should be replaced with a new unit, and it should be determined whether the motor has proper starting torque. If it does not run perfectly after mechanical starting, the running capacitor must also be replaced.

In the type of motor using two capacitors in one container, it is usually the electrolytic capacitor that becomes defective. The electrolytic capacitor is the outer part of the double unit. If it becomes defective, it is necessary to replace the entire unit; or, since this may involve considerable expense, it may be more economical to attach another electrolytic capacitor to the motor in place of the old one.

Another method of repair is to remove the unit, substituting for it an electrolytic capacitor whose capacity is approximately equal to that of the double unit. This converts the motor from a two-value capacitor-run type to a capacitor-start type. Such an alteration lowers the efficiency of the motor slightly, but not enough to interfere with its performance.

If the running capacitor in a two-capacitor motor is defective, a simple repair consists of disconnecting the running capacitor from the circuit, as shown in Figure 2-84. The motor then runs as a capacitor-start motor with slightly lowered efficiency. It is assumed that the rest of the motor is in good condition.

Two-value Capacitor-transformer Motor The usual trouble when this motor fails to run is a defective capacitor-transformer unit. Either the capacitor or the transformer, or both, may break down, with the result that the motor has very poor starting torque, if it runs at all. Repairing the transformer is a lengthy process and is not recommended. A better method is to remove the transformer and replace it with an electrolytic capacitor, as shown in Figures 2-85 and 2-86. This results in a two-value two-capacitor motor, if the oil capacitor is in good condition. Another way of repairing this type of motor is to remove both the transformer and the capacitor from the iron container and replace them with an electrolytic capacitor whose value is equal to the effective capacity of the unit. This results in a capacitor-start motor having the required starting torque. The efficiency will be slightly less and it will not run as quietly. It may be difficult to determine the capacity, and so the repairman must effect the replacement with a capacitor usually employed on a motor of the same horsepower. The motor is run with the new capacitor and watched very carefully to see if the starting torque and starting current are within the required ranges.

Some shops have a setup whereby capacitors of different capacity can be inserted in the circuit. An ammeter is also connected in series with the line so that the current flow can be measured. The capacity rating that gives the highest torque with the lowest current flow is generally the correct one to use. This test setup is particularly valuable when a capacitor-start motor without the capacitor is brought to the shop to be repaired.

Other troubles on the two-value motor are similar to those on the split-phase motor. The following paragraphs provide a check list of symptoms and the typical troubles that they indicate. Remedies for these troubles appear in Chapter 1 and in this chapter.

1. If the motor has poor starting torque or starts with difficulty, the trouble may be due to:
- **a.** Defective capacitor
- **b.** Worn bearings
- **c.** Shorted windings
- **d.** Wrong connections.

2. If the fuse burns out when current is applied to the motor, look for:
- **a.** Shorted winding
- **b.** Shorted capacitor
- **c.** Open winding
- **d.** Grounded winding
- **e.** Overload
- **f.** Badly worn bearings
- **g.** Defective centrifugal switch.

3. When the motor hums, but does not run, suspect:
- **a.** Defective capacitor
- **b.** Open starting or running winding
- **c.** Overload.

4. Smoke from a motor while running may be due to:
- **a.** Shorted windings
- **b.** Failure of centrifugal switch to open starting-winding circuit
- **c.** Bearing trouble
- **d.** Overload
- **e.** Defective autotransformer.

Miscellaneous Diagrams

Figure 2-87 shows a variety of connection diagrams of capacitor motors and are reproduced with permission of the motor manufacturers.

CHAPTER 3

Repulsion-type Motors

In general, repulsion motors may be divided into three distinct classifications. These are (1) the repulsion motor, (2) the repulsion-start, induction motor, and (3) the repulsion-induction motor. These motors are called *single-phase wound-rotor motors* and are defined and classified by NEMA as follows:

Repulsion Motor A repulsion motor is a single-phase motor which has a stator winding arranged for connection to a source of power and a rotor winding connected to a commutator. Brushes on the commutator are short-circuited and are so placed that the magnetic axis of the rotor winding is inclined to the magnetic axis of the stator winding. This type of motor has a varying-speed characteristic.

Repulsion-start Induction Motor A repulsion-start induction motor is a single-phase motor having the same windings as a repulsion motor, but at a predetermined speed the rotor winding is short-circuited or otherwise connected to give the equivalent of a squirrel-cage winding. This type of motor starts as a repulsion motor but operates as an induction motor with constant-speed characteristics.

Repulsion-induction Motor A repulsion-induction motor is a form of repulsion motor which has a squirrel-cage winding in the rotor in addition to the repulsion motor winding. A motor of this type may have either a constant-speed or varying-speed characteristic.

These three classes are often confused by the beginner because of the similarity of names. But each is different from the others, having its own characteristics and applications. However, one feature common to all is that each has a rotor containing a winding that is connected to a commutator. Figure 3-1 shows a repulsion-start induction motor. These motors generally operate from a single-phase lighting or power circuit, depending on the size of the motor.

Construction

Most repulsion-type motors generally consist of the following parts:

1. A stator similar to that of the split-phase or capacitor motor and one winding, usually of two sections, similar to the running winding of a dual-voltage split-phase or capacitor motor. Figure 3-2 shows a stator of a repulsion-start induction motor.

2. A rotor having a slotted core into which a winding is placed and connected to a commutator. The rotor is similar in construction to the armature of a d-c motor and will henceforth be referred to, interchangeably, as the rotor or armature. The slots are generally skewed to produce the same starting torque regardless of the position of the armature and to reduce magnetic hum. Figure 3-3 illustrates the armature of a repulsion-induction motor.

The commutator may be one of two types: an axial commutator, with bars parallel to the shaft (Figure 3-3), or a radial commutator, with bars perpendicular to the shaft (Figures 3-4 and 3-5).

3. Two end plates or brackets that support the bearings in which the armature shaft must turn.

4. Brushes made of carbon which fit in the brush holders. The brushes ride against the commutator and are used to conduct current through the armature winding.

5. Brush holders, supported either on the front end plate or on the armature shaft, depending on the particular type of motor.

The Repulsion-start Induction Motor

This is a single-phase motor ranging in size from approximately ¼ to 10 h.p. It has high starting torque and a constant-speed characteristic. It is used in commercial refrigerators, compressors, pumps, and other applications requiring high starting torque.

Repulsion-start induction motors are of two different designs.

In one, known as the *brush-lifting* type, the brushes are automatically moved away from the commutator when the motor reaches approximately 75 percent of full speed. This type generally has the radial or vertical form of commutator (Figure 3-5 and 3-24). In the other, called the *brush-riding* type, the brushes ride on the commutator at all times. This type has the axial form of commutator, as shown in Figure 3-3. In other operating principles, these motor types are identical.

Operation of the Brush-lifting, Repulsion-start Induction Motor

To produce a reasonably high starting torque in the repulsion-start induction motor, a winding is placed on the armature. When the winding on the stator is excited by current supplied from the line, a flux is set up which induces current in the armature winding. The poles formed on the stator and on the armature have the same polarity, thus causing a repulsion torque from which the motor obtains its name.

After the motor reaches approximately 75 percent of full speed, the commutator bars of the armature winding are short-circuited by means of a centrifugal device and the brushes are automatically moved away from the commutator. The armature then acts like a squirrel-cage rotor. The motor continues to rotate as an induction motor, just as the split-phase motor did (see Chapter 1).

The Centrifugal Short-circuiting Device

The centrifugal mechanism consists of several parts which are located in the armature. These are shown in Figure 3-5 and consist of (1) governor weights, (2) short-circuiting necklace, (3) spring barrel, (4) spring, (5) push rods, (6) brush holder and brushes, and (7) lock washers. These are assembled as shown in the cutaway view of a complete rotor in Figure 3-6.

When the armature reaches approximately 75 percent of full speed, the governor weights are thrown outward, causing the push rods to move forward. These in turn push the spring barrel forward and allow the short-circuiting necklace to contact and short the commutator bars. At the same time, the brush holder and brushes are moved away from the commutator to save the brushes and the commutator from unnecessary wear and also to eliminate objectionable brush noises.

When assembling the centrifugal device, each part must be placed in its proper position. Figure 3-6 shows the parts in the order in which they are placed in position. Note that the brush holder is part of the armature assembly.

Some manufacturers use parts which may not be identical with those shown, but they are essentially the same and have a corresponding position in the armature. When the mechanism is completely assembled, the brush holders should be spaced approximately 0.030 in. from the commutator. This distance will vary, depending on the size and make of motor.

Many repulsion-start induction motors have the brush holder mounted on the end-plate assembly instead of on the armature, but the operation of this motor is similar to that of the other in all respects. Instead of the brush holder being moved forward, only the brush springs are moved away. This has the same effect as moving the brushes away from the commutator. The centrifugal device is actuated by a governor, as before, which moves the push rods forward and causes the necklace to short-circuit the commutator.

Instead of a lock washer, a threaded shaft and nut may be used to hold the centrifugal mechanism in place. When dismantling this mechanism, it is important to count the number of threads before taking off the nut, so that, upon reassembling the mechanism, the proper pressure will be placed on the governor spring. Figure 3-7 shows the order in which these parts are assembled.

Brush-riding, Repulsion-start Induction Motor

In this motor, an axial commutator is used on which the brushes ride. Such a commutator is shown in Figure 3-8.

The centrifugal apparatus generally used on this motor consists of a number of copper segments which are held in position by an encircling garter spring, as shown in Figure 3-9. This assembly is placed in position adjacent to the commutator, so that at a preset speed centrifugal force will cause the copper segments to short-circuit the commutator bars. The segments are returned to their original position by the garter spring when the motor stops. The motor runs as an induction motor while the commutator is short-circuited. Many types of short-circuiting mechanisms are made for this motor, but the working principle is essentially the same in all.

In the brush-riding type of repulsion-start induction motors, the brushes do not conduct any current after the motor attains speed, even though they ride on the commutator.

The number of brushes that ride on the commutator ordinarily depends on the number of poles in the motor. A four-pole motor would have four brushes (Figure 3-10). Two brushes will suffice if the armature is wave-wound or cross-connected, as will be explained later in the chapter (Figure 3-11). Note that in Figures 3-10 and 3-11 all the brushes are connected together or shorted. This is true of all repulsion-start induction motors regardless of the number of poles or brushes. They are not connected to an outside line nor are they connected to the stator winding.

Stator Windings and Connections

The stators of repulsion-start induction motors have one winding, like the running winding of the split-phase or capacitor motor. The coils of each pole are concentric and are put in the slots in exactly the same manner as in the split-phase motors. Since skeins are impractical, because of the many turns and the large size of wire used, hand or form windings are generally utilized. Insulation of the proper size and thickness is placed in the slots to prevent grounds.

Dual Voltage Most repulsion-start motors are made for dual-voltage operation, regardless of the number of poles and the frequency of the current. The usual method of connecting a motor is to connect all poles in series for high-voltage operation and in two-parallel for low-voltage operation. Figure 3-12(a) illustrates a four-pole dual-voltage (115-230) stator connected for 230-volt operation using the short jumper connection. Figure 3-12(b) shows the terminal markings used on a dual-voltage repulsion-type motor. Each wiring diagram shows four leads out of the motor which are lettered T_1, T_2, T_3, and T_4. For 230-volt operation T_2 and T_3 are connected together and taped. The line leads are connected to T_1 and T_4. For 115-volt operation T_1 and T_3 are connected to L_1, and T_2 and T_4 are connected to L_2. Figure 3-13 shows the same motor as Figure 3-12(a) except that long jumper connections are used. All dual-voltage motors have four wires brought out of the motor to permit changeover from one voltage to another.

Some dual-voltage motors are connected two-parallel for high-voltage operation and four-parallel for low-voltage operation. Examples of these methods of connection are shown in Figures 3-14(a), 3-14(b), and 3-15.

The majority of repulsion-start induction motors are wound for four-pole, 1,750-r.p.m. operation, but some are wound for six- and eight-pole operation. To acquaint the student with the many different types of connections used on these motors, illustrations for the six- and eight-pole motors are included. Figures 3-16, 3-17, and 3-18 show the stator windings of a six-pole motor, and Figure 3-19 shows the windings of an eight-pole motor. Figure 3-18 shows long jumper connections.

Recording Data When it is necessary to rewind the stator of a repulsion-start induction motor, care must be taken to record the proper data. Include the pitch of the individual coils, the turns, and the size of wire. Of utmost importance is the recording of the position of poles in the stator. The coils of each pole must be put back into the same slots in which they were located before the windings were stripped. If the coils are put in other slots, the armature may not rotate, or, if it does rotate it may not have the desired torque.

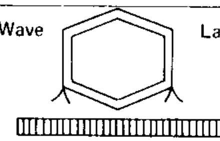
A simple method of recording the position of the original winding is to mark the center slot or slots of each pole with a center punch (see Figure 3-20). Another method is to make a drawing of the position of the poles in the frame. Some motors have stator slots that are so constructed that it is impossible to make an error in winding. On these motors the section of the core at the center of each pole is wider than the other sections. This construction is shown in Figure 3-21. The method of recording the winding data is similar to that used for the other types of single-phase motors so far discussed. Figure 3-22 illustrates a typical record of the pitch data of a 24-slot, four-pole motor. Since the stator winding is similar to that of the main winding of a split-phase motor, it is stripped as described in Chapter 1, "Split-phase Motors." A typical data sheet follows.

DATA SHEET FOR REPULSION MOTOR

Make

H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	Style
Temp.	Model	Serial #	Phase

Rotor	Bars	Stats	Coil Pitch	Wave Lap
Lead Pitch	Turns	Coils/Slot	Size Wire	
	Equalizer	Pitch		



Stator	Poles	Slots	Size Wire	No. of Circuits

Slot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	1
Winding																																					

Armature Windings for Repulsion-start Induction Motors

Armature winding is taken up in detail in Chapter 6, Direct-current Armature Winding. However, some of the important points in the study of repulsion motors, such as cross connections and equalizer rings, are discussed here. This material applies not only to repulsion-start induction motors but to repulsion and repulsion-induction motors as well.

Construction of the Armature The details of the armature are shown in Figure 3-23. The core consists of laminations punched from annealed high-grade electrical sheet steel. These are tightly pressed together and then pressed onto the shaft. The slots in the core are generally skewed to reduce hum and to eliminate a variation in starting torque at different positions of the rotor.

Commutators of the radial type are either pressed on the shaft or screwed on, depending on the make and type of motor. Usually on small motors the commutator is pressed on, but on large motors it is screwed on the shaft. When replacing a press-on commutator, care must be taken to apply even pressure on the shaft to avoid tilting the commutator; otherwise, too much of the commutator will have to be turned down in a lathe in order to have the commutator run true. These two commutators are illustrated in Figures 3-24 and 3-25.

Some commutators can be reinsulated by taking them apart, but most commutators are constructed in such a manner that reinsulation is impossible. These commutators are assembled with a composition of Bakelite or other material that may crack when subjected to the excessive heat caused by short circuits. When a repulsion-start induction motor must be rewound because of burnout, it is often found that the commutator must also be replaced.

Winding the Armature Armature windings are either lap or wave. Figure 3-26 shows a lap winding in which the end lead of a coil is connected to a commutator bar adjacent to the starting lead of the same coil.

A wave winding is one in which the starting lead and the end lead are connected on opposite sides of the commutator for a four-pole motor. See Figure 3-27. For a six-pole motor, the starting lead and the end lead are connected approximately one-third the number of commutator bars apart; for an eight-pole motor, one-fourth the number of bars apart.

There may be the same number of coils as slots, in which case the number of commutator bars must equal the number of coils or slots. This is called a *one-coil-per-slot* winding. Such windings are shown in Figures 3-26 and 3-27. An armature may have twice as many coils as slots. In this case, the commutator has twice as many bars as slots. This is called a *two-coil-per-slot* winding and is a very popular type of winding on small motors. It is shown in Figures 3-28 and 3-29. When each slot contains three coils, there are three times as many commutator bars as slots. This is called a *three-coil-per-slot* winding and is shown in Figures 3-30 and 3-31. Notice the pitch of the coils. In these illustrations the coil pitch is 1 and 8. All coils in an armature have the same pitch, turns, and size wire.

Winding Procedure Assuming a two-coil-per-slot lap winding having four poles and 28 slots, the procedure for winding the armature is as follows:

1. Mark the core on each side of one coil with a punch or file and trace the leads of this coil to the commutator bars to which it connects. These bars are also punch-marked. Determine by measurement the number of bars to the left or right of the slot to which the leads of

this coil connect. This is done by stretching a string from the center of the slot to the commutator to see which commutator bar lines up with the slot. The number of bars to the left or right is recorded as shown in Figure 3-32.

Strip the armature and record all necessary data such as coil pitch, number of turns, type of winding (lap or wave), coils per slot (one, two, or three), pitch of leads, size of wire, and so on. Stripping an armature is explained in Chapter 6, Page 181.

After the armature is stripped and the data taken, test the commutator for faults. If it is of the radial type and replacement is necessary, the portion of the commutator into which the short-circuiting mechanism fits will have to be bored out and enlarged to accommodate the necklace. This is done on the lathe with a boring tool either prior to or after winding. Extreme care must be exercised, since some commutators may be easily broken if not handled properly.

Before new insulation is placed in the slots, remove all the old insulation. Appropriate insulation about 0.007 to 0.015 in. thick is usually sufficient for motors of less than 3 h.p. The insulation, preferably cuffed, must extend on either side of the core about ¼ in. and cut a trifle below the top of the slot. To insulate a stator, the procedure is, generally, to replace the insulation with the same quality and thickness of insulation as the motor originally contained.

2. Set up the armature on horses in the position shown in Figure 3-33(a) or in an armature holder shown in Figure 3-33(b) and start winding with two wires of the same size in hand. To identify the wires it may be necessary to test each wire end when it is placed into the commutator bar. This can be avoided by the use of sleeving of different colors for lead identification or by cutting the end leads of different lengths. Sometimes wires of different colors are used.

Place the beginning leads of the two wires in the notches of the correct two commutator bars according to the data taken. These wires are usually tapped lightly with a drift punch to secure them in the notches. Make sure that all insulation on each wire is removed before putting it into the notch. Wind the proper number of turns and cut the wires at the slot nearest you, allowing sufficient length of leads for connection to the bars. Bend the wires back on the core.

3. Start the next two coils in the next open slot and put the beginning leads in the next two bars as shown in Figure 3-34. Wind the proper number of turns; then cut the wires and bend them back on the core as was done with the previous coils. This procedure is continued until the entire armature is wound.

4. When all the coils are wound, the end leads of each coil are resting on the core ready to be connected to the commutator bars. Place each

end lead in the notch of the commutator bar adjacent to the beginning lead of that coil, as illustrated in Figure 3-35. Thus, each notch holds two leads—a beginning lead on the bottom and an end lead on top. Wedges are fitted into each slot on top of the wires in order to prevent the wires from being thrown outward by centrifugal force when the armature rotates.

If the armature is coil-wound, that is, if the coils are made up on a form and then put into the armature, the method of placing the coils in the slots is slightly different. When the armature is coil-wound, only the bottom side of each coil for the first one-fourth of the total number of slots is placed therein. The entire coil is then put into the slots. In other words, the top side of the coil is not placed in a slot until the bottom half of the slot has a coil unit.

Make sure that the top leads are connected in the right order to avoid having reversed coils. After all the leads are connected, proceed to complete the winding by soldering all leads, testing, varnishing, and turning down the commutator.

Equalizer or Cross Connections Cross connections are lengths of insulated wire which connect commutator bars of the same potential. For a four-pole motor these commutator bars will be 180 mechanical degrees apart; for a six-pole motor, bars 120 degrees apart are connected. These connections are generally placed behind the commutator bars and should be made with the same size of wire as the armature winding. New commutators are often supplied with the cross connections already in place.

Nearly all lap-wound armatures used on repulsion motors are cross-connected. Circulating currents due to unequal air gaps between the armature and the stator are thus minimized. Such currents occur when a worn bearing causes the bottom side of the armature to be closer to the stator than the top side. In addition, the use of two brushes instead of four on a four-pole motor is permitted. On some armatures, the cross connections close the circuit through the armature.

To determine the bars in which cross connections are placed, it is necessary to know the number of bars, the number of poles, and whether the commutator is completely cross-connected or half cross-connected. A completely cross-connected commutator is one in which all commutator bars contain equalizer wires.

To determine the number of bars spanned by each cross connection, use the formula

$$\text{Span} = \frac{\text{no. of bars}}{\text{no. of pairs of poles}}$$

For example, if a commutator has 50 bars and if the motor has four poles, the span will be

$$\text{Span} = \frac{50}{2} = 25 \text{ bars}$$

Therefore, to span 25 bars, the first cross connection will be between bars 1 and 26; the next connection is between 2 and 27; and so on. If a six-pole motor has 81 commutator bars, the equalizer span will be $^{81}/_{3} = 27$ bars, and cross connections are made between bars 1 and 28, 2 and 29, 3 and 30, and so on. Figures 3-36 to 3-38 illustrate a 36-bar commutator cross-connected for four, six, and eight poles.

On lap windings that have no cross connections, it is necessary to have as many brushes as poles. On cross-connected commutators, only two brushes are necessary, although more may be used.

If cross-connected armatures are tested for shorts on the growler, a hacksaw blade will vibrate completely around the armature, ordinarily indicating a short circuit. However, this is not the case, and to determine whether or not the armature is shorted, it is necessary to use a meter for testing. Another method of testing for a shorted armature is described on page 98.

Rewinding a Wave-wound Armature The method of winding a wave-wound armature is similar to that for a lap-wound armature, except for the position of the leads in the commutator. Figure 3-39 shows a commutator for a 23-slot, four-pole armature having 45 bars. It has two coils per slot and is to be connected as a retrogressive wave winding. The procedure for winding this motor is as follows:

1. Record all necessary data, being careful to note the commutator pitch. The formula for determining the commutator pitch of a retrogressive winding is

$$\text{Commutator pitch} = \frac{\text{no. of bars} - 1}{\text{no. of pairs of poles}} = \frac{45 - 1}{2}$$

$$= 22, \text{ or 1 and 23}$$

Any four-pole, wave-wound armature must have an odd number of commutator bars. If the commutator has an even number of bars, two of them must be shorted.

Since the armature has two coils per slot, there are 2 × 23 or 46 coils called for in the armature. However, only 45 coils can be connected to the 45-bar commutator. Therefore, one coil is not connected in the armature circuit. Nevertheless, the dead coil must remain in the armature for mechanical balancing (see Figure 3-40).

In all two-coil-per-slot, four-pole, wave-wound armatures, it is necessary to add a coil in the form of a jumper lead where the number of bars is one more than the number of coils. For instance, if the armature had 22 slots instead of 23, only 44 coils could be wound on the armature; but, since 45 are necessary, an extra coil is put on the armature by connecting a jumper between the commutator bars that would ordinarily have been used for the forty-fifth coil. Figure 3-41 shows the connection of such a jumper lead.

2. Start winding the armature by hand with two wires, and place the bottom leads in the proper bars according to the data. The leads are placed away from the center of the coil, as shown in Figure 3-42. This is nearly always the case in wave-wound armatures.

Wind the proper number of turns for each coil; then cut the wires, one long and one short for identification, and bend them back on the core. If the armature is coil-wound, apply colored sleeving on each lead before it is placed in the armature slots.

3. Connect beginning leads into the commutator bars and wind the next two coils as shown in Figure 3-43. If the armature is coil-wound, the coil is placed in the slots *before* the beginning leads are connected to the commutator bar.

4. After the coils are wound, the end leads are put in the commutator bars on top of the beginning leads, as shown in Figure 3-44. The first top lead is usually tested to make sure it is placed in the right commutator bar. All the others are put down in sequence, since each one is identified either by its length or by its color. It is essential that the proper commutator pitch be used, otherwise the armature may not operate. In this wave winding the top and bottom leads go away from each other. In a lap winding, the leads go toward each other.

5. The procedure from here on is the same as that given for d-c armatures in Chapter 6. The armature can be tested for shorts on the growler as described on page 189.

Reversing the Repulsion-start Induction Motor

If a closed coil of wire is placed alongside and in the same plane as a field pole supplied with alternating current, the coil will turn until it is at right angles to the field pole, as illustrated in

Figure 3-45. For this to take place, the coil must be slightly tilted; otherwise a torque will be produced in both a clockwise and a counterclockwise direction, with the result that the coil will not turn at all. The current induced in the coil of wire causes a pole to be formed similar in polarity to that of the field pole. Consequently, the two poles are repelled from each other, until the movable one rotates to the horizontal position.

Figure 3-46 shows the armature of a repulsion motor substituted for the coil. If the two brushes of a two-pole motor are shorted, as shown by the heavy line in Figure 3-46, current induced by the stator winding into the armature winding by transformer action causes poles to be formed on the armature core, identical to those on the stator core. No motion takes place because the repelling forces on both sides of the rotor are in a horizontal direction. The stator winding is usually known as the *inducing winding*.

If the brushes are shifted either to the right or to the left (shown in dashed lines), rotation of the armature takes place just as it did in the case of the closed coil. If the brushes are shifted clockwise, the armature rotates in that direction. If the brushes are shifted counterclockwise, the armature rotates in that direction. Thus, a repulsion motor is reversed by shifting the brushes 15°. Actually, to shift the brushes, the entire brush holder assembly or rocker arm must be moved. Usually there are markings on the end bracket, like those shown in Figure 3-47, which correspond to the direction of rotation. To reverse a motor, a small screw on the brush holder bracket is loosened, and the brush holder shifted to either of the two marks. The screw is then tightened before the motor is started. This method of reversing applies to both brush-riding and brush-lifting types of motors.

Stationary Brush Holders Many motors, especially the brush-riding type, do not have movable brushes. The brush holders may be cast as part of the end bracket and therefore cannot be moved. Some of these motors are constructed so that the field poles are off center. If the entire pole frame is reversed, the effect is the same as if the brushes were shifted. On some motors, additional stud holes in the stator are provided to permit the stator to be moved. To reverse such a motor, the end brackets are removed, the frame reversed end to end, and the motor reassembled. The two positions are shown in Figures 3-48 and 3-49.

Cartridge Brush Holders Another type of motor has two off-center brush holders, which are individually moved. To reverse such a motor, each brush holder is moved 180 mechanical degrees. On some motors, the entire brush holder is removed and then set back in place after it is turned through 180 degrees. On other motors, a small setscrew is loosened, and the brush holder turned by means of a screwdriver. These brush holders are illustrated in Figures 3-50 and 3-51. They usually have an arrow on the cap indicating the direction of rotation. Turning the off-center brush holders shifts the brushes to a new position on the commutator and produces reversed rotation.

Some motors are constructed for only one direction of rotation. On motors of this kind the brush holders cannot be shifted, nor can the frame be moved. One good way to reverse such a motor is to unsolder the commutator leads and move them over several bars, but this cannot always be done. Another method is to rewind the stator so that the center of each pole is moved at least one slot away from its original position.

Making a retrogressive winding from a progressive one will not usually reverse the motor, as it does in a d-c armature. However, on some motors reversal of rotation may result.

Brushes Motor brushes are made in different sizes, shapes, and grades, depending on the individual machine. Since they carry current and ride on the commutator they will wear, and consequently must be replaced. A good rule to follow is to replace with a brush identical to that in the motor. Replacements can easily be obtained by ordering from supply houses, using the name-plate data as information.

Most brushes are made from some form of carbon or graphite. Ordinarily these materials are processed so that they will be suitable for operation in the motor for which it is intended. The treatment consists of subjecting the carbons to high temperatures and pressures, resulting in brushes with different characteristics such as hardness, electrical and thermal conductivity, and toughness. Some brushes are made from a mixture of powdered metal with graphite to carry larger current than can be obtained just from graphite.

Brushes are made in various shapes and usually equipped with a short length of stranded copper wire called a *pigtail*. The purpose of the pigtail is to conduct current from or to the brush proper and may or may not be connected to the brush holder, depending on the type of motor. On repulsion-start motors having radial commutators, the brush is wedge-shaped so that it will resemble the shape of the commutator bar, wide on top and narrower on the bottom. These brushes usually come in pairs with a pigtail between them as shown in Figure 3-52 and do not connect to the brush holder.

Locating the Neutral Point If new marks are to be made in the end bracket for clockwise and counterclockwise rotation, it is first necessary to locate the neutral point or setting of the brushes. At this setting, the motor will not run in either direction. Two such points will be found in the ordinary repulsion-start induction motor, one of which is the correct setting (hard neutral) and the other the incorrect one (soft neutral). To determine which is correct, move the brushes to a point where the motor does not run in either direction and then shift the brush holder slightly to the right of this point. The motor should then run in a clockwise direction. Next shift the brush holder to the left of the neutral point. The motor should then run counterclockwise. If the motor runs in the direction in which the brushes have been shifted, the correct neutral (hard neutral) point has been used. If the wrong neutral point has been used, shifting the brush holder to the right would produce counterclockwise rotation.

The Repulsion Motor

This motor is distinguished from the repulsion-start induction motor by the fact that it is made exclusively as a brush-riding type and does not have any centrifugal mechanism. This motor both starts and runs on the repulsion principle. In common with a d-c series motor, it has high starting torque and a variable-speed characteristic. It is reversed by shifting the brush holder to either side of the neutral position. Its speed can be decreased by moving the brush holder further away from the neutral position. This motor is sometimes called an *inductive-series motor.*

The stator of the repulsion motor is like that of the repulsion-start induction motor, and the stator poles are connected in the same manner. The stator is generally wound for four, six, or eight poles. Usually four leads are brought out for dual-voltage operation.

The rotor consists of an armature constructed in the same manner as the d-c type. It is laminated and generally skewed. The winding may be either hand or coil wound and is connected either lap or wave. The commutator is the axial type and the brushes always ride on the commutator. The brushes are all connected together as in the repulsion-start motor. Figure 3-53 illustrates a four-pole repulsion motor.

Compensating Winding

Some repulsion motors use an additional winding called a *compensating winding,* the purpose of which is to raise the power factor and provide better speed regulation. The compensating winding is much smaller than the main winding and is usually wound in the inner slots of each main pole and connected in series with the armature. Figure 3-54 shows the compensating winding and its connections to the brushes. Four brushes are necessary. Two of these are connected together, and the other two are connected in series with the compensating winding. The motor illustrated may be connected for dual-voltage operation. To reverse this motor, it is necessary to reverse the compensating leads as well as to shift the brush holder. A typical data layout diagram for a 36-slot, six-pole motor of this type is shown in Figure 3-55.

The Repulsion-induction Motor

It is sometimes impossible to tell the difference between the repulsion-induction motor and the repulsion motor by external appearance. However, the repulsion-induction motor has a squirrel-cage winding on the armature in addition to the regular winding. The squirrel-cage winding is located underneath the slots of the armature, as shown in Figure 3-56. The armature is usually lap-wound and cross-connected.

To tell the difference between a repulsion and repulsion-induction motor, connect the motor to the line and permit it to reach full speed. Then raise all brushes so that they no longer contact the commutator. If the motor continues to operate at full speed, it is a repulsion-induction motor.

Repulsion-induction motors are made in sizes up to about 10 h.p. They are dual-voltage types and can be used for general-purpose duty. Figure 3-57 illustrates the connections of this motor for 230-volt operation. In the field of repulsion motors, this type is becoming very popular, because of its good all-round characteristics, which are comparable to those of the d-c compound motor.

The advantage of this motor lies in the fact that no centrifugal short-circuiting mechanism is used. It has high starting torque and, owing to the squirrel-cage winding, a fairly constant speed regulation. These motors are also made with compensating coils to increase the power factor of the motor circuit. An illustration of a compensated repulsion-induction motor connected for 115-volt operation is shown in Figure 3-58.

Electrically-reversible Repulsion Motors

Repulsion motors are reversed usually by shifting the brush rigging approximately 15° either side of neutral. Actually, the direction of rotation depends on moving the brushes mechanically from one side of hard neutral to the other. Reversal of rotation can be accomplished by moving the magnetic field instead of the brushes. The brushes remain in a fixed position at all times. This is done by using two sets of windings on the stator instead of one. These are wound 90 electrical degrees apart, just like the windings on a split-phase motor.

There are several ways of arranging the windings for the electrically reversed repulsion motor. The main or inducing winding is wound on the stator as heretofore described, and the reversing winding is wound 90 electrical degrees from the main winding. Both windings are connected in series. To reverse the motor it is only necessary to reverse the leads of either winding.

Another method of winding is to wind the reversing winding in two sections. In operation, the main and one section are connected in series for clockwise rotation. For counterclockwise rotation, the main winding is connected in series with the other section. The two sections are so connected as to give opposite polarities for the same pole. This procedure shifts the magnetic axis either to the left or right, producing the required rotation. Schematic diagrams of these and other repulsion-type motor connections are shown in Figure 3-59 on page 89 of the illustrations. They are reproduced through the courtesy of NEMA.

Rewinding and Reconnecting Repulsion Motors

Rewinding for a Change in Voltage

This is the only change which does not involve too much cost. Only the stator winding must be changed. The rules in this change are similar to those in the split-phase or capacitor main winding.

RULE 1.

$$\text{New turns} = \frac{\text{new voltage}}{\text{orig. voltage}} \times \text{orig. turns/coil}$$

RULE 2.

$$\text{New c.m. area} = \frac{\text{orig. voltage}}{\text{new voltage}} \times \text{orig. c.m. area}$$

Example:

A 115/230-volt repulsion-start induction motor is to be changed to a 230/460-volt motor.

Solution:

$$\text{New turns} = \frac{230}{115} \times \text{orig. turns}$$

$$= 2 \times \text{orig. turns}$$

Therefore, twice as many turns per coil are used.

$$\text{New c.m. area} = \frac{115}{230} \text{ orig. c.m. area}$$

$$= \frac{1}{2} \text{ orig. c.m. area}$$

Therefore, wire one-half of the original gauge is used. For example, if the original wire size was No. 16, use a No. 19 instead.

In a voltage change, the armature need not be disturbed in any way.

Troubleshooting and Repair

Testing

As in the case of other motors, repulsion motors are tested for grounds, shorts, opens, and reverses. Both the armature and stator must be given these tests.

Test for Grounds The usual method of testing the stator for grounds is to use the test lamp. Connect one test wire to the frame and the other test wire to a stator lead. If the lamp lights, a ground is indicated. The method of location and repair of the ground is the same as that described for the split-phase and capacitor motors.

The armature windings and the commutator are tested for grounds in exactly the same way. On some motors, the brush holders are grounded to the end plate. Consequently before the armature is tested for grounds, the brushes must be lifted away from the commutator. If a ground is indicated in the armature, test for location by the meter method as described in Chapter 6. A voltage of approximately 1000 volts, applied between winding and ground, may flash at the point of ground and show its location.

Test for Shorts The stator is tested for shorts by using the internal growler, by measuring the drop in voltage across each pole, by a resistance measurement of each pole, or by feeling for the hottest coil after the motor runs for a short time. A shorted coil can also be detected by applying direct current to the winding and determining the strength of each field with a piece of iron. The pole having the least attraction or pull is the shorted one. If a coil is burned or charred, visual inspection alone will reveal the defective coil.

The armature is tested for shorts with the millivoltmeter, or it may be tested on the growler, if the armature is wave-wound. It must be emphasized that lap-wound armatures with cross connections cannot be tested on the growler. Shorted coils produce a low reading on the millivoltmeter and, if tested on the growler, cause a hacksaw blade to vibrate. This is explained in Chapter 6.

A highly satisfactory method of testing for a short circuit in the armature of a repulsion motor is illustrated in Figure 3-60. Remove the brushes or prevent them from contacting the commutator. Connect the power line to the motor. With the brushes removed, the motor will not rotate. Turn the armature by hand, and if there is a shorted coil in the armature, it will have a tendency to stick at certain points. Otherwise the armature will turn freely. This test should be made only if the bearings are in good condition.

Test for Opens and Reverses The stator winding of the repulsion motor is tested for opens and reverses as described in the previous chapters. The armature is tested for such trouble in the manner described in Chapter 6.

Repairs

This section applies to all three types of repulsion motors. The symptoms that are encountered in practice are given below. Under each are listed the possible troubles. The numbers in parentheses after each trouble indicate the correspondingly numbered remedies to be found in the following pages.

Since only the repulsion-start induction motor has a centrifugal short-circuiting mechanism, it is only this type that is referred to when the centrifugal switch is mentioned.

1. If the motor fails to start when the switch is closed, the trouble may be:
- **a.** Burned-out fuse
- **b.** Worn bearings (1)
- **c.** Brushes stuck in holder (9)
- **d.** Worn brushes (9)
- **e.** Open circuit in stator or armature (2)
- **f.** Wrong brush-holder position (5)
- **g.** Shorted armature (3)
- **h.** Dirty commutator (9), (12), (17)
- **i.** Wrong lead connections (6)
- **j.** Necklace shorting armature (11).

2. If the motor does not start properly, the trouble may be:
- **a.** Worn bearings (1)
- **b.** Dirty necklace or commutator (9), (12)
- **c.** Brushes moving from commutator too soon (10)
- **d.** Centrifugal mechanism not assembled properly (14)
- **e.** Brush holder set in wrong position (5)
- **f.** Short-circuited mechanism worn, broken, or improperly assembled (14)
- **g.** Governor weights jammed (15)
- **h.** Improper tension in the spring (16)
- **i.** Shorted armature (3)
- **j.** Excessive end play (8)
- **k.** Overload (7)
- **l.** Shorted stator (4)
- **m.** Worn lip on brush holder (18).

3. If the motor becomes excessively hot, the trouble may be:
- **a.** Motor connected for 115-volt operation but being run on 230 volts
- **b.** Shorted armature or stator (3), (4)

c. Overload (7)
d. Worn bearings (1)
e. Broken or burnt necklace (12), (13)
f. Brush holder out of position (5).

4. If motor is noisy in operation, it may be caused by:
   a. Worn bearings or shaft (1)
   b. Loose centrifugal device (14)
   c. Shorted stator coil (4)
   d. Excessive end play (8)
   e. Dirty short-circuiting device (12).
5. If the motor burns out a fuse, the trouble may be:
   a. Grounded field (19)
   b. Incorrect connections (6)
   c. Brushes not contacting commutator (9)
   d. Shorted armature (3)
   e. Incorrect setting of brushes (5)
   f. Frozen bearings.
6. If the motor hums but does not run, the trouble may be:
   a. Wrong lead connections (6)
   b. Worn bearings (1)
   c. Incorrect brush setting (5)
   d. Shorted armature (3)
   e. Shorted stator (4)
   f. Grounded stator (19)
   g. Brushes sticking or not making contact (9)
   h. Dirty commutator (9), (12).
7. If the motor does not come up to speed, the trouble may be:
   a. Wrong spring tension on brushes (10), (16)
   b. Dirty or burned necklace (12)
   c. Dirty commutator (9)
   d. Shorted armature (3)
   e. Shorted stator coil (4)
   f. Worn bearings (1)
   g. Push rods too long (10).
8. If the motor sparks internally, the trouble may be:
   a. Open armature coils (2)
   b. Dirty commutator (9)
   c. High mica (20)
   d. Short or sticking brushes (9).

(1) *Worn Bearings* If the bearings are so worn that the rotor touches the stator, the motor hums when the switch is closed, and the armature has only a slight tendency to rotate. With no voltage applied to the motor, test the bearings by trying to move the shaft vertically. Movement indicates worn bearings, and the remedy is replacement

with new bearings. When the bearings are in such a condition, the armature has smooth worn sections on the core, indicating that it has been rubbing against the stator. If the bearings are slightly worn, the motor will be noisy and run hot, and in some instances it will run slower than normal speed.

(2) *Open Circuit in Stator or Armature* To locate the position of the open, use the test lamp and proceed as described in Chapter 1. After the open is located, repair or rewind as the case demands.

In testing the stator for opens in a repulsion motor, make certain to test two circuits. Since nearly all repulsion motors are dual-voltage motors, four leads are brought out, two for each set of poles.

Opens in the armature are tested and located with a meter, as in the case of d-c motors. A burned spot on the commutator will indicate the position of the open coil. The remedy is to repair the open by reconnecting the broken wire or, if the break is not readily accessible, by rewinding the entire coil or armature.

(3) *Shorted Armature* If most of the coils of an armature are shorted, the motor will make a feeble attempt to start, then hum, and remain inoperative. If only one or two coils are shorted, the motor will run but will have poor starting torque. The shorted coil will become hot at start and may smoke if starting is prolonged.

A good method of testing an armature for shorted coils is to remove the brushes and then turn the armature while current is flowing through the stator. If the armature turns freely without sticking, it is in good condition. Usually a visual inspection of the armature winding of a repulsion motor will reveal shorted coils. The armature is generally completely burned and charred so that the odor of burnt insulation is evident.

It is not a good policy to cut out coils on repulsion motors. If one or more coils are shorted, the entire armature should be rewound. Be sure the commutator is perfect before the armature is rewound.

(4) *Shorted Stator* A shorted stator will cause the motor to run at a slower-than-normal speed and produce a growling noise. In addition, the shorted coils will become hot and smoke. Sometimes the motor will not reach the speed required for the centrifugal mechanism to operate, and, consequently, it draws an excessive current and burns out a fuse. Test for this condition with an internal growler.

(5) *Wrong Brush holder Position* On repulsion motors, the brush holder must be set in a definite position for rotation. If the holder moves from this position, either the motor will have poor starting torque or it may not run at all and a fuse will burn out. This condition will occur when the setscrew holding the brush rigging in place becomes loose and permits the holder to shift. A similar condition arises when

the armature is rewound and the leads are not put in the proper commutator bars. If the leads are placed one or two bars away from the proper position, a new neutral point must be located.

This will also occur if the stator has been rewound and the coils placed one slot away from the original position. In either case, a new neutral position must be located, and from this, the new position for clockwise and counterclockwise direction is located. This can be found by shifting the brush holder back and forth until the motor has the required torque.

(6) *Wrong Lead Connections* Figures 3-61 and 3-62 show the errors that are sometimes made by beginners when connecting the four external leads of a repulsion motor. In both cases, the motor will hum when power is applied. To remedy this, reverse one set of motor leads.

Another error which is made in the lead connections consists of joining terminals T_1 and T_2 together and to line L_1, and terminals T_3 and T_4 together and to line L_2. Study of the diagram of Figure 3-63 shows that such a connection is equivalent to having an open circuit. With this connection, the motor will not even hum when connected to the line.

(7) *Excessive Load* Overloading a motor prevents it from operating at the required speed and causes an excessive flow of current. In repulsion-start induction motors, the centrifugal mechanism will not operate because the speed will be insufficient. Instead, they will attempt to operate as repulsion motors and will be noisy and very hot.

(8) *Excessive End Play* On some repulsion-start induction motors having radial commutators, excessive end play will cause the brush holder to be too great a distance from the commutator, resulting in poor brush pressure which will produce sparking and may prevent the motor from coming up to speed. Allow at the maximum $\frac{1}{64}$-in. end play by placing washers on the shaft of the armature. Make sure, however, that the washers are so placed that the core of the armature lines up with that of the stator. Quite often, excessive end play will cause noisy operation.

(9) *Brushes Not Contacting Commutator* If the brushes are stuck or worn, they may not touch the commutator and the motor will not start. A dirty commutator or poor spring tension will have the same result. If the motor does start, considerable sparking will occur. These defects are easily detected by inspection and are remedied by cleaning the commutator, renewing the brushes or springs, or renewing both.

(10) *Brushes Lifting from Commutator Too Quickly* A repulsion-start induction motor operates as a repulsion motor until it reaches approximately 75 percent of full speed and then comes up to speed

as an induction motor. It is obvious that if the brushes are moved away from the commutator before this speed is reached, the motor will not attain full speed. Instead, it will slow down, causing the brushes to ride on the commutator again. This cycle of operations may continue indefinitely.

Premature movement of the brushes from the commutator may be due to poor spring tension. On the type of motor that has the brush-holder assembly on the armature, it may be necessary to replace the spring. On the other type, the tension on the spring may be increased by tightening the nut.

If the push rods are too long, the brush holder is held too far away from the commutator. At start, the brush holder should be approximately $\frac{1}{32}$ in. from the commutator. The push rods should be shortened when the commutator is turned down on the lathe. Incorrect assembly of the centrifugal mechanism will also cause premature movement of the brush holder.

(11) *Necklace Shorting Armature* It is usually the fault of the assembly when the necklace shorts the armature. This can easily be rectified by referring to Figure 3-6 and reassembling the parts in the proper order, as shown there.

On the brush-riding, repulsion-start motor, the short-circuiting segments may become welded to the commutator bars, or the commutator bars may become grounded.

(12) *Dirty Centrifugal Necklace or Commutator* If the necklace is dirty or broken or if that part of the commutator which is shorted by the necklace is dirty, then the commutator will not become entirely shorted at the right time. Consequently the motor will run in a manner similar to that of a squirrel-cage rotor with open-circuited bars. Such a motor will not pull a load and will slow down and overheat. The motor will also be noisy. The brush-lifting type will slow down sufficiently so that the brushes will again ride on the commutator, and this in turn, will make the motor speed up. But as soon as a load is placed on it, it will slow down again. This operation will repeat itself until a fuse blows.

The remedy is to remove all the mechanism and clean the necklace, replacing parts if necessary. The commutator must also be cleaned thoroughly.

(13) *Short-circuiting Necklace Broken or Not Operating Properly* If the necklace is of the type which consists of many individual pieces of copper segments held together with a length of wire through holes in each piece, make sure that it is placed on its holder so that the holes are toward the rear of the commutator. Each segment also has a shoulder that must be in a position to contact the commutator.

If the necklace is the one-piece type, it is so constructed that it curves. It is very important that it be assembled on the necklace spool to fit the curvature of the spool.

If the necklace is broken, burned, or assembled improperly, the armature may not be completely shorted after it reaches speed. The motor then operates at all times as a repulsion motor. The remedy is a new necklace or proper assembly.

(14) *Centrifugal Mechanism Not Assembled Properly* If the necklace is assembled in such a position that it always short-circuits the commutator, the motor will not start. If the spring barrel is assembled improperly, the mechanism will jam. Incorrect tension on the spring will cause the brushes to lift from the commutator too quickly or too slowly. An improperly assembled mechanism may also be loose and cause this condition during operation.

If the centrifugal device is suspected, dismantle it entirely, clean all parts, make sure that each part is in perfect condition, and then reassemble correctly. Use Figure 3-6 as a guide.

(15) *Centrifugal Weights Jammed* When the centrifugal weights are jammed, the motor operates as a repulsion motor at all times; it will be noisy and have poor torque. If the weights are jammed, the push rods will not operate, and consequently the short-circuiting apparatus will be inoperable. Further, the brushes will ride on the commutator at all times.

(16) *Incorrect Tension of the Spring* If the spring tension is insufficient, the commutator will become shorted at a very low speed, and the brushes will be lifted from the commutator too quickly. This will have the effect of producing a low starting torque, and the motor will be unable to achieve the speed necessary to change over from the repulsion-start condition to the induction-run. The spring may have to be replaced or adjusted for the proper tension.

If there is too much tension, the brushes will not release nor will the armature become shorted. This will cause the motor to run as a repulsion motor at all times, with resultant noisy operation and sparking. Remedy this fault by adjusting the nut for the proper tension.

(17) *Dirty Commutator* This condition is similar to that of sticking brushes, since no current will flow through the armature if dirt on the commutator prevents the brushes from making contact on the commutator. If such a condition exists, the motor will hum and sparking may take place between the commutator and the brushes. The remedy is to clean the commutator with a clean cloth and with sandpaper.

(18) *Worn Lip on Brush Holder* A worn lip on a brush holder is a common cause of failure, particularly where the holder is of

white metal. The worn lip causes the holder to wobble and give poor brush contact. To remedy, replace the brush holder.

(19) *Grounded Field* If the field is grounded in one place, the operator may get a shock if the motor is touched. If the frame of the motor is grounded according to code regulations, a fuse will blow. Two or more grounds on the field winding are equivalent to a short and in nearly all cases will cause a fuse to blow. The motor may hum for a while before the fuse blows.

(20) *High Mica* When the copper bars of a commutator wear more than the mica strips between the bars, the condition known as *high mica* develops. The high mica does not allow the brushes to make good contact to the commutator and sparking is caused. The remedy is to turn down the armature in a lathe and then undercut the mica.

CHAPTER 4

Polyphase Motors

Polyphase motors are a-c motors that are designed for either three-phase or two-phase operation. The two types are alike in construction, but the internal connections of the coils are different.

Three-phase Motors

Three-phase motors vary from fractional-horsepower size to several thousand horsepower. These motors have a fairly constant speed characteristic and are made in designs giving a variety of torque characteristics. Some three-phase motors have a high starting torque; others, a low starting torque. Some are designed to draw a normal starting current; others, a high starting current. They are made for practically every standard voltage and frequency and are very often dual-voltage motors. Three-phase motors are used to drive machine tools, pumps, elevators, fans, cranes, hoists, blowers, and many other machines.

Construction of Three-phase Motor

A three-phase motor is shown in Figure 4-1. It has three main parts: stator, rotor, and end plates. Its construction is similar to that of the split-phase motor, but it has no centrifugal switch.

The stator is shown in Figure 4-2 and consists of a frame and a laminated steel core like that used in split-phase and repulsion motors and a winding formed of individual coils placed in slots. The rotor may be a die cast aluminum squirrel-cage type or a wound rotor. Both types contain a laminated core pressed onto a shaft. The squirrel-cage rotor is shown in Figure 4-3 and is like that of a split-phase motor. The wound rotor is shown in Figure 4-4. It has a winding on the core that is connected to three slip rings mounted on the shaft.

The end plates or brackets are bolted to each side of the stator frame and contain the bearings in which the shaft revolves. Either ball bearings or sleeve bearings are used.

Operation of the Three-phase Motor

The coils in the slots of the stator are connected to form three separate windings called *phases*. These are shown in Figure 4-5. The windings or phases are connected so that a magnetic field is formed inside the stator that causes the rotor to turn at a certain speed.

Rewinding the Three-phase Motor

Many separate steps are involved in rewinding the three-phase motor, as follows:

1. Taking data
2. Stripping the winding
3. Insulating the stator
4. Winding the coils
5. Placing the coils in the slots
6. Connecting the coils
7. Testing the winding
8. Varnishing and baking

Taking Data The following information is recorded: (1) nameplate data, (2) number of slots, (3) number of coils, (4) type of connection, (5) number of turns per coil, (6) size of coil, (7) pitch of coil, (8) kind of insulation, (9) size and kind of wire.

All these data must be recorded adequately enough to enable the repairman to rewind the motor without loss of time.

Figure 4-6 shows the appearance of the stator of the most common type of three-phase motor.

If the stator were cut apart and the slot assembly flattened, it would appear as shown in Figure 4-7, provided all coils were individually wound. It would appear as in Figure 4-8 if the coils were wound in groups or gangs, as most small- to medium-sized motors are wound. This type of winding is explained on page 110.

DATA SHEET FOR POLYPHASE MOTOR

Make

H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	Style
Temp.	Model	Serial #	Phase

No. of Coils	No. of Slots	Connection
Size Wire	No. of Turns	No. of Groups
Coils/Group	No. of Poles	Pitch of Coil

When the coils are wound individually, they must be connected as shown in Figure 4-9. A predetermined number of coils are connected in series to form each group in the motor. In this illustration, three coils are connected together to form one group. All coils in three-phase motors have the same number of turns and the same coil pitch.

From the illustrations it can be seen that the number of coils is equal to the number of slots. These are counted and recorded. On some motors, there are half as many coils as slots; this type is known as a *basket winding*. In this chapter only those motors having as many coils as slots will be discussed.

Stripping the Winding During the process of stripping the winding, the remainder of the information necessary in taking data can be obtained. Before the wires are removed from the stator, the type of connection must be recorded. This can only be obtained if one is familiar with methods of winding the three-phase motor and connecting the phases and poles to one another. Three-phase motors are connected for single voltage, dual voltage, two speed, three speed, four speed, delta, star, series, parallel, and any combination thereof. In order to be able to recognize these connections, the repairman must have some basic knowledge of windings and their connections. It is best, therefore, to read and study the sections Connecting the Three-phase Motor, (page 113) and How to Recognize a Connection (page 118), before attempting to record a connection.

Large three-phase motors have open slots in the stator, as shown in Figure 4-10(a). On these it is necessary merely to remove the slot wedges and pry out the coils one at a time. The small- and medium-sized stator has the semiclosed slots shown in Figure 4-10(b), and stripping the winding from these stators could be more difficult. Since the windings are usually hard-baked, some are encapsulated (covered with an epoxy compound for additional protection), it is necessary in most cases to char the insulating material on the windings by placing the stator in a burn-off oven. The temperature must be controlled. In many shops the winding is cut on one side of the stator and then pulled out from the other side after charring. This is shown in Figure 4-11(a) and (b).

One coil must be saved in order to provide the dimensions for the new coils. While stripping the winding, the pitch of the coils, (see Figure 4-7), the number of turns in each coil, the size of the coil, and the size and kind of wire are recorded.

It is very important to measure the end room of the coils before they are removed from the slots. This distance should be recorded and care taken that the new coils do not extend further than this distance from the ends of the slots.

Insulating the Stator The stator insulation may be replaced with the same thickness and type used in the old winding. Many shops use cuffed insulation (Figure 4-12) for the small- to medium-sized motor, employing material applicable for the particular motor. Some shops use insulation without cuffs and apply edging on the ends. The cuffed insulation is sold in rolls in standard widths and can be cut to size with a paper-cutting machine and then shaped to fit the sides of the slots. Many shops use a small machine called an *insulation former* for this purpose.

Winding the Coils Examination of a coil taken from a stator will reveal that it has six sides, as shown in Figure 4-13. This type is called a *diamond coil,* and the winding is called a *diamond-coil winding.* However, coils of the smaller motor may have only four sides, two of which are rounded. This is explained on page 110. It should be understood that polyphase motor coils are always wound on forms, or coil winding heads as they are called, and then installed in the slots. Motors up to approximately 75 h.p. are wound with "mush"-type coils. This name has been given to these coils because they are wound in random rather than in layers.

On the large three-phase motor, the slots are generally open, and the coils are usually completely taped, as shown in Figure 4-13.

Cotton tape is often used for this purpose, although varnished cambric or fiberglass tape is preferable. Use tape compatible with the class of insulation used in the motor.

On the medium-sized motor the slots generally are semiclosed. The coils on such motors cannot be completely taped because the turns of the coil must very often be fed into the slot one at a time. Only that part of the coil which extends on either side of the slot is taped. This construction is shown in Figure 4-14. Many shops do not tape the coils at all, but tie them with twine or adhesive paper tape on the back ends and leads to prevent unraveling, as in Figure 4-15.

Coils of small motors may be wound into rectangular form and then two sides shaped into a rounded or diamond form by pulling at the center of opposite sides as shown in Figure 4-16. This forms a four-sided coil of two straight sides for the slots and two rounded sides on the ends. This type of coil takes up less end room. Of course, diamond-shaped coils also are used very frequently for the small motor. Most shops use a coil winder as shown in Figure 4-17 to wind small diamond-shaped coils and a coil winder as shown in Figure 4-18 to wind rounded coils. One coil may be wound at a time, or several can be wound in group form as described below.

GROUP WINDING. Most polyphase motors, with the exception of very large ones and those with open slots, use coils wound in groups. The number of coils in each group will depend on the number of slots and number of poles, as described under Connecting the Three-phase Motor. This practice of winding coils in groups is called *group* or *gang winding*. In group winding several coils are wound before the wire is cut. This saves time by eliminating the necessity of connecting coils to one another or stubbing. Figure 4-19 shows a winding head mounted on a bench-type coil winding drive. The wire is wound around six wheels mounted on shafts. Other types of forms are used, as in Figure 4-20. This type has four permanently attached cranks to adjust the winding arms equidistantly in pairs from the center of the head. This type makes mush-type coils for any three-phase motor up to 75 h.p. The finished coils are easily removed simply by pulling the arms out slightly and turning them inward. This unlocks the coils which can then be slid off effortlessly. Group-wound coils are used almost exclusively on small and medium sizes of polyphase motors. Figure 4-21 shows how coils are wound.

The two types of coils shown thus far are used in stators that have semiclosed slots. Whether or not these coils are taped depends on the individual shop and winder. Many shops do not tape the coils on small- and medium-sized motors. If the coils are not taped, creased separators or insulation of the proper width and thickness is usually placed between coils when they are inserted in the slots. It is essential that insulation be placed between phase-coils. This term is explained later.

Coils for open-slot stators require a special form and must be wound to conform to the shape of the slot. Their sides must be square or rectangular. Such coils are completely taped with a hand taper or taping machine. The coils are usually spread by means of a coil spreader before taping.

If a coil is to be taped after winding, the following method may be used: Start taping near the end lead of the coil, as shown in Figure 4-22. Continue around the coil until the second lead is reached. Be sure that each turn of tape laps over each preceding turn. The amount of lap should be one-half the width of the tape.

Tape over the second lead and its sleeving for about 1 in. Continue taping the coil until the first lead is reached. Tape this lead for about 1 in. until the start of taping is reached. Tie with adhesive tape.

Coils for semiclosed slots are taped in a similar manner except that they are taped at the ends only; that portion of the coil which enters the slot is left untaped. Coils are taped by hand, taping machine, and hand-throwing taper.

Placing Coils in Slots The turns of the coils are inserted one by one into semiclosed slots. The ends are sometimes taped after each coil is placed in the slot. Most shops do not tape coils for semiclosed slots.

Use the following procedure: Spread or fan out the turns on one side of the coil, and hold the coil at an angle so that all the turns can be fed into the slot. Figure 4-23 shows this procedure. Make sure that each turn is placed inside the insulation. Sometimes the wires are placed between the insulation and the iron core by mistake, and a ground results.

Pull the side of the coil through the slot until all the turns are in the slot. The other side of the coil remains free, as shown in Figure 24. Note that a coil side occupies half a slot.

Continue by placing one side of the second coil in the slot beyond the first, as shown in Figure 4-25. Following coils are fitted in the same manner until the slots of a complete coil pitch hold one side of each coil. The second side of each coil is left out until the bottom half of a slot is occupied by a coil side. The second side of each coil is then fitted on top of the first side of a coil several slots away, according to the pitch of the coil. When coils are wound in groups, the winder always works with a complete group of coils at a time, placing them into the slots as explained above and illustrated in Figure 4-26.

In this method one side of each coil is in the bottom half of a slot, and the other side of the coil is in the top half of another slot several slots away, depending on the pitch of the coil. The number of coils of which the top side is left out is usually one or two more than the coil pitch, and they are not put into slots until the stator is nearly completed. Make certain that each coil side extends beyond the slot at both ends and does not press against the iron core at the corners.

Before inserting the second side of each coil, it is necessary to insulate it from the coil already in the slot.

To insulate between the coil sides in the same slot, follow the procedure given in Figure 4-27 for both open and semiclosed slots. A creased separator or insulation of the proper width and thickness (usually 0.010 to 0.015 in.) is used to insulate between top and bottom coil sides in the slot. Slide a separator over the bottom sides of the coil in the slot before installing the top side. It should extend about ½ in. beyond the slot ends. When the top side is placed into the slot, slip a wooden or formed fiber wedge (round or square) over the top coil. This should extend about an ⅛ in. beyond the slot ends. As each group of coils is placed in the slots, phase insulation must be used between groups. Varnished or glass cambric or canvas is used for this purpose. Phase insulation between groups is shown in Figure 4-28. Heavy separators are placed between coils in the slot and U-shaped insulators over the top coils. Slot wedges are inserted to hold the coils securely in place. Note also that coils are wound with three wires in parallel.

Connecting the Three-phase Motor

In the following discussion, we will assume a 36-coil, four-pole and connect it as a three-phase motor.

All three-phase motors are wound with a number of coils, usually as many coils as slots. These coils are so connected as to produce three separate windings called *phases,* and each of which must have the same number of coils. The number of coils in each phase must be one-third the total number of coils in the stator.

Therefore, if a three-phase motor has 36 coils, each phase will have 12 coils. These phases are usually called *phase A, phase B,* and *phase C.*

RULE 1. To find the number of coils in each phase, divide the total number of coils in the motor by the number of phases.

Example:

$$\frac{36 \text{ coils}}{3 \text{ phases}} = 12 \text{ coils per phase}$$

All three-phase motors have their phases arranged in either a *star* (Y) connection or a *delta* (Δ) connection.

A star-connected three-phase motor is one in which the ends of each phase are joined together. The beginning of each phase is connected to the line. Figure 4-29 shows the star connection. Because of the pattern formed by the phases in the diagram, this circuit is also called a *Y* (wye) *connection* (actually an inverted Y). Henceforth, star and wye (Y) will be used interchangeably.

A *delta* connection is one in which the end of each phase is connected to the beginning of the next phase. Figure 4-30 shows the end of the *A* phase connected to the beginning of the *B* phase. The end of the *B* phase is connected to the beginning of the *C* phase, and the end of the *C* phase is connected to the beginning of the *A* phase. At each connection, a wire is brought out to the line. Another way is to connect the end of *A* to the beginning of *C*, the end of *C* to the beginning of *B*, and the end of B to the beginning of *A*.

Poles In the motor under discussion, the coils are connected to produce four poles. Thus, in a 36-coil, four-pole motor, each pole consists of nine coils, as shown schematically in Figure 4-31.

RULE 2. To find the number of coils in each pole, divide the total number of coils by the number of poles.

Example:

$$\frac{36 \text{ coils}}{4 \text{ poles}} = 9 \text{ coils per pole}$$

To the eye, the coils appear as shown in Figure 4-32. To simplify the connection process, each coil can be eliminated from the drawing so that only two leads of the coil are shown. Figure 4-33 is such a simplified drawing.

Group A group is a definite number of adjacent coils connected in series. In all three-phase motors there are always three groups in each pole, one from each phase. Thus, one group is from phase *A*, another group from phase *B*, and a third group from phase *C*.

Therefore, if a pole has nine coils, there must be three coils in each group. This section of three coils is often called a *pole-phase group*. Three groups in one pole are shown in Figure 4-34.

The coils of any one group are always connected in series. This is illustrated in Figure 4-35. Here the end of coil *1* is connected to the beginning of coil *2*. Likewise, the end of coil *2* is connected to the beginning of coil *3*. The beginning of coil *1* and the end of coil *3* are coil-group leads for connection to other groups. Another view of the same connection is shown in Figure 4-36(a).

Coils are connected into a group when they are individually wound. When coils are group-wound, the groups are automatically formed by the method of winding, as shown in Figures 4-21 and 4-36(b). Most motors are group-wound.

CONNECTING THE COILS INTO GROUPS. When the number of coils in each group is known, the coils can be connected into groups, as shown in Figure 4-37, or they can be wound into groups, as shown in Figure 4-21, thereby eliminating connections between coils. This is an important point to remember. After determining the number of coils per group as in Rule 4, always wind that number of coils in each group.

RULE 3. A simple method to determine the number of groups is to multiply the number of poles by the number of phases. For example, in the motor being discussed, 4 poles $\times$ 3 phases $=$ 12 groups, or *groups* $=$ *poles* $\times$ *phases.*

If the number of groups is known, it is easy to determine the number of coils in each group.

RULE 4. The number of coils in each group is equal to the total number of coils in the motor divided by the number of groups:

$$\text{Coils per group} = \frac{\text{total number coils}}{\text{number of groups}} = \frac{36}{12} = 3$$

When a three-phase motor is to be connected, the number of groups is first determined, and then the coils per group are computed. For example, a six-pole, 54-coil three-phase motor would have 3 phases $\times$ 6 poles or 18 groups. Then, 54 coils $\div$ 18 groups equals 3 coils per group.

Star (wye) Connection The windings of the motor can now be connected. Assume a 36-slot, four-pole, star-connected motor. The procedure is as follows:

1. Connect the coils into groups. There are three coils in each group and the coils in each group are connected in series. This is shown in Figure 4-37. If the coils are group-wound, the coils are already connected.

2. Connect the groups of the *A* phase together as shown in Figure 4-38. The groups must be connected so that the current will flow through the first *A* group in a clockwise direction and through the second *A* group in a counterclockwise direction, and so on. This will produce alternate north and south poles.

The beginning of the *A* phase is spliced to a flexible lead wire and brought out of the motor. The end of the *A* phase is connected later to the ends of the *B* and *C* phases and taped.

3. Connect the *C* phase exactly like the *A* phase. To simplify connections, skip phase *B*. The connections of phase *C* are shown in Figure 4-39.

4. Connect phase *B* in the same manner as phases *A* and *C* were connected. Figure 4-40 shows that the start of phase *B* begins at the fifth group. This type of connection, where a group is skipped in order that connection of the next phase can be started, is called a *skip-group connection.* In Figure 4-40, the arrows under each group point in opposite directions; that is, the first arrow indicates clockwise, the second arrow, counterclockwise; the third, clockwise; the fourth, counterclockwise. This is one method of checking connections for the correct polarity of groups.

To simplify these diagrams, each group can be shown as a rectangle, as shown in Figure 4-41. Usually they are arranged in circular form, as shown in Figure 4-42.

In these diagrams, the arrows on the line leads all point in the same direction. Actually the current at one moment flows in one line lead and out of the other two, and the next moment in two lines and out of one. To be certain of correct connections, the arrows will be shown pointed inward. In all of the diagrams just presented, the *B* phase, or middle phase, has the arrow drawn in the opposite direction from the two other phases. This provides a check for correct connections of three-phase motors.

A schematic diagram of a three-phase, four-pole, series-star (1Y) motor is shown in Figure 4-43. In this diagram, each phase consists of four groups, and this factor determines the number of poles in the motor. If there are four groups in each phase, it is a four-pole motor. By looking at the schematic diagram, it is possible to tell the number of poles in the motor by counting the number of groups in any phase.

The star point indicates that it is a star-connected motor. The diagram also shows that the groups in a phase are connected in series. Therefore, the schematic diagram indicates that the motor is a three-phase, four-pole, series-star (1Y) connection.

Delta Connection The same motor will next be connected as a four-pole, series-delta-connected motor. A better understanding of this connection may be gained if the schematic diagram of Figure 4-44 is studied before connections are made. This diagram shows that the groups are connected in series and, since there are four groups in each phase, that it is a four-pole motor. Since it has no star point and is connected by joining the end of the *A* phase to the beginning of the *C* phase, and so on, it is delta-connected. Thus, this is a three-phase, four-pole, series-delta (1Δ) connection.

As in the star connection, the first step is to connect the coils into groups. Since this is a three-phase, four-pole motor, it will have 3 phases $\times$ 4 poles $=$ 12 groups of three coils each. It is not necessary to show the individual coils, since these were shown in the star-connected diagrams. Each group has three coils connected in series. It is a good policy, when making these diagrams, to mark the phase above the group and the arrow underneath the group. The next step is to connect the groups of phase *A* for proper polarity, as shown in Figure 4-45. Show the first arrow clockwise, the second arrow counterclockwise, third arrow clockwise, and the fourth arrow counterclockwise.

1. Connect phase *A* in the same manner as in the star connection.
2. Connect the phase *C* for proper polarity, as shown in Figure 4-46. The groups are connected so that the current flows into the groups in the direction of the arrows. Connect the end of *A* phase to the start of *C* phase. To check polarity, see that all arrows indicating line leads are in the same direction.
3. Continue by connecting the end of phase *C* to the beginning of phase *B*. These connections are given in Figure 4-47. In tracing this diagram, start at the beginning of phase *A*, trace the current through this phase to the beginning of phase *C*, through *C*, and finally through phase *B* to the beginning of phase *A*.

Since the coils and groups are located in a circle, the diagram of Figure 4-48 shows their true position in the motor.

The procedure in connecting either a star or delta motor is the same except for the point at which the ends of the phases are connected. For a star connection, the ends of each phase are connected together for a star point; for a delta connection, the ends of each phase are connected to the beginning of another phase.

The star and delta connections shown so far have been connected in accordance with the skip-group method. It is permissible to connect these motors without skipping a group. Figure 4-49 shows a star connection in which phases *A, B,* and *C* are connected in that order.

Although this connection is just as effective as the skip-group connection, many winders and repairmen prefer the latter for ease in connecting.

Parallel Connections Many three-phase motors are designed so that each phase has two circuits or two paths for the current to travel. These are called *two-circuit,* or *two-parallel,* connections. For comparison, the schematic diagrams of a series-star (1Y) and a two-parallel star (2Y) connection are given in Figures 4-50 and 4-51. The parallel connection of the groups in each phase provides two paths for the current to follow.

Phase *A* of the two-parallel star (2Y) connection diagram with rectangles is illustrated, with the groups indicated, in Figure 4-52. Begin by connecting one line wire to groups *1* and *3* of the *A* phase. Continue as shown in the diagram. After connecting phase

A, connect phase *C*, as shown in Figure 4-53. So far, four leads are connected to the star point. Figure 4-54 shows a complete diagram of a three-phase, four-pole, two-parallel star connection. Figure 4-55 shows a circular diagram of the same motor.

How to Recognize a Connection It was pointed out previously that determining the connections on a three-phase motor when stripping it is very important and involves a knowledge of connections. A simple method of taking connection data requires that the winder or repairman visualize the schematic diagram of each type of motor.

It is important at this point to take several precautionary measures which may be helpful in recognizing these connections. Do not cut or remove any wires or leads from the winding until you are certain of the connection. Read and record the name-plate data. This will usually tell you if the motor is wound and connected for single or two speed, single voltage or dual voltage, and sometimes star or delta. The speed is always recorded on the name plate, and, since the speed depends on the number of poles, it is a simple matter to find the number of poles: Just divide 7200 by the speed for a 60-cycle motor. Remember also that the number of groups in each phase is equal to the number of poles. If the motor is connected for two voltages (dual voltage), nine leads are brought out and these may be connected series or parallel and star or delta, as explained in the section Connecting a Two-voltage Motor (page 120). If the motor is a two-speed motor, only six leads may be brought out. Thus, if the schematic diagram of the above motors is mentally pictured, little trouble should be encountered in determining the connection. With this in mind, proceed as follows.

First, trace out a line lead to the winding and count the number of groups or coils each line or terminal lead connects to. Refer to 4-56 and note that each line lead connects to just one group. Figure 4-56 is a schematic of a two-pole series-star or 1Y-connected motor, probably the simplest of all three-phase motors. Look at 4-57, a four-pole series-star or 1Y and note again that each line lead still connects to just one group. Consequently, if a line lead connects to just one group the connection must be a series-star. This is the only three-phase motor in which a terminal lead connects to one group. The only difference between these two motors is in the number of pole-phase groups. A two-pole motor will always have 2 poles × 3 phases = 6 groups (two in each phase); a four-pole motor will always have 4 poles × 3 phases = 12 groups (four in each phase); and so on. The number of groups can always be obtained from the name-plate speed and sometimes by actual count. It should be remembered that schematics for recognizing connections do not have to take into consideration the number of poles; this information can be obtained from the name plate. The important points are type of connection (star or delta) and the number of circuits (1Y, 2Y, 1Δ, 2Δ, and so on).

If each line lead connects to two groups, it can be assumed that the connection is either series-delta (1Δ) or two-parallel star (2Y). Both circuits are shown in Figure 4-58. To identify the two-parallel star connection, look for a star connection in which six groups are joined. If this cannot be found, the connection must be series-delta. Sometimes two separate star points of three groups each will be found, as in Figure 4-69.

If each line lead connects to three groups, as shown in Figure 4-59, the motor can be only a three-parallel star (3Y) type. No other type has such a connection. If each line lead connects to four groups, as shown in the two circuits of Figures 4-60(a) and (b) the motor may be either a two-parallel delta (2Δ) or a four-parallel star (4Y). Identification of the four-parallel star (4Y) is then indicated by the connection of twelve groups at the star point. These examples show that if the schematic diagram is visualized, the type of connection can easily be determined.

To determine the number of poles, several different methods may be used. If the speed of the motor is known, the number of poles is easily found since the speed of a three-phase motor bears a definite relationship to the number of poles. This was explained in Chapter 1. Thus, if the speed marked on the name plate is 1725 r.p.m., it is a four-pole motor; if 1150, it is a six-pole motor, and so on.

Another method of determining the number of poles is to count the number of groups and divide by the number of phases. For instance, if twelve groups are found, divide 12 by 3 phases, and the result is four poles. The groups are easily recognized because each group has two jumper leads.

Another method is to count the number of jumpers. For instance, if it is found that a motor has a two-parallel star connection and there are six jumpers, this indicates that it is a four-pole motor, and it is connected as shown in Figure 4-61. In this illustration, the numbers indicate the jumpers.

Connecting Three-phase Motors for Two Voltages Most small- and medium-sized three-phase motors are made so that they can be connected for either of two voltages. The purpose in making motors for two voltages is to enable the same motor to be used in localities that have different power-line voltages.

Usually the leads external to the motor may be connected to provide a series connection for the higher voltage and a two-parallel connection for the lower voltage.

Figure 4-62 shows four coils, which, if connected in series, may be used on a 460-volt, a-c power supply. Each coil receives 115 volts. If the four coils are connected two-parallel to a 230-volt line as shown in Figure 4-63, each coil still receives 115 volts. A third method of connection of the four coils is given in Figure 4-64. This is a four-parallel connection for 115-volt operation of the motor. Each coil still receives 115 volts. Thus, regardless of the line voltage, the coil voltage is the same. This is the principle used in all two-voltage machines. Therefore, if four leads or brought out of a single-phase motor designed for 460- and 230-volt operation, it can be readily connected for either voltage. Figure 4-65 shows the series connection for 460 volts, and Figure 4-66 gives the parallel circuit for 230 volts.

This principle of voltage dividing between the coils is applied to a three-phase, four-pole, star-connected motor in Figure 4-67. This motor is a series-connected star for 460-volt use. If it is used on a 230-volt line, it is connected for two-parallel, as shown in Figure 4-68. An alternative connection using two star points is shown in Figure 4-69. Either diagram is correct.

Connecting a Two-voltage (Dual-voltage) Star (wye) Motor Practically all three-phase dual-voltage motors have nine leads brought out of the motor from the winding. These are marked T_1 through T_9, so that they may be connected externally for either of two voltages. These are standard terminal markings and are shown in Figure 4-70 for star-connected motors. There are four circuits in this motor—three circuits of two terminals and one circuit of three terminals. This information will be used later for testing.

Note that each phase has a two-section winding so that these sections may be connected in series for the higher voltage and in parallel for the lower voltage. To connect for the high voltage, connect groups in series, as shown in Figure 4-71. Use the following procedure: Connect leads T_6 and T_9, and tape; connect leads T_4 and T_7 and tape; connect leads T_5 and T_8, and tape; connect leads T_1, T_2, and T_3 to the three-phase line.

To connect this same motor for the low voltage, the groups are connected two-parallel, as shown in Figure 4-72. Use the following procedure: Connect lead T_7 to T_1 and to line lead L_1; connect lead T_8 to T_2 and to line lead L_2; connect lead T_3 to T_9 and line lead L_3; connect T_4, T_5, and T_6 together to form an external star.

Figure 4-73 is a straight-line diagram of a two-voltage, four-pole, star-connected motor which is connected as explained for the motor shown in Figure 4-71. Figure 4-74 shows a circular diagram of a three-phase, dual-voltage, star-connected motor.

Connecting a Two-voltage Delta Motor Refer to Figure 4-75 for the standard terminal markings of a dual-voltage delta-connected motor. Note that a dual-voltage delta-connected motor has three circuits of three terminals each. Figure 4-76 shows a schematic diagram for both high and low voltage connections. For high-voltage operation: Connect lead T_4 to T_7; connect lead T_5 to T_8; connect lead T_6 to T_9; connect leads T_1, T_2, and T_3 to L_1, L_2, and L_3, respectively.

For low-voltage operation: Connect leads T_1, T_7, and T_6 to the line lead L_1; connect leads T_2, T_4, and T_8 to line lead L_2; connect leads T_3, T_5, and T_9 to line lead L_3.

A straight-line diagram of a two-voltage, four-pole, delta-connected motor is shown in Figure 4-77 and is connected for the higher voltage.

Wye-delta Dual-voltage Some motors are designed so that they may be connected delta for low voltage and wye (star) for high voltage. The voltage ratio between high and low should be $\sqrt{3}$ to 1. Figure 4-78 shows the terminal markings for this type of motor. Note that six leads are brought out of the motor, two from each phase.

Short and Long Jumpers

All the connections that have been shown thus far have been made with short jumper connections in which the end of a group is connected to the end of the following group of the same phase; in other words, an end-to-end or beginning-to-beginning connection, as shown in Figure 4-79. Only one phase of a star-connected motor is illustrated. These are also known as *top-to-top* connections.

Long jumper connections are those which connect the end of the first group to the beginning of the third group of the same phase, as shown in Figure 4-80. These are also called *top-to-bottom* connections. Long jumpers are used mainly on two-speed motors and for parallel connections. Figure 4-74 illustrates a four-pole, dual-voltage motor with long jumpers.

Name Plates for Dual-voltage Three-phase Motors

Figure 4-81 shows a typical name plate for a three-phase, dual-voltage, wye-connected motor. Note the connections for both the higher voltage and lower voltage. Examination of the name plate reveals that it is for a 220-440 volt, 3-phase, 60-cycle, 5 h.p., 1750-r.p.m. motor. Usually, these plates provide a connection diagram for high and low voltage operation.

Although we are primarily interested in the repair of motors, it is important to understand the meaning of some of the other identifying characteristics listed on the name plate. For example, such terms as *design, type, frame, rating, degrees centigrade rise, code,* and *service factor* need explanation.

Design Polyphase squirrel-cage integral-horsepower induction motors have been designated as being either design A, B, C, or D. These motors are designed to withstand full voltage starting. Motors with design A, B, and C, have a slip at rated load of less than 5 percent. Design D motors have a slip at rated load of 5 percent or more. Design A and B motors of ten poles or more may have a slip at rated load of 5 percent or more. The locked rotor and breakdown torques which are developed and the locked rotor currents drawn depend on the design. Tables of such value can be found in the NEMA publication, *Motor Standards.*

Type Motor manufacturers use certain symbols to designate the characteristics of the particular motor. In this case, "EPI" refers to a totally enclosed, nonventilated motor of design A or B, having normal starting torque and a normal slip of less than 5 percent.

Frame This figure for an integral-horsepower motor gives the dimension *D* of this motor which is the distance from the center of the shaft to the bottom of the feet. For a frame 215, the distance *D* is the first two digits, 21, divided by 4, and is equal to 5¼ in. The third digit, 5, is obtained from the *F* dimension of the motor, which is the distance from the center-line of base or feet of the machine to the center-line of mounting holes in feet (side view).

Rating The term *"Cont."* indicates the period of time the motor will develop full horsepower at the stated voltage and frequency shown on the name plate without overheating and without exceeding the temperature rise on the name plate.

Centigrade Rise This is the temperature rise above the ambient or room temperature when operating at the rated load. Open, general-purpose, continuous time rating motors with Class A insulation will generally carry full load without exceeding 40°C rise. Totally enclosed Class A motors will carry full load without exceeding 55°C rise.

Code A code letter is a letter which appears on the name plate of a-c motors to show the locked rotor K.V.A. (Kilovolt Amperes) per horsepower. Locked rotor amperes can be computed from tables listing the K.V.A. per horsepower for the different code letters. For example, for code letter H, the K.V.A. per horsepower is 6.3 to 7.1. The K.V.A. input for a 5-h.p. motor should not exceed $5 \times 7.1 = 35.5$ K.V.A. This figure is necessary to compute overcurrent protection in branch circuits.

Service Factor The service factor of an a-c motor is a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried at the rated voltage, frequency, and temperature. The multiplier 1.15 indicates that the motor may be overloaded to 1.15 times the rated horsepower.

Part-winding-start Motors

NEMA Definition A part-winding-start induction or synchronous motor is one arranged for starting by first energizing part of its primary winding and, subsequently, energizing the remainder of this winding in one or more steps. The purpose is to reduce the initial values of the starting current drawn or the starting torque developed by the motor. A standard part-winding-start induction motor is arranged so that one-half of its primary winding can be energized initially and, subsequently, the remaining half can be energized, both halves then carrying the same current.

As noted above, the main purpose of using part-winding-start motors is to reduce the inrush starting current or to reduce the starting torque developed by the motor. Although part-winding-start induction motors are single-voltage motors, some dual-voltage type polyphase motors (for example, 208, 220/440) are suitable for part-winding-starting on 220 volts. The dual-voltage motor is used on the lower voltage by connecting half the winding for start and then connecting both halves in parallel for run. Many of these motors are connected star or delta with the nine leads brought out. See Figure 4-82(a), (b), and Figure 4-83.

Refer to Figure 4-82(a) and note that connecting T_4, T_5, T_6 together produces two wyes or star points for the motor. Connecting T_1, T_2, and T_3 to L_1, L_2, and L_3 energizes one-half of the winding. Connecting T_7, T_8, and T_9 to L_1, L_2, L_3 completes the sequence with both 220-volt wyes in parallel. If the motor has just six leads brought out, leads T_4, T_5, T_6 are connected together permanently inside the motor.

For the delta motor in Figure 4-83, one-half the motor is connected delta by connecting T_1 and T_6 to L_1; T_2 and T_4 to L_2, and T_3 and T_5 to L_3. This sequence is completed by connecting T_7 to T_1, and T_6 and T_8 to T_2 and T_4, and T_9 to T_3 and T_5, placing both halves in parallel and across the line. If a delta motor has six leads brought out instead of nine, leads T_1 and T_6, T_2 and T_4, and T_3 and T_5 are connected permanently for start. For run, connect T_7 to T_1 and T_6; T_8 to T_2 and T_4; and T_9 to T_3 and T_5. In practice, all connections are made automatically by means of a controller designed specifically for this purpose. This is explained in the chapter on a-c controls.

Winding the Part-winding-start Motor These motors are wound for single voltage but with nine leads as in the dual-voltage motor previously explained. The connections and windings are similar to those of Figures 4-73 and 4-77. These diagrams show a top-to-top or short jumper connection. If connected as shown in Figure 4-80, long jumper connections, the motor would have a tendency to operate more quietly on the first step.

How to Identify the Nine Leads of an Untagged Three-phase, Dual-voltage, Star-connected Motor

The following equipment is used for this test:

1. An a-c voltmeter. Scale up to 460 volts.
2. A source of three-phase current—either 208, 220, or 230 volts.
3. A circuit tester, a test lamp or buzzer and battery.

The test may be broken down into two main parts:

A. Testing for the four circuits. Continuity test.
B. Connecting the two-lead circuits to their proper phase.

A. Testing for the Four Circuits

STEP 1. Refer to Figure 4-84(a). Test the nine leads for complete circuits using the buzzer, lamp, or other circuit tester. If there are four circuits—three of two leads and one of three leads—this motor must be star (wye) connected. Note that the circuits will be T_7, T_8, T_9—the internal star; T_1-T_4; T_2-T_5; T_3-T_6. If the test had showed three circuits of three leads each, this would have been a delta-connected motor. Assuming a star-connected motor, continue with the next step.

STEP 2. Tag the circuits. Use T_7, T_8, T_9 *permanently* for the three-lead circuit. *Temporarily* tag the three two-lead circuits T_1, T_4-T_2, T_5, T_3-T_6. We are not certain at this point that the three two-lead circuits are marked correctly, and our main problem is to locate and mark them correctly.

B. Connecting the Two-lead Circuits to Their Proper Phase

STEP 1. Assuming a three-phase, 230-460 volt motor in good condition; apply the lower voltage (230) to leads T_7, T_8, T_9. The motor should run without load. The other leads must remain open.

STEP 2. Measure the voltage across each of the two lead sections. This voltage should be $230/\sqrt{3}$ or approximately 130 volts. See Figure 4-84(b).

STEP 3. With the motor running, connect temporarily marked T_6 to T_9 and measure the voltage across T_3 and T_7 and across T_3 and T_8 [Figure 4-84(c)]. If these voltages are equal and approximately 340 volts, the connection of T_6 to T_9 is correct and should be tagged permanently. If equal readings of approximately 130 volts are recorded, reverse T_6 and T_3. If the voltages are unequal, try the connection with another two-lead section until approximately 340 volts is obtained.

STEP 4. Repeat this procedure for each of the other two-lead circuits; for example, connect T_5 to T_8 and test between T_2 and T_7 and between T_2 and T_9. Connect T_4 to T_7 and measure the voltage between T_1 and T_8 and between T_1 and T_9.

STEP 5. In order to check if the connections are correct, connect the motor for low-voltage operation according to the terminal marking chart. The motor should be able to pull a normal load, and line amperes should be equal and of normal value.

All of the above tests may be done by using test lamps as a substitute for the voltmeter. It is necessary, however, to use the correct number of lamps in series and to note the brilliance of each light in each circuit to determine the voltage of the circuit tested.

Untagged Dual-voltage Delta-connected Motor

The following equipment is used for this test:

1. An a-c voltmeter. Scale up to 460 volts.
2. A source of three-phase current—230 volts.
3. An ohmmeter.
4. A test lamp or buzzer with battery.

The test consists of the following:

A. Test for three circuits. Continuity tests.
B. Identifying center tap.
C. Connecting the circuits in the proper places.

A. Testing for Three Circuits

STEP 1. Refer to Figure 4-85(a) and note that there are three circuits of three wires each. This is true of all nine-lead, dual-voltage, delta-connected motors. Test with buzzer or lamp to identify the three circuits, and mark them *A*, *B*, and *C*.

B. Identifying the Center Tap

STEP 1. Use an ohmmeter for this test and measure the resistance between leads of this three-lead circuit. The two leads showing the highest resistance should be marked temporarily as T_4 and T_9. The other lead is marked T_1 permanently and is the center tap. Refer to Figure 4-85(b) and note that the resistance between T_4 and T_9 is twice that between T_1 and T_4 or T_1 and T_9.

STEP 2. Repeat this test for the other two circuits, *B* and *C*.

C. Connecting the Circuits in the Proper Phases

STEP 1. Connect circuit *A* to a three-phase, 230-volt line. The motor should run without a load as an open delta motor. Figure 4-85(c).

STEP 2. Since we know lead T_1, and we know that the other two leads are T_4 and T_9, we connect what we think is lead T_4 to one of the outer leads of circuit *B*.

STEP 3. Measure the voltage between T_1 and T_2. This should be approximately 460 volts.

STEP 4. If lead T_5 is connected to T_4, approximately 390 volts will be obtained. This, of course, is wrong. It will be necessary to use the trial-and-error method until the proper voltage is recorded. Stop the motor when making lead changes.

STEP 5. Repeat the above procedure with all the circuits and work the leads according to terminals shown in Figure 4-85(c).

Two-speed, Three-phase Motors

It was pointed out previously that the speed of three-phase motors depends on the number of poles and frequency of the current. If the frequency remains the same, then to obtain a different speed from a three-phase motor, the number of poles must be changed. This alteration can be effected by changing the connection between groups. For example, if one phase of a four-pole motor is connected in the usual manner, as shown in Figure 4-86, four poles are produced, causing rotation just under 1800 r.p.m. If the same four poles are connected for like polarity, as in Figure 4-87, four additional poles will be produced, making eight magnetic poles in all and giving a speed just under 900 r.p.m. The theory of this action was explained in Chapter 1 (page 30 and Figure 1-76). This type of connection is called a *consequent-pole connection.* In all consequent connected motors producing more than one speed, long jumper connections must be used.

The two-speed, three-phase motor can be connected to have constant horsepower at both speeds, to have constant torque at both speeds, or to have variable torque at both speeds. For constant torque, the motor is usually connected two-parallel star (2Y) for *high* and series-delta (1Δ) for *low* speed. Figure 4-88 shows the connection of the *A* phase for high-speed operation of a four- and eight-pole, three-phase-connected, constant-torque motor. In tracing out the circuit from T_6, note the opposite polarity in adjacent groups of the *A* phase, indicating a four-pole or higher speed motor, and also that the circuit is two-parallel. Figure 4-89 illustrates the same motor with the current entering T_1. All groups now have like polarity, thereby forming four consequent poles and making a total of eight poles. This will give the motor *low*-speed operation. T_6 is not used in the series-delta connection.

For a constant-horsepower motor the connection is two-parallel star (2Y) for *low* speed and series-delta (1Δ) for *high* speed. Figure 4-90 shows the connection of the *A* phase of a four- and eight-pole, three-phase, constant-horsepower motor. For *low* speed, trace the current from T_1 and note that like polarity is formed in this two-parallel connection. For *high* speed, trace the circuits in Figure 4-91 from T_4. This gives opposite polarity in each *A* group, producing in effect a four-pole motor. Note that this is a series connection.

The entire connection of a four- and eight-pole, constant-torque motor is shown in Figure 4-92. Six leads are brought out of the motor. For *high*-speed operation, T_6, T_5, and T_4 are connected to the three-phase power supply. T_1, T_2, and T_3 are connected together and taped. For *low*-speed operation, T_1, T_2, and T_3 are connected to the three-phase power supply, and T_6, T_5, and T_4 are taped individually and not used.

Figure 4-93(a) shows a four- and eight-pole constant-horsepower motor. For *low*-speed operation T_1, T_2, T_3 are connected to the power line, and T_4, T_5, and T_6 are connected together and taped. For *high*-speed operation, T_4, T_5, and T_6 are connected to the power supply. T_1, T_2, and T_3 are taped separately and not connected. Of course, two-speed motors can be operated with two separate windings having different numbers of poles.

Quite often two-speed, single-winding motors have seven leads brought out. Figure 4-93(b) shows the position of lead 7. For normal operation lead T_7 is joined to lead T_3. The purpose of bringing seven leads out is to permit this winding to be used in conjunction with another two-speed or one-speed winding in the same motor. For a three- or four-speed motor it is necessary to keep one winding open while the other is being used in order to prevent inbred circulating currents.

Multispeed Polyphase Motor Connections The motor connections shown in Figure 4-94 are reproduced with permission of the Allen-Bradley Company.

Odd Grouping Odd grouping is the term used when the number of coils in each group varies. For example, in a 48-coil, six-pole, three-phase motor, the number of coils in each group is found by the formula

$$\frac{\text{coils}}{\text{poles} \times \text{phases}} = \text{coils per group}$$

Thus,

$$\frac{48 \text{ coils}}{6 \text{ poles} \times 3 \text{ phases}} = \frac{48}{18} = 2\tfrac{12}{18} \text{ coils per group}$$

Because of the fraction, it will be necessary to have some groups of three coils and some of two coils. A simple method of determining the number of coils in each group follows:

1. Determine the total number of groups: 6 poles × 3 phases = 18 groups.
2. Determine the number of coils per group:

$$\frac{48 \text{ coils}}{18 \text{ groups}} = 2\tfrac{12}{18}$$

3. Using the fraction $\tfrac{12}{18}$, the numerator 12 determines the number

of groups with the greater number of coils, that is, 12 groups of 3 coils.

4. The remaining number of groups, 6, will have 2 coils.

To check: 12 groups of 3 coils = 36
6 groups of 2 coils = 12
Total = 48 coils

Example 1: A 54-slot, 4-pole, 3-phase machine must be grouped. How many coils per group will there be?

1. Find the number of groups:

$$4 \text{ poles} \times 3 \text{ phases} = 12 \text{ groups}$$

2. Find the number of coils per group:

$$\frac{54 \text{ coils}}{12 \text{ groups}} = 4\tfrac{6}{12} \text{ coils per group}$$

3. Therefore, using the numerator of the fraction, we have 6 groups of 5 coils and remaining 6 groups of 4 coils.

4.
$$\begin{aligned} 6 \times 5 &= 30 \text{ coils} \\ 6 \times 4 &= \underline{24} \\ & 54 \text{ coils} \end{aligned}$$

After the number of coils per group is determined, the next step is to place the groups so that there is the same number of coils in each phase. In this problem, there will be $^{54}\!/_{3}$ or 18 coils in each phase. Proceed by drawing the groups as shown in Figure 4-95. Thus, four groups constitute the *A* phase. The *A* phase must also have 18 coils since there are 54 coils in the three phases. If a group of four coils is placed in the first *A* group, five coils in the second group, four coils in the third, and five coils in the fourth, then 18 coils will be used. The same method can be used in the *B* phase, except that we start with five coils. The *C* phase can be grouped exactly like the *A* phase. The grouping will be 4–5–4—5–4–5—4–5–4—5–4–5.

Example 2: A 48-coil, 6 pole, 3-phase motor is to be grouped.

1. Find the total number of groups:

$$\text{Poles} \times \text{phases} = 6 \times 3 = 18 \text{ groups}$$

2. Find the number of coils per group:

$$\frac{\text{coils}}{\text{groups}} = \frac{48}{18} = 2\tfrac{12}{18}$$

3. Therefore, 12 groups have 3 coils, 6 groups have 2 coils.

The best way to lay out the groups is to put three coils in all the groups and then subtract one coil from each of six groups. Be sure to subtract an equal number from each phase.

A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
1					1		1		1					1		1	
2	3	3	3	3	2	3	2	3	2	3	3	3	3	2	3	2	3

In all odd number groups, be sure that there is an equal number of coils in each phase and that the groups are distributed symmetrically. If the total number of coils in the motor cannot be divided equally by the phases, some coils may have to be eliminated. For instance, if a four-pole, three-phase motor has 32 slots, we must first determine the number of coils in each phase. In this problem, if each phase had ten coils, the total number of coils is 30. Therefore two coils must be left out of the circuit. The two coils are left in the motor, but their leads are taped up and not connected. The coils are left out of the circuit on opposite sides of the stator, as indicated in Figure 4-96.

After the two coils are eliminated we proceed as before.

1. Compute the number of groups:

$$4 \text{ poles} \times 3 \text{ phases} = 12 \text{ groups}$$

2. Compute the number of coils per group:

$$30/12 = 2\,6/12$$

3. Therefore, there will be 6 groups of 3 coils, and 6 groups of 2 coils.

Layout Groups

A	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	*A*	*B*	*C*	
2			3			2			3			= 10 coils
	3			2			3			2		= 10 coils
		2			3			2			3	= 10 coils
											Total	= 30 coils

Therefore we have 2–3–2—3–2–3—2–3–2—3–2–3.

Caution. In odd-grouped, parallel-connected, polyphase motors, such as two-circuit star or delta, it is essential that each circuit have the same number of coils. Mistakes of this kind can easily be made on this type of motor. Check all circuits and make certain that each contains the same number of coils.

Two-phase Motors

Two-phase motors are like three-phase motors in all respects except for the number of groups and the connections of the groups. As in the three-phase motor, the number of groups is equal to the number of phases multiplied by the number of poles.

In a 48-coil, four-pole, two-phase motor, there are

$$2 \text{ phases} \times 4 \text{ poles} = 8 \text{ groups}$$

The number of coils per group is equal to

$$\frac{\text{no. of coils}}{\text{no. of groups}} = \frac{48}{8} = 6$$

The coils of the two-phase motor are connected to produce two windings instead of three. These windings are phase *A* and phase *B*. The arrangement of groups is shown in Figure 4-97. In all diagrams of two-phase motors, two adjacent arrows are clockwise, the next two, counterclockwise, and so on.

Group connections in two-phase motors are shown in Figure 4-98. They are exactly like the connections of split-phase motors.

The phase *A* connection is similar to that of the running winding, and the phase *B* connection is similar to the starting-winding connection. However, there is no centrifugal switch in a two-phase motor, and both windings have voltage applied to them all the time.

Two-phase motors have windings connected in series, as shown in Figure 4-98, or in parallel, depending on the design of the motor. Figure 4-99 is a schematic diagram of a four-pole, two-phase series connection, and Figure 4-100 shows a four-pole, two-phase, two-parallel connection. Circular diagrams of the two types are shown in Figures 4-101 and 4-102.

Reconnecting Two-phase Motors for Three-phase Operation

Very often two-phase motors are converted to three-phase because more economical operation is provided.

We will assume that a 48-coil, four-pole, two-phase series motor is to be converted into a three-phase motor. This can be done by means of a T, or Scott, connection, by actual three-phase connection, or by rewinding.

T Connection A T, or Scott, connection is one in which the end of the *A* phase is connected to the center of the *B* phase. Figure 4-103 is a schematic diagram of a two-phase motor converted to a three-phase motor by the T connection.

The usual procedure when making a Scott connection is to disconnect about 16 percent of the coils in the *A* phase before connecting the remainder to the *B* phase. The coils that are left out of the *A* phase are distributed equally among the groups in the *A* phase.

The Scott method of reconverting is recommended only as a temporary measure and should never be considered a permanent repair. An example of the procedure followed is given for converting a two-phase, 48-coil series motor to a three-phase motor. Figure 4-104 shows the two-phase motor before reconnecting.

The procedure is to disconnect approximately 16 percent of the *A* phase. The entire motor has 48 coils, and therefore the *A* phase has 24 coils; 16 percent of 24 is 3.8 coils, or 4 coils. Thus, one coil from each *A* phase group is disconnected and left out of the circuit. The new circuit is given in Figure 4-105. This is practical only if the coils are not gang wound.

Three-phase Connection The method whereby the two-phase motor is converted to a three-phase star connection is recommended. In this method, the first step is to remove all jumpers to form the circuit of Figure 4-106. The next step is to compute the number of coils to disconnect, that is, between 15 and 20 percent of all the coils in the motor. This figure may have to be changed, so that less than 15 percent is used, depending on the requirements of the motor. In this problem it is 0.15×48 or 7.2 coils. Since 7.2 is an odd number, and since it is necessary to deduct the same number of coils from each phase, the nearest number to 7.2 that is divisible by 3 must be chosen. In this case, it is 6. Nine coils, which is approximately 20 percent, could also be disconnected from this motor with equally good results. If 6 coils are disconnected, it leaves 42 coils, or 14 for each phase in the new three-phase connection. There will be 12 groups of $^{42}/_{12}$ $(3^{6}/_{12})$ coils per group or 6 groups of 4 coils and 6 groups of 3 coils. We can now proceed to make the new connection, disconnecting two coils from each phase.

With these figures we can lay out the grouping, as shown in Figure 4-107, for a series-star connection.

Rewinding The third method of changing a two-phase motor to three-phase is to rewind the coils, using 20 percent fewer turns in each coil and using one size larger wire. For example, if a two-phase motor is wound with 30 turns of No. 21 A.W.G. magnet wire in each coil, make new coils with 24 turns of No. 20 wire. This is computed in the following manner. Deduct 20 percent of 30 turns, which equals 6. Therefore 6 from 30 leaves 24 turns. One size larger than No. 21 is No. 20. Therefore 24 turns of No. 20 wire are used. The number of circuits per phase should remain the same.

Rewinding and Reconnecting Polyphase Motors

Reconnecting for a Change in Voltage

Motors are often brought into shops to be changed to operate on a voltage other than that on the name plate. For example, it may be a 220-volt polyphase motor to be changed to operate on 440 volts.

There are several methods, depending on the original connection. If the motor originally had a series connection, it can be converted to a two-parallel connection for half-voltage operation. If the motor was originally a two-parallel-connected motor, it can be changed to operate on twice the voltage by connecting the windings in series.

Thus a six-pole, three-phase, series-star, 440-volt motor can be converted to operate on 220 volts by reconnecting it as a six-pole, two-parallel star. If it is a six-pole, three phase, two-parallel star type operating on 220 volts, it can be changed to series-star for 440 volts.

The principle involved in all reconnections is that the coil voltage remains the same in spite of the line-voltage change. This was explained when two-voltage motors were discussed. Delta-connected motors can also be reconnected from series to parallel for the lower voltage, and from parallel to series for the higher voltage.

Three-phase motors can be reconnected for voltage changes by converting from star to delta or vice versa. Many variations are possible: for example, from series-delta to two-parallel star; from parallel-delta to series-star; and so on.

After some of these changes, the voltage required by the motor may not be a multiple or simple fraction of the original. Thus a star-connected motor changed to delta should operate on 58 percent of the original voltage. A delta motor changed to a star connection should operate on 173 percent of the original voltage. In this book no attempt will be made to cover these reconnections in great detail since many excellent books treat the subject thoroughly.

Example: What voltage should be used on a motor if it is changed from two-parallel delta, 220 volts, to series-star?

Solution: If changed to series-delta, the motor would require 440 volts; a change to series-star would require $440 \times 1.73 = 760$ volts.

Voltage changes by means of reconnections are not always possible. For example, a four-pole, 220-volt, series-star cannot be changed for higher voltage operation, because if a higher voltage is impressed on the series connection, more current will flow through the coils than they were designed for and they will therefore burn out. Likewise, four-pole, four-parallel star cannot be reconnected for a lower voltage because there can be no more than four parallels in a four-pole motor.

Rewinding for a Change in Voltage

Three-phase motors can also be rewound for a change in voltage. The only changes necessary are in the number of turns and the size of the wire.

Example: If a 220-volt motor is to be rewound to operate on

440 volts, use twice as many turns on each coil and one-half the circular-mil area of wire. In other words, if forty turns of No. 17 wire were used on the original motor, eighty turns of No. 20 should be used on the new motor.

Reconnecting the Polyphase Motor for Change in Speed

It has been mentioned that the speed of a three-phase motor decreases if the number of poles is increased, and vice versa. (A change in speed is also caused by a change in line frequency.) Most methods of changing speed involve rewinding the coils and altering the coil pitch. However, one method of obtaining a different speed is to change the number of poles by reconnecting. If the applied voltage remains the same when changing from a low speed to a higher speed, the number of turns per phase must be decreased. From a high speed to a lower speed, the number is increased.

Example: It is desired to reconnect a six-pole, 220-volt, two-circuit delta to a four-pole, 220-volt motor. What connection should be used?

Use the following procedure:

1. Regroup the coils for 3 phases $\times$ 4 poles $=$ 12 groups.
2. If reconnected as the original, that is, two-circuit delta, the motor should operate on $^{1800}/_{1200} = 150$ percent of original voltage, which is 330 volts.
3. To operate this motor on 220 volts, change from two-circuit delta to four-circuit star since the four-circuit star requires $330 \times 86.6 =$ 286 volts. This will prove satisfactory since the pitch of the coils has not been changed.

Rewinding for a Change in Speed To work out the previous problem by rewinding, proceed as follows:

1. Change the coil pitch to 1 and $\dfrac{\text{no. of coils}}{\text{no. of poles}} - 1$.

Thus for a 48-slot motor the pitch is 1 and $^{48}/_{4} - 1 = 1$ and 11.

2. Rewind each coil, using new turns equal to

$$\frac{\text{orig. speed}}{\text{new speed}} \times \text{orig. turns} = \frac{1200}{1800} = 66\% \text{ of orig. turns}$$

3. Use a size of wire equal in circular mils to

$$\frac{\text{new speed}}{\text{orig. speed}} \times \text{c.m. of orig. wire} = \frac{1800}{1200} = 1.5 \times \text{c.m. of orig. wire}$$

4. Use original method of connection.

Changes for New Frequency

Polyphase motors can be changed to operate on new frequencies by reconnecting or rewinding. Usually rewinding is required. Sometimes it is possible to operate a motor on a different frequency and a different line voltage. For example, a 25- or 30-cycle, 110-volt motor can operate on 60 cycles at 220 volts. This approximately doubles the original speed.

If a change in frequency is desired without an appreciable change in speed, it will be necessary to rewind the motor.

Example: It is desired to change a four-pole, 25-cycle motor to operate on 60 cycles at approximately the same speed.

1. 4 pole, 25 cycle = 750 r.p.m.
   8 pole, 60 cycle = 900 r.p.m.
2. Change the pitch of coil for an 8-pole motor.
3. The number of turns in each coil is $^{750}/_{900}$ = 83 percent of the number of original turns. Therefore each coil should be wound with approximately 83 percent of the original turns.
4. Use the next larger size of wire.
5. If the motor had 48 slots and 50 turns of No. 18 wire, it should be rewound with 42 turns of No. 17 wire and a pitch of 1 and 6.

Reversing Two- and Three-phase Motors

Figure 4-108 shows the three leads of a three-phase motor connected to a three-phase power line for clockwise rotation. To reverse any three-phase motor, it is necessary only to interchange any two of the motor leads, as shown in Figure 4-109. Reversal can also be accomplished by interchanging two of the power leads.

Two-phase motors are reversed by interchanging the leads of one phase to the power line. Figure 4-110 shows the connection for clockwise rotation and Figure 4-111 shows the connection for counterclockwise rotation. To reverse a two-phase, three-wire motor, it is necessary to interchange the outer two wires marked *1* and *2* in Figure 4-112.

Troubleshooting and Repair

Testing

The three-phase motor should be given tests for the following defects after a repair or winding job: grounds, opens, shorts and reverses.

Grounds Use the test leads as shown in Figure 4-113. Connect one test lead to the frame of the motor and one test lead to one of the leads of the motor. If the lamp lights, a winding is grounded. To ensure a thorough test, move the test lead to each lead of the motor.

If the motor is grounded it will be necessary to locate and remove the ground before making other tests. Just as in other motors, first try to locate the ground by inspection. If it cannot be found in this manner, determine its location by disconnecting each phase and test separately.

In a star-connected motor, disconnect at the star point and test each phase separately as indicated in Figure 4-114.

In a delta-connected motor, disconnect the phases at the leads and test each phase separately as shown in Figure 4-115.

After the grounded phase has been located, it will be necessary to locate the coil that is grounded. The procedure follows: Disconnect the jumpers between groups of the grounded phase and test each group separately for a ground as shown in Figure 4-116. After the group is located, the defective coil can easily be located by opening the coil splices as indicated in Figure 4-117 and testing each coil for a ground. After the grounded coil is found, it will be necessary to reinsulate the slot or place a new coil in the stator. Sometimes one lamination is pushed out of place so that its sharp edges cut into the wire. This can usually be remedied by pressing the lamination back into its proper position. Frequently the fault will be found to be the insulation in the slot. Too, the wire may be placed by mistake between the insulation and the slot, or the insulation may have shifted and left the slot core uncovered.

Open Circuits Open circuits in a two- or three-phase motor may be due to a break in the coil or a loose connection at the splices or jumpers. To locate the open, proceed as follows:

Use the test lamp and determine which phase is open. If the motor is star-connected, place one test lead at the star point and the other test lead on each of the other three phase leads in succession, as shown in Figure 4-118. The lamp should light on all three wires. If the lamp does not light when touched to one wire, that phase is open. If the motor is delta-connected, disconnect the phases and test each phase separately as indicated in Figure 4-119. The lamp will not light when the open phase is tested.

Once the open phase is known, it is a simple matter to determine the location of the open. Assuming it is in the *A* phase, place one test lead at the beginning lead of the *A* phase, and with the other test lead touch the end of each group in succession, as shown in Figure 4-120. If the lamp lights at the end of the first group and not at the end of the second, the second group is defective. Continue in this manner until the faulty group is found. It is possible that the fault may be at a jumper connection in which case the wires should be reconnected and soldered. When the open group is found, the defective coil can be located by opening the splices at the coil ends and testing each coil separately. This is illustrated in Figure 4-121. If the trouble is due to a loose connection of the stub or jumper, resolder and tape the connection. If the trouble is due to a broken wire in the coil, replace the coil or cut it out of the circuit. If the motor is connected two-parallel star, it will be necessary to determine in which circuit the open is located. This is done by connecting one test lead to the star point as in Figure 4-122 and the other test lead to both sections of each phase in succession. The procedure from here on is the same as in the single-circuit star. If the motor is connected two-circuit delta, all windings connected in parallel will have to be disconnected in order to determine the open section.

Shorts Poor workmanship in placing coils in slots is responsible for shorts due to failure of the wire insulation. Shorted coils in polyphase motors are located in the same manner as in split-phase motors. The usual method is to use an internal growler as shown in Figure 4-123 and locate the coil or group that is shorted by noting the vibrations of a hacksaw blade. It must be remembered that the growler is not effective on parallel-connected motors. All parallels must be disconnected in order to test the winding with the growler. If the growler is held in position for a few minutes, the defective coil or coils will become hot.

Another method of determining a shorted coil or group is to operate the motor for a few minutes. The defective coil will become much hotter than the others and can be located easily by touch.

Still another method of determining whether a polyphase motor is shorted is to connect the motor to a three-phase line and then measure the current in each phase by means of an ammeter (preferably the clip-on type). The current should be the same in each phase. This is called a *balance test.* A higher reading in one phase usually indicates a shorted phase. This test is usually made while the motor is running.

Reverses Reverses occur when a coil, group, or phase is improperly connected. In all cases this is due to oversight or lack of knowledge on the part of the winder. Reverses in polyphase motors may occur in (1) coils, (2) groups, and (3) phases.

REVERSED COILS. In all polyphase motors, the coils of a group are connected so that the current flows through each coil in the same direction. It is possible that the winder may have connected these coils incorrectly so that the current through each coil is not flowing in the same direction. This condition could not exist in a gang-wound motor unless the coils are placed in the slots in the wrong direction.

Visual inspection is the best method of detecting a reversed coil; however, this is not always possible. An accurate check is to pass low-voltage direct current from a battery through each phase and place a compass against the core. The compass needle should reverse at each group of one phase, and indicate N at one group, S at the next group, etc. If at any group the compass needle is indefinite, there may be a reversed coil in that group. The reversed coil builds up a magnetic field which opposes that set up by the other coils, and this causes a very weak field, which has little effect on the compass needle.

REVERSED COIL GROUPS. To test for reversed groups, connect one lead of a low-voltage d-c line to the star point and the other lead to each phase in order. Move a compass inside the stator to indicate the polarity of each group. If the compass needle reverses at each group as shown in Figure 4-124, the correct polarity is indicated. To test a delta-connected motor for reversed groups, open one delta point and connect a source of low-voltage direct current to the two wires. If the compass needle reverses at each group, the polarity is correct.

Reversed Phases. A common error in connecting a three-phase motor is to connect the middle phase in the wrong manner. This mistake is easily found with the compass. Connect the phases to the low-voltage direct current as in testing groups—and test with the compass from group to group for reversal of the needle. If the needle indicates three north poles and three south poles, as shown in Figure 4-125, it is an indication of an improperly connected middle phase. Reverse the *B*, or middle, phase to obtain the correct connection.

After the motor is tested, bake it in an oven for about two or three hours at a temperature of approximately 250° F. Dip it in a good grade of varnish for about five minutes and then allow it to drip. Place it in the oven again and bake at the same temperature for three hours.

Common Troubles and Repairs

The symptoms encountered in defective two- and three-phase motors are given below. Under each symptom are listed the possible troubles. The number in parentheses after each trouble indicates the correspondingly numbered remedy to be found in the following pages.

1. If a polyphase motor fails to start, the trouble may be:

- **a.** Burned-out fuse (1)
- **b.** Worn bearings (2)
- **c.** Overload (3)
- **d.** Open phase (4)
- **e.** Shorted coil or group (5)
- **f.** Loose rotor bars (6)
- **g.** Wrong internal connections (7)
- **h.** Frozen bearing (8)
- **i.** Defective controller (9)
- **j.** Grounded winding (10).

2. If a polyphase motor does not run properly, the trouble may be:

- **a.** Burned-out fuse (1)
- **b.** Worn bearings (2)
- **c.** Shorted coil (5)
- **d.** Reversed phase (11)
- **e.** Open phase (4)
- **f.** Open parallel connection (12)
- **g.** Grounded winding (10)

h. Loose rotor bars (6)
i. Incorrect voltage or frequency.

3. If the motor runs slowly, trouble may be:
   a. Shorted coil or group (5)
   b. Reversed coils or groups (7)
   c. Worn bearings (2)
   d. Overload (3)
   e. Wrong connection (reversed phase) (11)
   f. Loose rotor bars (6).
4. If the motor becomes excessively hot, the trouble may be:
   a. Overload (3)
   b. Worn bearings (2), or tight bearing (8)
   c. Shorted coil or group (5)
   d. Motor running on single phase (4)
   e. Loose rotor bars (6).

(1) *Burned-out Fuse* Remove fuses and test with test lamp as shown in Figure 4-126. If the lamp lights, the fuse is good. A burned-out fuse is indicated when the test lamp does not light.

To test the fuses without removing them from their holders, place a test-lamp circuit across the fuse while the switch is closed, as shown in Figure 4-127. The fuse that causes the lamp to light is the one that is burned out.

If the fuse burns out while a polyphase motor is in operation, the motor will continue to operate as a single-phase motor (Figures 4-128 ant 4-129). This means that only part of the winding is carrying the entire load. If the motor continues to operate in this manner, even for a short time, the winding will become very hot and burn out. Further, the motor will be noisy in operation and may not pull the load. To find the trouble, stop the motor and try to start it again. A polyphase motor will not start with a burned-out fuse. To remedy this condition, locate and replace the defective fuse.

If the motor is a parallel-connected star, current will be induced in the open phase and cause the winding to burn out quickly. This should be prevented if possible.

(2) *Worn Bearings* If a bearing is worn, the rotor will ride on the stator and cause noisy operation. When the bearings are so worn that the rotor rests firmly on the core of the stator, rotation is impossible. To check a small motor for this condition, try moving the shaft up and down as shown in Figure 4-130. Motion in this manner indicates a worn bearing. Remove and inspect the rotor for smooth, worn spots. These indicate that the rotor has been rubbing on the stator. The only remedy is to replace the bearings.

On a larger motor, the check for worn bearings is made with a feeler gauge. This type of gauge is shown in Figure 4-131. The air space between the rotor and the stator must be the same at all points (Figure 4-132). If it is not, the bearing must be replaced.

(3) *Overload* To determine whether a three-phase motor is overloaded, remove the belt or load from the motor and turn the shaft of the load by hand (Figure 4-133). Usually a broken part or dirty mechanism will prevent the shaft from moving freely.

Another method is to connect an ammeter in series with each line wire. A higher current reading than on the name plate may indicate an overload. Many shops and motor repairmen use a snap-around volt ammeter and ohmmeter to test the current in the main line leads feeding the motor. The current in each lead should be the same and approximately the same as the name-plate reading. An excessive reading in one phase indicates a shorted phase. This instrument can be used on all motors from split-phase through three-phase and can be used to test voltage, resistance, and current. It can be used to test unmarked leads on split-phase motors by using the ohmmeter and also to test voltage across components in motors and starters. Figure 4-134 illustrates a method of testing line current in a three-phase motor.

(4) *Open Phase* If an open occurs while the motor is running, it will continue to run but will have less power. An open circuit may occur in a coil or group connection and prevent the motor from starting. This may also be due to a broken wire or a loose connection.

If the open is located within a coil, a new coil may be necessary. However, should it be impossible to supply a new coil, the old coil is cut out in the following manner:

Locate the open coil. Connect together the beginning and the end of the open coil as shown in Figures 4-135 and 4-136. This is a temporary measure and should only be used when rewinding is impractical. It cannot be employed when the coils are gang-wound.

The motor will continue to run if a phase opens while the motor is in operation, but will not start if at standstill. Conditions are similar to those of a blown fuse.

(5) *Shorted Coil or Group* Shorted coils will cause noisy operation and also smoke. After locating such defective coils by means of the eye or balance test, replace them with new coils or cut them out of the circuit.

When the insulating enamel on the wire fails, the individual turns become shorted and cause the coil to become extremely hot and burn out. Other coils may then burn out, with the result that an entire group or phase will become defective. A shorted coil is cut out of the circuit differently from an open coil.

Locate the shorted coil visually or by means of the growler. A shorted coil looks and smells burned. Cut the entire coil at one point at the back and twist the turns on both sides, as shown in Figures

4-137 and 4-138. Be certain that the turns are free of insulation before the wires are twisted together. This method applies also to gang-wound coils. If an entire group is burned out, the motor should be rewound.

(6) *Loose Rotor Bars* These will produce noisy operation and will keep the motor from carrying the load. Sparks may be seen between the bars and end rings while the motor is turning.

On squirrel-cage rotors, the copper bars are all connected to end rings on both sides of the rotor. If one or more of these bars become loose (Figure 4-139) and do not contact the end rings, improper operation of the motor may result. In many instances the motor will not rotate.

Loose rotor bars may be found by placing the rotor on a growler. Vibration of a hacksaw blade should be felt at every bar; otherwise an open bar is indicated. Open rotor bars can also be observed by eye.

The remedy for this condition is resoldering or welding.

The above information does not apply to rotors having a die cast aluminum winding.

(7) *Wrong Internal Connections* A good method of determining whether or not a polyphase motor is connected properly is to remove the rotor and place a large ball bearing in the stator. The switch is then closed to supply current to the winding. If the internal connections are correct, the ball bearing will rotate around the core of the stator, as shown in Figure 4-140. If the connections are incorrect, the ball bearing will remain stationary.

For medium- and large-sized motors, reduced voltage should be used; otherwise, a fuse may blow.

(8) *Frozen Bearing* If oil is not supplied to that part of the shaft which rotates in the bearing, the shaft will become so hot that it will expand sufficiently to prevent movement in the bearing. This is called a *frozen* bearing. In the process of expansion, the bearing may weld itself to the shaft and make rotation impossible.

To repair, try to remove the end plates. The end plate that cannot be removed easily contains the bad bearings. Remove the end plate and armature as a unit; hold the armature in a stationary position, and turn the end plate back and forth. If it is impossible to move the end plate, loosen the setscrew that holds the bearing in the housing and try to remove the armature and bearing as a a unit. Be careful to keep the oil ring free from the bearing while this is being done. The bearing can then be removed by tapping it with a hammer. The shaft will probably have to be turned down on a lathe to a new size and a new bearing made. If ball bearings are used, replace with new ones.

(9) *Defective Controller* If the contacts on the controller do

not make good contact, the motor will fail to start. To locate trouble and repair this unit see Chapter 5.

(10) *Grounded Winding* This will produce a shock when the motor is touched. If the winding is grounded in more than one place, a short circuit will occur which will burn out the winding and perhaps blow a fuse. Test for a grounded winding with test lamp and repair by rewinding or by replacing the defective coil.

(11) *Reversed Phase* This will cause a motor to run more slowly than rated speed and produce an electrical hum indicative of wrong connections. Check the connections and reconnect them according to plan.

(12) *Open Parallel Connection* This fault will produce a noisy hum and will prevent the motor from pulling full load. Check for complete parallel circuits.

CHAPTER 5

Alternating-current Motor Control

If an a-c motor is started on full voltage, it will draw from two to six times its normal running current. Because the motor is constructed to withstand the shock of starting, no harm will be caused by this excessive flow of current. However, on very large motors, it is generally desirable to take some measure to reduce the starting current; otherwise, damage may be done to the machinery driven by the motor, and line disturbances may be created that affect the operation of other motors on the same line.

For the small motor, or where the load can stand the shock of starting and no objectionable line disturbances are created, a hand-operated or an automatic starting switch can be used for control of the motor. This type of switch connects the motor directly across the line and is called an *across-the-line-starter,* or full-voltage starter.

In the case of the large motor, where the starting torque must develop gradually, or where the high initial current will affect the line voltage, it is necessary to insert in the line some device which will reduce the starting current. This device may be a resistance unit or an autotransformer. Controllers which use this method of starting a motor are called *reduced-voltage starters.* Controllers are also used to protect the motor from overheating and overloading, to provide speed control, to provide for reversing the motor, and to provide undervoltage protection.

The following popular types of controllers will be described: pushbutton switch starters for small motors, magnetic across-the-line starters, reduced-voltage resistance starters, compensator starters, wye-delta starters, drum starters, part-winding starters, two-speed controllers, plugging and braking controllers.

Starters

Pushbutton Switch Starter for Fractional Horsepower Motors

This is a simple type of switch which connects the motor directly to the line. Two pushbuttons are located on the switch, one for starting and the other for stopping the motor. Pressing the START button causes the contacts inside the switch to make and connect the motor across the line. Pressing the STOP button causes the contacts to break apart and open the circuit to the motor. This type is shown in Figure 5-1.

The usual type of pushbutton switch starter is equipped with a thermal overload device connected in series with the line. It opens the circuit to the motor if an overload current persists for a short period of time. Figure 5-2 shows one type of overload device that consists of a small cylinder containing an alloy that will melt when an overload persists. Imbedded in the metal is a small shaft to which is attached a ratchet wheel. When the START button is pressed, the shaft is held in place by a spring which engages the ratchet wheel. If an excessive current passes through the overload device, the alloy in the cylinder will melt and cause the START button to spring to its OFF position and disconnect the motor from the line. To restart the motor, it is necessary to wait several seconds until the metal hardens.

Another switch used on fractional-horsepower motors is of the ordinary snap-action type. This switch contains a thermal relay to provide overload protection. A coil of resistance wire is connected in series with one motor lead so that it heats when excessive current flows. A solder film that will melt from heat is located inside the coil. When the solder film melts, a trigger is tripped, releasing the main contacts of the switch.

Most of these starters can be used for single-, two-, or three-phase motors. Figure 5-1 shows a diagram of a pushbutton starter connected to a single-phase motor, and Figure 5-3 shows such a starter connected to a three-phase motor. In Figure 5-1, when the START button is pressed it closes the contacts of L_1 and L_2 and connects the motor across the line. If an overload occurs, the thermal relay will trip the releasing mechanism and cause the contacts to open, thereby stopping the motor. To reset the tripping mechanism, it is usually necessary to press the STOP button. If the motor is running normally and it is necessary to stop it, the contacts are released by pressing the STOP button. Figure 5-4 is an illustration of a manual starter.

Magnetic Full-voltage Starter

A starter which connects a motor directly across the line is called a *full-voltage* starter. If this starter is operated magnetically, it is called a *magnetic* full-voltage starter. A magnetic starter designed to operate a three-phase motor is shown in Figures 5-5 and 5-6. Some of the wiring symbols in this and other diagrams are shown in Figure 5-7. Figure 5-6 has three normally open main contacts which when closed connect the motor directly to the line. It also has a magnetic holding coil, which closes the main contacts upon being energized, and also closes a normally open auxiliary or maintaining contact to maintain the current in the holding coil. The main and auxiliary contacts are generally joined by an insulating connecting bar so that all contacts will close when the holding coil becomes energized. It is obvious that any size of magnetic switch can be operated just by sending a small current through the coil. Starters are often equipped with dual-voltage coils for operation on either high or low voltage. Coils are made in two sections—series for high voltage, parallel for low voltage.

It should be noted that two overload relays are shown in Figure 5-5. Most three-phase starters are made with provisions for a third overload relay as standard equipment, as shown in Figure 5-6. The reasons for having two or three overload relays are explained more fully on page 150.

The holding coil on an a-c magnetic starter is excited by a pulsating current, and therefore its pull is not continuous, but rather alternates according to the frequency of the current. This tends to cause chattering; to overcome this condition, the core of the magnet is equipped with a shading coil which produces an out-of-phase flux. The shading coil is a small, single-turn copper coil which is embedded around a portion of the core tip. The current induced in this coil is sufficient for the magnet to retain the contactor during the reversal of current. A complete magnetic starter is pictured in Figure 5-8.

An advantage of a magnetic starter over a manual starter is that it may be operated merely by pressing a pushbutton which may be located some distance from both the starter and the motor. This lends to convenience and safety in starting and stopping a motor, especially if it is of high voltage or if it must be controlled from one or more remote points.

Overload Relays Nearly all magnetic starters are equipped with an overload device to protect the motor from excessive current. Two types of overload relays are used on magnetic starters, and these are either magnetic or thermal in operation. The thermal overload relay may be either the bimetallic or solder-pot type.

A thermal relay is illustrated in Figure 5-9(a) and (b). This bimetallic type of relay consists of a small heater coil or strip which is connected in series with the line and which generates heat by virtue of the current flowing through it; the amount of heat generated depends on the current flow in the line. Mounted adjacent to, or directly inside, the coil is a strip formed of two metals. This is fixed at one end, the other end being free to move. The two metals have different degrees of expansion, and the strip will bend when heated. The free end normally keeps two contacts of the control circuit closed. When an overload occurs, the heater heats the thermostatic bimetal so that it will bend and separate the two contacts, thereby opening the holding-coil circuit and stopping the motor. The bimetallic type of overload relay is usually designed with a feature which permits automatic resetting, although it is also designed for manual resetting. Some overload relays are ambient-compensated to provide maximum protection where the temperature surrounding the relay differs from the temperature surrounding the motor. A number of manufacturers feature a bimetallic overload relay which can be converted from manual to automatic by positioning a reset selector lever. Automatic reset is desirable where control is not readily accessible or regularly attended. Some overload relays are trip free. This means that the starter contacts cannot be held closed during an overload and cause damage to the motor.

The solder-pot type of thermal overload relay consists of a eutectic alloy element, heater coil, normally closed contacts and a reset button (Figure 5-10). The eutectic alloy element contains a solder which changes from a solid state to a liquid state immediately at a specific temperature. The heater coil carries the main line current and surrounds the thermal element. When an excessive current flows through the heater coil, the heat generated by the coil melts the eutectic alloy in the thermal element, allowing a shaft and ratchet wheel assembly within the sleeve to turn and trip the normally closed contacts. This opens the holding coil circuit, causing the main contacts to open and disconnect the motor from the line. To restart the motor, the reset button is pressed after the solder has cooled. This type of relay is manually reset and is trip free. This prevents holding the contacts closed by pressing the reset button. This important protective feature prevents forcing the motor to operate under persistent overload conditions. Use of this type of overload relay is desirable because the necessity of resetting the relay draws attention to the cause of the overload and because the possibility of injury to persons by the automatic restarting of a motor is eliminated.

Number of Overload Relays Required

The National Electrical Code clearly indicates the minimum number of overload units to be used for the protection of a-c single-, two-, and three-phase motors, and d-c motors.

The Code, generally, requires one overload unit for single-phase and d-c motors and two units for two- and three-phase motors. However, three running overcurrent units shall be used for three-phase motors under certain circumstances. If three-phase motors are installed in isolated, inaccessible locations or in places lacking the presence of a person capable of exercising responsible control of the motor under consideration, three running over-current units shall be used unless the motor is protected by other approved means. Three overload units should be used in three phase applications where the power supply may be unstable or where there may occur appreciable unbalance between phases. An open phase in the primary of a wye-delta transformer or a single-phase motor connected in parallel with a three-phase motor may cause an unbalanced condition. Three overload units are desirable in installations using combinations of single-phase and three-phase motors.

Three-phase controllers are usually provided with two overload relays, but provision is made for conversion from two- to three-coil overload protection simply by adding a heater coil or using a kit available for on-the-spot addition. Some controllers just require a plug-in unit. Some manufacturers produce three-phase starters with three overload units as standard equipment.

Many of the three-phase diagrams in this chapter will show two overload relays, but all of the starters can easily be converted to three-coil overload protection by the simple addition of an overload symbol in the third wire of the controller. Figure 5-11(a), (b), and (c) shows three controllers manufactured by three different companies. Note the overload units.

Pushbutton Stations

Magnetic starters are controlled by means of pushbutton stations. The most common station has START and STOP buttons, as shown in Figure 5-12. When the START button is pressed, two normally open contacts are closed; and when the STOP button is pressed, two normally closed contacts are opened. Spring action returns the buttons to their original position when finger pressure is removed. To operate a magnetic switch by a START-STOP station, it is necessary to connect the holding coil to the station contacts so that when the START button is pressed, the coil will become energized; and when the STOP button is pressed the holding coil circuit is opened.

A diagram of a typical full-voltage magnetic starter equipped with two thermal overload relays and connected to a START-STOP station is shown in Figure 5-13. In the diagrams to follow, the motor circuits are indicated by heavy lines, and the control circuits are shown by light lines. The operation of this starter is as follows:

When the START button of Figure 5-13 is pressed, it completes the circuit from L_1 to the normally closed contacts of the STOP button through the holding coil M and normally closed contacts of the overload relays to L_2. Thus, the coil is energized and it closes contacts M and connects the motor across the line. A maintaining circuit is completed at point 2 to keep the holding coil energized after the finger is removed from the START button. Pressing the STOP button opens the coil circuit and causes all contacts to open. If a prolonged overload should occur during the operation of the motor, the overload relay contacts will open and de-energize the holding coil. If an overload condition has caused the relay to trip, it will be necessary to reset the relay contact by hand before the motor can be restarted.

Figure 5-14 shows a line diagram of the control circuit. Figure 5-15 is a line diagram of the starter. Coil *M* is used to close main contacts *M; OL* is the normally closed overload relay contact.

Magnetic full-voltage starters are made by all controller manufacturers. A typical controller is shown in Figure 5-16. Figures 5-17 and 5-18 show controllers with a step-down transformer in the control circuit. This permits operating the control circuit at a lower voltage than the line voltage, and is usually done for safety reasons.

If a control circuit transformer is used, the primary should be connected to the line terminals of the starter. A separate voltage source is hazardous to personnel and machine unless it is disconnected when the contactor coil is opened.

Note that in these diagrams one end of the secondary is grounded and one side of control coil *M* is connected to the grounded side. It is important when one side of the control circuit is grounded that the control circuit be so arranged that an accidental ground in the remote control devices will not start the motor. Quite often the overload contacts are connected between the START button and coil *M*.

Combination Starters A combination starter consists of a magnetic starter and disconnect switch mounted in the same enclosure. These starters are supplied with either a fused disconnect switch or circuit breaker. The fuses or circuit breaker provides short-circuit protection by disconnecting the line. A combination starter with circuit breaker will prevent single-phasing by simultaneously opening all lines when a fault occurs in any one phase. This type of starter can be quickly reset after the fault has been cleared. Figure 5-19 illustrates a fused combination starter. Figure 5-20 shows a combination starter with circuit breaker.

Pushbutton-station Connections A number of control circuits will be illustrated involving various combinations of pushbutton stations. All of these diagrams employ one type of magnetic switch, but others can be used. Figure 5-21 illustrates a magnetic switch which is operated from either of two stations. The pushbuttons are shown in two positions. Figure 5-22 shows a straight-line diagram of the control circuit of two START-STOP stations. Figure 5-23 gives the control circuit of three START-STOP stations. In these diagrams, the START buttons are connected in parallel and the STOP buttons are connected in series. This must be done, regardless of the number of stations. Note that the maintaining contact is always connected across the START button. All STOP buttons are connected in series with each other and in series with the holding coil, so that the motor can be stopped from any position in case of emergency.

Jogging Magnetic switches can be "jogged" or "inched." By this method the motor is made to run only while the finger is pressing the JOG button. As soon as pressure is removed, the motor stops.

Jogging may be accomplished by using (1) a station with a selector pushbutton, (2) a station with a selector switch, (3) a station with standard pushbuttons and a jog relay.

Figure 5-24 shows a full-voltage magnetic starter connected to a START-JOG-STOP station having a selector pushbutton. This button is constructed with a sleeve that may be turned to either a JOG or RUN position. With the sleeve turned to the RUN position, the START and STOP buttons function as in an ordinary START-STOP station. With the sleeve in the JOG position, the circuit to the holding contacts is broken and the motor will run only when the JOG button is held down. Depressing the START button cannot cause the motor to run.

The operation of the control circuit of Figures 5-24 and 5-25 is as follows. With the selector sleeve on RUN, pressing the START button completes a circuit from L_1 through the STOP button and the closed contacts of the JOG selector button, the start contacts, the holding coil, the overload contacts and to L_2. This energizes the holding coil, causing contacts M to make and connect the motor across the line. The maintaining contact keeps the holding coil in the circuit after the finger is removed from the START button. Pressing the STOP button opens the coil circuit and stops the motor. With the selector sleeve on JOG, current cannot flow to the START button because the front contacts are in OPEN position. Depressing the JOG selector button completes a circuit through the STOP button, the back contacts of the selector button, the holding coil, the overload contacts and to L_2. The motor will run only when the button is depressed.

Figures 5-26, 5-27, and 5-28, show jog stations which use a selector switch rather than a selector button. The START button is used to jog or to run the motor, depending on the position of the switch. In each case, with the button in the JOG position, the circuit to the holding contact is broken. A station in which the START button is used for starting and jogging is shown in Figure 5-29. A magnetic switch operated by this type of station is illustrated in Figure 5-30. Another method of jogging is through the use of a jogging relay, as shown in Figures 5-31 and 5-32.

When the START button is pressed, the relay coil is energized, thus closing the relay contacts, *CR; CR* closes the circuit for the holding coil, causing contacts *M* to close. This completes the maintaining circuit for the holding coil, *M*, when the start button is released. In the meantime all the main contacts are made, closing the circuit to the motor. If the JOG button is pressed while the motor is at standstill, a circuit is formed through the holding coil only as long as the button is pressed. It is impossible for the starter to lock in no matter how quickly the finger is withdrawn.

Another diagram showing the connections of a jog relay and magnetic switch is given in Figure 5-33. Pushing the START button operates the motor starter and jog relay, causing the starter to lock in through one of the relay contacts. When the JOG button is pressed, the starter operates, but this time the relay is not energized, and thus the starter cannot lock in.

A control circuit is shown in Figure 5-34. In this diagram, when the JOG button is depressed, the jog relay is bypassed and the main contactor coil is energized solely through the JOG button. When the button is released, the contactor coil releases immediately. Pushing the START button closes the control relay, and it is held in by its own normally open contacts. The main contactor coil in turn is closed by another set of normally open contacts on the jog relay and is held in.

START-STOP *Station with a Pilot Light* Sometimes it is advisable to have a pilot light on the pushbutton station to indicate if the motor is running. The lamp usually is mounted on the station and is connected across the holding coil. Such a connection is shown in Figures 5-35 and 5-36. Figure 37 shows a control circuit with pilot light ON when motor is *stopped.* Normally closed contacts are needed on this starter. With the motor running these contacts are open. Contacts are closed when the motor is stopped and pilot light goes on. A START-STOP station with a pilot light is pictured in Figure 5-38.

Full-voltage Reversing Starter The magnetic starters shown thus far are designed to operate the motor in one direction, either clockwise or counterclockwise. If it is necessary to reverse the motor, its connections must be changed.

Some applications, such as conveyors, hoists, machine tools, elevators, and others, require a motor starter that can reverse the motor when a button is pressed. Thus, two of the line leads can be interchanged to reverse a three-phase motor by means of a magnetic reversing switch. A reversing starter of this type is shown in Figure 5-39. The circuit is given in Figures 5-40 and 5-41. Note that it is necessary to use a FORWARD-REVERSE-STOP station, with three buttons, and that two operating coils are used, one for forward rotation and the other for reverse rotation.

Two sets of main and auxiliary contacts are used. One set closes when forward operation is desired; the other set closes for reverse rotation. These contacts are connected in such a manner that two line wires feeding the motor are interchanged when the reverse contacts close.

In operation, pressing the FORWARD button completes a circuit from L_1, the STOP button, the FORWARD button, the forward coil, and the overload contacts to L_2. This energizes the coil, which closes the contacts for forward operation of the motor. Auxiliary contacts F also close, maintaining the current through coil F when the button is released. Pressing the STOP button opens the circuit through the forward coil which releases all contacts. Pressure on the REVERSE button energizes the reverse coil which closes the reverse contacts. Terminals T_1 and T_3 are now interchanged and the motor reverses.

Usually, reversing starters are equipped with a mechanical interlock in the form of a bar which will prevent the reverse contacts from making while the forward contacts are closed. This bar is pivoted in the center, and when the forward contactor goes in, it moves the bar into a position where it is impossible for the reverse contacts to make. This starter does not have an electrical interlock to prevent the forward and reverse coils from being energized simultaneously.

All of these starters are equipped with overload relays, generally of the thermal-relay type. Remember, however, that many starters use three relays for three-phase motors.

Sometimes more than one FORWARD-REVERSE-STOP station is used to control a magnetic reversing switch. Figure 5-42 shows connection diagrams of two such stations in different positions.

Besides having a mechanical interlock, most reversing starters are also electrically interlocked. In this system, additional normally closed auxiliary contacts are used to prevent the forward and reverse contactors from being energized at the same time. The holding circuit of each main contactor coil is wired through the normally closed auxiliary contacts of the opposing contactor, thus providing the electrical interlock.

Figure 5-43 shows a magnetic reversing starter with mechanical and electrical interlocks and a FORWARD-REVERSE-STOP pushbutton station. The STOP button must be depressed before changing directions. Limit switches can be added to stop the motor at a certain point in either direction. Connections *A* and *B* must be removed when limit switches are used. A line diagram of the control circuit is shown in Figure 5-44.

In operation, pressing the FORWARD button closes a circuit from L_1 through the STOP button, the FORWARD button, the reverse normally closed auxiliary contacts, the forward limit switch (if used), the forward coil, and the overload contacts to L_2. The maintaining contacts for the forward coil keep it energized when pressure is removed from the button. At the same time, the normally closed forward auxiliary contacts are opened, preventing a complete circuit through the reverse coil.

A momentary contact pushbutton station which permits immediate reversal of direction without first pushing the STOP button is shown connected to a full-voltage magnetic reversing starter in Figure 5-45. Note that this is also electrically interlocked. Note also that the FORWARD and REVERSE buttons each have a normally closed and normally open contact. Figure 5-46 shows a line diagram of the control circuit.

In operation, pressing the FORWARD button completes a circuit from L_1 through the STOP button, the normally closed contacts of the REVERSE button, the forward contacts, the limit switch (if used), the normally closed reverse auxiliary contacts of the electrical interlock, the forward coil, the overload contacts and to L_2. The forward coil becomes energized, all the contactors close, and the motor runs. At the same time the normally closed forward contacts are broken, preventing a circuit to the reverse coil. When the forward contactor coil is energized, the forward maintaining contacts are closed, keeping the coil energized, and the forward normally closed auxiliary contacts in series with the reverse coil are opened, preventing the reverse coil from becoming energized. To reverse the motor, press the REVERSE button. This opens the circuit to the forward coil and closes the circuit to the reverse coil.

It is sometimes necessary to operate a reversing magnetic controller from two places. Figure 5-47 shows how two stations can be connected for that purpose. Figure 5-48 is an elementary diagram of a reversing magnetic controller with electrical interlock controlled by a FORWARD-REVERSE-STOP station wired for changing direction without pushing the STOP button. Figure 5-49(a) shows a control circuit using a step-down transformer for reduced coil voltage.

Reversing magnetic starters are made in numerous designs. Figure 5-50 shows a starter similar to that of Figure 5-40, except that it is of the vertical type instead of the horizontal type. The starters are mechanically and electrically identical, the only difference being in the panel layout. The operation of this starter is exactly the same as that of the starter described in Figure 5-40.

Reduced-voltage Starters

If a squirrel-cage motor is connected directly across the line, the starting current will be several times the normal running current. In very large motors this abnormal flow may be injurious to the driven machinery.

On small motors this injurious effect is seldom noticeable, so that across-the-line starters may be used safely. For the large motor, however, it is sometimes necessary to use a starter that will hold the starting current at a safe value. The need for these starters depends a great deal on the construction of the motor and the use to which it is put.

The following controllers will be treated in this section: primary-resistance starters, secondary-resistance starters, autotransformer starters—compensators, wye-delta starters, and part-winding starters.

Primary-resistance Starters The current flow to a motor will be considerably reduced if resistance units are placed in series with the line. The motor will start up slowly, and as it accelerates, it sets up a counter e.m.f., which keeps the line current at a normal value. As a result, after the motor has reached a certain speed, the resistance can be removed from the circuit and the motor operates on the full-line voltage.

Resistance starters may be used in either the stator (primary) circuit or in the rotor (secondary) circuit. In the latter case, a wound rotor with three slip rings is used.

RHEOSTAT TYPE OF RESISTANCE STARTER. There are two types of primary-resistance starters: manual resistance starters of the rheostat type and automatic resistance starters. The rheostat type of starter (old) for a three-phase motor is shown in Figure 5-51. It can also be used for a two-phase and repulsion-induction motor. The resistances are connected in two of the three phase lines. The arm of this rheostat consists of two sections insulated from each other. Under each section, a metal strip, usually made of copper, rides on contacts which are connected to taps on the resistances.

As the arm is moved, sections of resistance are cut out, increasing the speed of the motor. The starter is so constructed that equal amounts of resistance are removed from each line as the arm is moved.

Some starters are equipped with a holding coil to keep the arm at the last contact point, and the rheostat is used only for starting. In other cases, the arm can be set in any position for speed regulation. The starting torque is cut down considerably when a resistance starter is used, because the voltage drop due to the resistance converts most of the energy needed for starting into heat.

MAGNETIC PRIMARY-RESISTANCE STARTER. Figure 5-52 is an illustration of a magnetically-operated resistance starter. Three resistance units are used in this starter. The diagram shows two sets of contacts. When the contacts marked *S* are closed, a resistance unit is placed in series with each line lead feeding the motor, thereby causing it to start slowly and on reduced voltage. After a definite time, another set of contacts, *R*, also close, cutting out the resistance and placing the motor directly across the line. An elementary diagram of this starter is shown in Figure 5-53. Its operation is as follows:

When the START button is pressed, the circuit is completed from

L_1 through coil S to line L_2. Coil S is energized, closing the starting contacts, and the motor starts slowly. When the starting contacts close, the auxiliary interlock contacts also close to maintain a circuit through coil S. At the same time, the coil TR of a time-delay relay connected across A and B is energized, setting in motion a timing mechanism. After a predetermined time, contacts TR close and a circuit is completed through coil R. This coil becomes energized and causes running contacts R to close. These cut out the resistance and connect the motor across the line. Pressing the STOP button opens all circuits through the holding coils, and thus all contacts to the motor are opened. Figure 5-54 shows a General Electric reduced-voltage magnetic primary resistance starter. This magnetic primary resistor consists of a three-pole start contactor, a three-pole run contactor, a pneumatic timing relay, a single-step primary resistor, and two or three bimetallic overload relays.

Pressing the START button energizes the start contactor coil. The start contactor closes, placing the motor on reduced voltage. The resistors in series with the line reduce the starting current drawn from the line. At the same time the timing relay coil is energized and, after a definite time delay, the run contactor coil is energized, closing the run contactors. The resistors are now bypassed, thus sending full voltage to the motor. Pressing the STOP button de-energizes all contactors and stops all power to the motor.

A sustained overload will cause the heaters to become hot and will trip the overload contacts, opening the holding-coil circuits. To start the motor again, the overload contacts automatically reset or must be reset manually before the pushbutton circuits become operative. A description of a dashpot and its operation and of a timing mechanism is given under the heading of Definite Mechanical Time Starter in Chapter 8 on d-c controls.

The two resistance starters just described placed resistance units in series with the line and thereby reduced the voltage applied to the stator winding. These are called *primary*-resistance starters. The starting torque produced by a motor is comparatively low if this type of starter is used.

Secondary-resistance Starter If the resistance is inserted in the secondary or rotor circuit instead of the primary, the starting torque can be increased considerably. This can be accomplished by using a wound-rotor type of motor and by inserting resistance in the rotor-winding circuit.

The rotors of this type of motor have a three-phase, star-connected winding, the leads of which are joined to three slip rings located on the shaft of the rotor. The stator of this motor is connected across the line by means of either a triple-pole fused switch or an across-the-line magnetic starter.

The principle of operation is as follows:

If the three slip rings are shorted, the effect is similar to having a motor with a squirrel-cage winding. This motor will draw an excessive current if connected directly across the line. However, if the three slip rings are connected through three resistance units, a much lower current will flow through the line wires. The motor will start slowly, and, as it accelerates, the resistance is gradually cut out until the motor runs at full speed.

This type of motor is always started with the entire resistance in the circuit. In Figure 5-55, the manual switch is first thrown in and then the handle on the resistance starter is slowly moved in a clockwise direction until all the resistance is cut out. This gradually increases the speed of the motor until it is running full speed. These controllers are also made as speed regulators so that any desired speed can be obtained. Figure 5-56 shows a resistance starter which uses a magnetic switch for line connections.

Wound-rotor resistance starters are designed for magnetic operation as well as for manual control. An elementary diagram of a simple starter with two steps of acceleration is illustrated in Figure 5-57. In operation, pressing the START button energizes coils *S* and *TR*. This closes all *S* contacts, placing the stator directly across the line and the rotor in series with the resistance units. A timing mechanism of the dashpot, escapement, or other definite-time type, prevents time-delay contact *TR* from closing until a set time has elapsed, whereupon coil *R* is energized and contacts *R* close, cutting the resistance out of the rotor circuit. This brings the motor up to full speed. If the STOP button is pressed, or in the event of a prolonged overload coil *S* is de-energized, the motor will stop.

Autotransformer Starters—Compensators Although resistance starters are used to a great extent, autotransformer starters are much more satisfactory for reducing the voltage in the motor. The advantage lies in the fact that the reduced voltage is accomplished by transformer action, and not by means of a resistance which wastes energy through heat.

The autotransformer is a coil of wire wound on a laminated iron core. Several taps are brought out to obtain different voltages. On the common type of compensator, three autotransformers, one for each phase of the line, are connected in star as shown in Figure 5-58. If each coil is tapped at the center and connected as shown to a three-phase motor, the voltage impressed would be one-half the line voltage. This is the manner in which the motor is connected when it is started. With this connection, the line current at start is considerably reduced.

On the ordinary compensator, two or three taps are usually brought out of the autotransformer so that different voltages can be applied to the motor at start. Whichever tap produces the most satisfactory starting torque at the lowest starting current should be used.

MANUAL AUTOTRANSFORMER STARTER. A typical manual autotransformer compensator is shown in Figure 5-59. It contains two sets of stationary contacts and a set of movable contacts. The movable contacts are mounted on an insulated cylinder to which a handle is attached.

When the motor is started, the handle is moved quickly in one direction. This connects the motor to the autotransformer so that it is started on a reduced voltage. After the motor accelerates, the handle is rapidly pulled in the opposite direction. This disconnects the motor from the autotransformer and connects it directly across the line.

On nearly all manual compensators, the handle can only be moved in one direction at start, this direction being the one that starts the motor on a reduced voltage. It is necessary that the handle be moved quickly from the start to the run position, otherwise the motor will slow down as a result of the momentary open caused by the movement of the contacts from start to run. Most compensators have the contacts immersed in oil. This is used in order to extinguish quickly the arc that develops when the handle is thrown from start to run and thereby prevent the contacts from pitting.

Once the handle and contacts are in the run position, a holding coil which is connected across two terminals of the motor becomes energized and holds the handle in place. To stop the motor, a

STOP button is pressed which opens the circuit in the holding coil, and this in turn releases the handle. Spring action returns the movable contact to its normal off position. If the voltage should fail or be reduced, the holding coil will be unable to hold the handle in the run position. If a prolonged overload should occur, the overload relay contacts will open and de-energize the holding coil. In order to restart the motor, it is necessary to reset the overload relay by pressing a RESET button. Figures 5-60 and 5-61 shw the wiring diagrams of a manually operated three-phase compensator.

In operation, the handle is thrown first to the starting position, causing the movable contacts to make contact with the stationary start contacts. This connects the motor through the autotransformer and starts it at a reduced voltage. After the motor accelerates, the operator pulls the handle back to the running position and this connects the motor to the line. The holding, or undervoltage, coil is connected across two leads of the motor with a STOP button and overload relay contacts in series with it. To stop the motor, the button is pressed and the coil de-energized, causing the handle and movable contacts to spring back to the off position.

Compensators are also made with two autotransformer coils instead of three. These can operate either three-phase or two-phase motors. Figure 5-62 shows a diagram of a two-coil compensator operating a two-phase motor. This type of compensator can also be used to operate a three-phase motor. Figure 5-63 shows a diagram of a two-coil compensator operating a three-phase motor. Its operation is as follows: When the handle is thrown to the start position, L_2 connects directly to the motor, while L_1 and L_3 connect directly to the autotransformers. Taps on the transformers are connected to the two other motor leads so that the motor starts on a reduced voltage. After it has accelerated, the handle is quickly thrown to the run position and is held there by the holding, or undervoltage, coil. Figure 5-64 shows the connection when the motor is starting. This is known as an *open-delta connection.*

MAGNETIC AUTOTRANSFORMER STARTER. Magnetic autotransformer compensators are essentially the same as the manually operated type just described, except that the contactors are closed magnetically and are also equipped with a timing device which connects the motor across the line after it has been running on reduced voltage for several seconds. An advantage of a magnetic compensator is that it can be controlled by just pressing a button, which can be located at a convenient remote place. Figure 5-65 is a diagram of the motor and control circuit.

The magnetic autotransformer type of reduced-voltage starter is much the same in principle of operation as the magnetic primary resistor type, the difference being that a transformer is used in place of a resistor for reducing line voltage to the motor during starting. This reduced-voltage starter has a three-coil autotransformer, three sets of contactors for the start, run, and wye contacts, a pneumatic timing relay, bimetallic overload relays (two or three), and an overtemperature unit for the protection of the autotransformer against overheating. The run and wye contactors are mechanically interlocked.

The operation of this starter (see Figure 5-66) is as follows: Pressing the START button energizes the start and wye contactor coils. The contactors for start and wye close, placing the motor on reduced voltage. The wye contactors connect the three coil ends of the autotransformers together to form the star point. After a preset time interval, the pneumatic timing relay opens the wye contactors, and for a very short period of time the autotransformer acts as a reactor. The run contactors are then closed, placing the motor directly across the line. The transition from start to run is accomplished without opening the circuit to the motor, hence it is called a closed-circuit transition autotransformer starter. The starter is mechanically and electrically interlocked to secure proper starting sequence. Pressing the STOP button or a sustained overload de-energizes all contactors and disconnects the motor from the line. Figure 5-67 is a typical wiring diagram of an Allen-Bradley autotransformer type of reduced-voltage starter. This is similar in many respects to the previous diagram. The timer is located on and triggered by contactor $2S$. Note that the run and $1S$ contacts are mechanically interlocked.

Wye-delta Starters This method of reduced-voltage starting applies only to three-phase, delta-connected motors. If a delta-connected motor is connected across a 208-volt, three-phase line, each phase will receive 208 volts as shown in Figure 5-68.

On the other hand, if the motor is reconnected star and the same line voltage applied, each phase will receive 58 percent of 208, as shown in Figure 5-69.

To apply this principle to a controller, it is necessary to bring six leads out of the motor so that they can be interchanged when connecting from star starting to delta running.

Manual or pushbutton magnetic controllers can be used to effect the change. Figure 5-70 shows a manual method of wye-delta starting by means of a three-pole, double-throw switch.

In starting, the main switch is first closed, then the double-throw switch is closed for the starting position. Leads T_4, T_5, and T_6 are connected together when the switch is down, forming the star point, while leads T_1, T_2, and T_3 are connected to the line. The motor starts rotating as a wye-connected motor, and each phase receives approximately 58 percent of its rated voltage. After the motor accelerates, the switch is closed in the running position, connecting T_2 to T_4, T_3 to T_5, and T_6 to T_1, which is a delta connection. The motor now runs on full voltage.

Figure 5-71 shows a magnetic wye-delta starter of the *open transition* type. This term refers to the momentary disconnection of the motor from the line during the period of changeover from star to delta connection. These starters are also made with closed transition. Closed transition is accomplished by placing resistors at the disconnecting points during the transition, thereby keeping the circuits closed. The operation of the open transition type of wye-delta starter is as follows: Pressing the START button energizes contactors *S*, 1*M*, and time delay *TR*. The *S* contactor connects motor terminals T_4, T_5 and T_6, and contactor 1*M* connects the incoming power lines to motor terminals T_1, T_2, and T_3, causing the motor to start as a wye-connected motor. After the time-delay relay times out, the timed-open (T.O.) contacts open, dropping out contactor *S*, the timed-close (T.C.) contacts close, energizing contactor 2*M*. The 2*M* contactor, upon energizing, applies the line wires to terminals T_4, T_5, and T_6, causing the motor to run at full voltage. Pressing the STOP button drops all contactors, stopping the motor. Contactors *S* and 2*M* are mechanically interlocked. Figure 5-72 shows another type of wye-delta starter.

Part-winding Starters

Part-winding reduced-voltage starters are usually two-step accelerating starters for use with wye or delta part-winding-start motors. These motors are described in Chapter 4. The controllers described here are for use with wye-connected part-winding-start motors.

The starters for the part-winding-start motors are constructed and wired so that part of the three-phase motor is energized first, and then the remainder of the winding is energized in one or more steps. The purpose of the starter is to reduce the initial inrush of current at start. The motors used for part-winding starting may be the standard nine-lead dual-voltage motor or the six-lead motor made especially for this purpose. If the standard nine-lead wye-connected motor is used for this purpose, leads T_4, T_5, and T_6 should be wired together externally.

Figure 5-73 is a wiring diagram of a nine-lead wye-connected motor connected to an automatic part-winding starter. Connecting T_4, T_5, and T_6 together produces two wyes in the stator winding. Connecting T_1, T_2, and T_3 to L_1, L_2, and L_3 energizes half the winding. Connecting T_7, T_8, and T_9 *to* L_1, L_2, and L_3 completes the sequence, all windings being energized with both wyes in parallel. The control circuit operates as follows: Depressing the START button energizes the 1*M* contactor and the time-delay relay, *TR*, causing the motor to run on half the winding, T_1, T_2, and T_3. After the time-delay relay has timed out, contacts *TR* close, causing the 2*M* contactors to close, connecting the power to the second half of the winding, T_7, T_8, and T_9. The total motor current of the wye-connected part-winding type of motor is divided equally between the two sets of windings with each winding handling half of full power.

Other wiring diagrams of a two-step accelerating starter for use with wye-connected part-winding-start motors is shown in Figure 5-74.

Figure 5-75 shows a diagram which can be used for various part-winding schemes. This is a General Electric diagram for both wye and delta motors having nine or six leads. The table on the right shows the lead connections for the motors on the bottom of the drawing. Note the four and two pole contactor arrangement.

Drum Starters

A manual drum type of controller, which can be used for starting or reversing small three-phase motors, is shown in Figures 5-76 and 5-77. This drum switch can also be used for split-phase, capacitor, or two-phase motors, as shown in Figures 5-78 and 5-79. Figure 5-80 shows typical connection diagrams of drum switches.

A switch of this type is used if the motor is located close to the operator, as on small lathes or other machine tools.

Figure 5-77 shows that when the handle is moved from one position to another, two line wires are interchanged and the motor reverses. This switch can be adapted to reverse any small motor whether it is a-c or d-c. A complete description of this controller is given in Chapter 8.

Multispeed Starters

The speed of a two- or three-phase motor can be changed by changing the number of poles in the motor. This may be done by reconnecting the motor so that the resulting number of poles is either twice or half the number of the original poles. This is known as a *consequent-pole connection.*

Two-speed motors that do not have a 2-to-1 speed ratio have two separate windings in the motor. When one or the other winding is connected to the line, the motor will run at different speeds because of the different number of poles in each winding.

Manual and magnetic starters are constructed for the purpose of changing the motor connections for different speeds, as in the case of the consequent-pole motor, and for changing from one to another where two-winding motors are used.

All these starters employ overload protection in the form of thermal or magnetic relays. Some applications require that the motor be first started on slow speed and then, if so desired, raised to high speed. This is done by equipping the controller with a relay which will permit this sequence.

Other applications require that the motor be started on low speed and then automatically be connected on high speed only after a definite time has elapsed. This is accomplished by equipping the starter with a definite time relay.

The following two-speed magnetic starters will be described and illustrated:

1. Two-speed starter for two separate-winding motors.
2. Two-speed starters for consequent-pole-winding motors.

Two-speed Starter for Motors with Two Separate Windings
Figure 5-81 shows a wiring diagram of a two-speed starter for

operating a three-phase motor that has two separate windings. When the HIGH-SPEED button is pressed, coil hi is energized, causing contacts hi to close and thereby connecting the high-speed winding directly across the line. Auxiliary contact hi also closes and keeps coil hi energized after the HIGH-SPEED button is released. Pressing the STOP button causes the main contacts to open and stop the motor. The same result will be produced if coil hi is de-energized when an extended overload occurs.

If the LOW-SPEED button is pressed while the motor is running at high speed, coil hi will immediately become de-energized because of its interconnection with the contacts of the LOW-SPEED button. Coil lo will then be energized, and the low-speed winding is connected to the line.

Figure 5-82 shows a wiring diagram of a starter somewhat similar to that of Figure 5-81. This is for a two-speed motor with separate windings for each speed. Note that the slow-speed winding is marked T_1, T_2, and T_3, and the high-speed winding has terminal markings T_{11}, T_{12}, and T_{13}. The operation of this starter is practically the same as the previous starter. The motor can be started in either fast or slow speeds. The change from slow to fast can be made without first pressing the STOP button. When changing from fast to slow, the STOP button must be pressed.

Two-speed Starter for a Constant-torque Motor Figure 5-83 is a wiring diagram of a starter that is used to change the speed of a two-speed, consequent-pole-winding motor with constant torque. Five contacts are used for high speed. Eight main contacts are needed for this type of controller.

The operation is as follows: When the SLOW-SPEED button is pressed, a circuit is formed from L_1 through the STOP button, the normally closed fast contacts (front contacts of the FAST button), slow contacts (when pressed), the normally closed fast interlocks, coil S, overload contacts and to line *2*. Coil S is energized and the motor starts and runs on slow speed. The motor can be started at either the fast or slow speeds. The STOP button need not be pushed for changing speeds. The motor is connected series-delta-consequent for slow speed. For high speed, five main contacts are closed connecting the motor two-circuit wye. (This starter can also be used for two-speed variable-torque motors.)

Motor leads T_1, T_2, and T_3 connect together, forming the star point of the two-circuit wye connection, and motor leads T_4, T_5, and T_6 are connected to the line. Figure 5-84 shows the control circuit for this motor.

Two-speed Starter for a Constant-horsepower Motor This motor is connected two-circuit wye for low speed and series-delta for high speed. Figure 5-85 shows a complete wiring connection for a two-speed constant-horsepower motor connected to a multispeed starter. Figure 5-86 shows a multispeed consequent-pole starter.

Two-speed Diagrams Multispeed motor connections for two-speed motors are shown in Figure 5-87.

Quick-stop A-C Starters

In many motor applications, it is necessary to have a method of quickly stopping or braking the motor to ensure safe operation and to save time.

While a three-phase motor is coasting to a standstill, current is sent through it in a direction that will cause it to tend to reverse its rotation. The power is then immediately disconnected. This is called *plugging* and is accomplished by reversing the current through two leads of a three-phase motor.

To effect plugging, the instant the motor circuit is opened, a new circuit is established that will tend to reverse the motor. This will immediately stop it and cause it to run in the opposite direction. If the line is disconnected at the instant the motor comes to a full stop and is about to reverse its direction, then the motor will remain at a standstill.

To accomplish this, a plugging relay is used. The relay is mounted on top of the motor and is operated by a belt attached to the shaft of the motor. Contacts located inside the relay close when the motor is running, but prevent operation in the reverse direction by opening as soon as the motor tries to reverse its direction. There are various designs in the construction of these relays, but essentially the operation of all of them is the same as that described.

A wiring diagram of a controller and plugging relay is shown in Figure 5-88. A reversing type of across-the-line starter is used. The simplified diagram of Figure 5-89 is traced in the following explanation of the circuit.

When the START button is pressed, coil F is energized and causes the three main contacts F to close and connect the motor across the line. At the same time, the normally open auxiliary contact F_1 is closed, maintaining the current through coil F. Also normally closed auxiliary contact F_2 is opened, thereby preventing current flow through the reverse coil R. The plugging relay contacts are closed by the rotation of the motor.

If the STOP button is pressed, coil F is de-energized, and it opens the line contacts to the motor, contacts F_2 close, thereby completing a circuit through the plugging relay to coil R. This coil is energized and closes main contacts R, which cause current to flow through the motor in the reverse direction.

The motor immediately comes to a stop, and the instant it reverses its direction, it opens the relay contacts de-energizing coil R. The main contacts R open and break the line circuit to the motor. This controller can be used for plugging in either direction.

There are several other methods that can be used for quickly stopping a polyphase motor. One of these is the application of low-voltage direct current to one phase immediately after the line switch to the motor is opened.

Troubleshooting and Repair

In this section it is assumed that the motor and fuse are in good condition. To make certain that the motor is not at fault, connect test lamps at the motor terminals and determine whether current is available when the contacts of the controller are closed. If there is no current, the trouble probably lies in the controller.

Since there are many different kinds and makes of controllers, a general procedure for locating the source of trouble is given.

1. If the motor does not start when the main contacts close, the trouble may be:

a. Open overload heater coil or poor connection

b. Main contacts not making (It is not unusual for one or more contacts to wear sufficiently so that they will not make when closed. This will also occur if the contacts become dirty, gritty, or burned.)

c. Broken, loose, or dirty terminal connection

d. Loose or broken pigtail connection

e. Open resistance units or open autotransformer

f. Obstruction on the magnet core, preventing the contacts from closing

g. Mechanical trouble, such as mechanical interlocks, gummy pivots, poor spring tension, and so on.

2. If the contacts do not close when the START button is pressed, the trouble may be:

a. Open holding coil (This can be tested by connecting a test lamp across the coil terminals when the START button is pressed. If the lamp lights when the START button is pressed, but the coil does not become energized, the coil is defective.)

b. Dirty START-button contacts or poor contact

c. Open or dirty STOP-button contacts (If more than one station is connected to the same controller, each station should be checked. If FORWARD-REVERSE stations are used and they are interlocked, check all contacts.)

d. Loose or open terminal connections

e. Open overload-relay contacts

f. Low voltage

g. Shorted coil

h. Mechanical trouble.

3. If the contacts open when the START button is released, the trouble may be:

a. Maintaining contacts that do not close completely or are dirty, pitted, or loose

b. Wrong connection of station to the controller.

4. If a fuse blows when the START button is pressed, the trouble may be:

a. Grounded contacts

b. Shorted coil

c. Shorted contacts.

5. If the magnet is noisy in operation, the trouble may be:

a. Broken shaded pole causing chattering

b. Dirty core face.

6. If the magnet coil is burned or shorted, the trouble may be:

a. Overvoltage

b. Excessive current due to a large magnetic gap caused by dirt, grit, or mechanical trouble

c. Too frequent operation.

Testing Component Circuits

By using a snap-around type volt ammeter-ohmmeter or individual instruments, many of the tests needed to determine opens, shorts, grounds, continuity, etc., may be conducted in a very short time. Shorted coils, open coils, grounded coils, open resistances, shorted resistances, low voltages, high voltages, excessive amperes, broken, loose, or dirty connections, and many other malfunctioning component circuits may be tested with comparative ease. This is true of all motors, as well as starters. Figure 4-134 shows one method of using this instrument.

CHAPTER 6

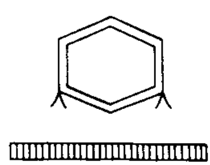
Direct-current Armature Winding

The complete process of armature winding involves a number of operations that are performed in sequence. These are: (1) taking data while stripping the armature; (2) insulating the core; (3) making and taping coils; (4) placing the coils in the slots; (5) connecting the coil leads to the commutator; (6) soldering the leads to the commutator; (7) testing; (8) turning the commutator in the lathe; and (9) baking and varnishing. A form for recording this data is shown below.

DATA SHEET FOR D.C. ARMATURES

Make

K.W. H.P.	R.P.M.	Volts	Amps.
Cycle	Type	Frame	Style
Temp.	Model	Serial #	Phase

No. of Slots	Bars	Coils/Slot
Size Wire	Coil Pitch	
Center of Slot to	Center of Bars Center of Mica	
Commutator Pitch Lap	Wave	

When armatures such as those shown in Figure 6-1(a), (b), and (c) require rewinding, sufficient information must be gathered in the process of stripping to enable the mechanic to rewind it exactly as it was wound originally. Unless the different types of windings and connections are familiar to the mechanic, it will be almost impossible to record the necessary data. The different types of windings and connections will be described, and directions given for rewinding the more important ones.

Typical Winding for a Small Armature

The simplest type of winding consists of a series of coils wound into the slots of an armature and connected in succession to the commutator. Figure 6-2(a) shows a diagram of this winding. The commutator is shown flattened for simplicity. A circular schematic diagram of the same winding is given in Figure 6-2(b).

Insulating the Core Before an armature is wound, however, the slots must be insulated to prevent the wires from touching the iron core causing grounds. As in the other types of motors, the same kind and thickness of insulation is inserted as was removed. On a small armature, the insulation is cut so that it protrudes approximately ⅛ in. on both ends of the armature slot and about ¼ in. above the slot, as shown in Figure 6-3. It is also necessary to insulate the shaft of the armature by placing several turns of insulating tape around it. Usually the end lamination is made of fiber that protects the coils from grounding. This is fitted over the shaft and extended outward to the bottom of the slots, as shown in Figure 6-4.

Winding Procedure

Small armatures, such as those used in vacuum cleaners and drills, can be held in one hand, as shown in Figure 6-5. Larger armatures are mounted between horses, as shown in Figure 6-6, or use an armature holder, as shown in Figure 3-33(b).

Assuming a nine-slot armature, and data taken during the stripping process, the winding procedure is as follows:

Insert insulation in the slots. Choose any slot and call it slot *1*. Wind the required number of turns into the slots of the proper pitch or span, in this case 1 and 5, and then make a loop, as shown in Figure 6-7. Use enough tension on the wire to make a tight winding without breaking the wire. Make the loop at the end of the first coil and the beginning of the second coil. Start the second coil in slot *2* and wind the coil with the same number of turns as coil *1*. Be sure that the coil span is the same as coil *1*.

Make a loop when the second coil is finished, and then start winding in slot *3*. Continue in this manner until nine coils have been wound. Connect the end lead of the last coil to the beginning lead of the first coil. After the entire armature is wound, there will be two coil sides in each slot. Figure 6-8 shows a step-by-step winding of an armature having nine slots. Note that all coils have the same pitch and turns. This type of winding, in which a loop is made of the end of each coil, is called a *loop winding.*

Placing Wedges in the Slot After the armature has been wound, the next operation is to close the slots so that the wires will not fly out while the armature is rotating at full speed. The procedure is illustrated in Figure 6-9. Note the insulation between the coils in the slot. This may be a standard separator creased for better protection.

Cut the insulation so that it extends out of the slot about $\frac{3}{16}$ in. Use a piece of fiber to press one side of the insulation into the slot and then the other side of the insulating strip into the slot. Slide a wooden (or fiber) wedge of the proper size into the slot over the insulation. On large armatures, the insulation is cut flush with the top of the slot and then banded.

Lead Swing

One of the most important operations in the winding of an armature is placing the coil leads in the proper commutator bars. Leads may be placed in the bars in any one of three different positions, depending on the original location. If a slot in the armature is viewed from the commutator end, the leads to the commutator may swing to the right of the slot or to the left, or they may be aligned with it.

The following method is used in determining the position of the leads in the commutator.

Stretch a piece of cord or string through the center of a slot, as shown in Figure 6-10. Note whether it is in alignment with a commutator bar or with the mica between bars. If the data call for a lead swing of three bars to the right, place the lead of the first coil three bars to the right, counting the bar that lines up with the slot as No. 1. All the other leads follow in succession, as shown in Figure 6-11. If the center of the slot is in line with the mica, consider the bar to the right of the mica as bar No. 1.

Windings with More than One Coil per Slot

In the armature so far discussed the number of slots is equal to the number of commutator bars. This is not true of all armatures. Some have twice as many bars as slots, and it is not unusual for them to have three times as many bars as slots. In an armature of this type, the number of coils is always equal to the number of bars; therefore, an armature that has nine slots and eighteen bars has eighteen coils. The procedure in winding an armature of this type is exactly the same as for the simple loop winding, except that each slot has two loops.

Winding a Loop Armature with Twice as Many Commutator Bars as Slots Assume a nine-slot, 18-bar armature. The procedure for winding this two-coil-per-slot armature is as follows: Wind the first coil into slots *1* and *5* in the same manner as in the simple loop winding. Make a loop and wind the second coil into the same slots. Make a loop and start the third coil in the slot *2*. Continue in this manner, winding two coils before going to the next slot. The windings should appear like those shown in Figures 6-12 and 6-13. There should be two loops for each slot. To distinguish between the first and second loops of each slot, sleeving of different colors may be put on the loops, or the second loop of each slot may be made longer than the first. This procedure enables the winder to place the leads in the proper commutator bars without testing each lead.

Lap Winding

Armature windings are classified in two main groups, lap and wave windings. The difference between them is the manner in which the leads are connected to the commutator bars. Lap windings may be classified in three ways: simplex lap winding, duplex lap winding, and triplex lap winding.

The simplex lap winding is one in which the beginning and the end leads of a coil are connected to adjacent commutator bars, as shown in Figure 6-14. Thus, the end lead of the first coil connects to the same commutator bar as the beginning lead of the second coil, and so on.

The duplex lap winding is one in which the end lead of a coil is connected two bars away from the beginning lead, as shown in Figure 6-15. Thus, the end lead of the first coil is placed in the same commutator bar as the beginning lead of the third coil; the end of the third in the same bar as the beginning of the fifth; and so on.

The triplex lap winding is one in which the end lead of a coil is connected three bars away from the beginning lead, as illustrated in Figure 6-16. Thus, the end of the first coil is connected to the same commutator bar as that of the fourth coil; the end of the fourth to the beginning of the seventh; and so on.

The simplex winding is most frequently used on small- and medium-sized armatures. Duplex and triplex windings are not employed to any great extent, but simplex windings can generally be reconnected as duplex or triplex windings when it is desired to run a motor on a lower voltage. Brushes used on duplex-wound armatures must contact at least two commutator bars, while brushes for triplex-wound armatures must touch at least three commutator bars.

The statement that any winding in which the beginning and end leads of the same coil are connected to adjacent bars is a simplex lap winding is true for any number of poles that a motor may have. To illustrate the lap winding, several types of armature windings will be described.

Lap Winding with Loops

A simple lap winding having one coil for each slot is shown in Figure 6-7. This nine-slot armature has nine coils, one for each slot. In this armature, the number of slots and commutator bars must be the same. The loops are connected to the commutator bars in succession, as shown in Figure 6-17.

A lap winding with two coils for each slot is shown in Figure 6-18. A nine-slot armature in this case has eighteen coils. There must be twice as many commutator bars as slots, because there are eighteen loops, and each loop requires one commutator bar. As illustrated, one loop is made short and the next one long, so that the leads may be put in the bars in the proper rotation.

Loop windings may also have three coils for every slot. It is then necessary to have three times as many commutator bars as slots.

Lap Winding without Loops

In a lap winding, it is possible to place the beginning lead in the proper commutator bar as each coil is wound and to connect all the end leads to the proper bars after the entire armature is wound. This requires the end lead of each coil to be left free until all the coils are wound.

Armature with One Coil per Slot

The procedure for winding and connecting an armature having one coil per slot follows:

Start in any slot and wind one complete coil in the slots of proper pitch. Place the beginning of coil *1* into the proper commutator bar, and leave the end lead free for connection after the armature is wound. Wind the entire armature in this manner, leaving all the end leads disconnected, as shown in Figure 6-19. After all coils are wound, connect all the top or end leads to the commutator. Place each top lead in the bar adjacent to the bottom lead of the same coil to produce a simplex lap winding like that given in Figure 6-20.

Armature with Two Coils per Slot

Simplex lap-wound armatures having two coils per slot are more common than those having one coil per slot. The procedure for winding this type of armature is as follows:

Start winding with two wires and place the beginning leads in the commutator bars according to the data taken. Cut the wires when the proper number of turns have been wound into the slots, and leave the end leads free, as shown in Figure 6-21. Start the next coil one slot to the left of the first coil as viewed from the commutator end. (When the coils proceed to the left, the winding is called *left-handed,* and to the right, *right-handed.*) Follow this procedure until all coils have been wound. Then place the top, or end, leads in the commutator bars in the proper succession. This is shown in Figure 6-22.

If it is difficult to identify the leads after all the coils are wound, the following method can be used to locate the proper top leads for correct connection. Use the test lamp as shown in Figure 6-23, and place one test lead on a commutator bar. Apply the other test lead to each free lead until one is found that causes the lamp to light. This lead must be placed in the commutator bar adjacent to the beginning lead.

Sleeving of different colors is sometimes used for identification of the leads. One color is used for the beginning and end of the first coil, and another color for the second coil in the same slot; the third coil uses the same color as the first, and so on. It will be necessary to test the first top lead, and the colors identify all the others.

Using short and long leads for the two coils in the same slot is another method of identifying the leads so that they can be connected properly.

Armature with Three Coils per Slot

Lap-wound armatures with three coils per slot are wound in the same manner as armatures with two coils. Three bottom leads and three top leads are connected from each slot. These leads are placed in consecutive commutator bars, as was done in the case of the two-coil-per-slot windings, and the leads are similarly identified. Figure 6-24 shows three coils in one slot.

Coil Windings

The windings discussed thus far are hand windings in which the turns are wound into the slot one by one. This method is used on the small armatures, but on large armatures (and on a few small ones) the coils are wound on a form and then placed in the slots as a complete unit. The leads of a coil-wound armature are connected to the commutator in the same way as those of a hand-wound armature. The procedure of winding, taping, and placing the coils in the slots is similar to that followed on three-phase motors. Figure 6-25 shows several coils of a coil-wound armature with two coils per slot.

Wave Windings

There are three groups of wave windings, namely, simplex wave winding, duplex wave winding, and triplex wave winding.

The difference between a wave winding and a lap winding is in the position of the armature leads on the commutator. In the simplex lap winding, the beginning and end leads of the same coil are connected to adjacent bars. In the wave winding, the beginning and end leads of a coil are connected to commutator bars quite far apart. Thus, on a four-pole motor they are connected on opposite sides of the commutator; on a six-pole motor they are connected one-third of the commutator bars apart; on an eight-pole motor, one-fourth the bars apart. A wave winding is one in which the beginning and end leads of a coil are connected a definite number of commutator bars apart, depending on the number of poles in the motor and the number of bars on the commutator. In a lap winding the leads face each other, as shown in Figure 6-26. In wave winding the leads face away from each other, as shown in Figure 6-27.

In a wave winding for a four-pole motor the current must travel through at least two coils before reaching a bar adjacent to the starting point. For a six-pole motor the current will travel through three coils before reaching an adjacent bar. Two-pole motors cannot be wave wound.

Commutator Pitch

The number of bars between the coil leads is called the *commutator pitch,* usually written c.p. Thus,

$$\text{c.p.} = \frac{\text{no. of commutator bars} \pm 1}{\text{no. of pairs of poles}}$$

Assuming a four-pole, 49-bar armature,

$$\text{c.p.} = \frac{49 \pm 1}{2} = 24 \text{ or } 25 \text{ bars}$$

Usually the number of bars is expressed as 1 and 25 or 1 and 26. Thus, if the commutator pitch is 24 bars, the leads are placed in bars *1* and *25*, as shown in Figure 6-28. If the commutator pitch is 25 bars, the leads are placed in bars *1* and *26*. It is important to remember at this point that all four-pole wave-wound armatures must have an odd number of commutator bars. Six-pole motors can have an even or odd number and eight-pole motors must have an odd number of bars. All two-pole motors are lap wound. Read the section in Chapter 3 on Rewinding a Wave-wound Armature, page 90.

Retrogressive and Progressive Windings According to the formula, the commutator pitch may be either of two figures. If the smaller number is used, the motor will run in one direction; if the larger number is used, the armature will rotate in the opposite direction. These connections are known as retrogressive and progressive windings, respectively, and they are used in both lap and wave windings. A simplex progressive lap winding is one in which the current flowing in a coil terminates one bar beyond the starting point. This type is shown in Figures 6-29 and 6-31. A simplex retrogressive lap winding is one in which the current flowing in a coil terminates one bar before the starting point. This type appears in Figures 6-30 and 6-32.

If a progressive connection is changed to a retrogressive connection, the armature will rotate in the opposite direction.

Assuming a four-pole motor, a simplex progressive wave winding is one in which the current flowing through two coils in series terminates one bar beyond the starting point. A four-pole simplex progressive wave winding is shown in Figures 6-33 and 6-35.

A simplex retrogressive wave winding is one in which the current flowing through two coils in series terminates one bar before the starting point. This type is shown in Figures 6-34 and 6-36.

Connections for a progressive lap winding with two coils per slot are shown in Figure 6-37. Several coils of a retrogressive lap winding are shown in Figure 6-38.

Connections of both types of wave windings of 23-slot, 45-bar armatures with two coils per slot are shown in Figures 6-39, 6-40, 6-41, 6-42, and 6-43.

Equalizer Connection Equalizer connections, also known as *cross connections*, are used in large d-c armatures to minimize circulating currents. These circulating currents are usually due to uneven air gaps between the field poles and the armature and may be eliminated by connecting commutator bars of equal potential together. The bars to be connected together depend on the number of poles in the motor and the number of commutator bars. Since equalizer connections are used mostly on repulsion motors, this subject is discussed in more detail in Chapter 3. It should be understood that equalizer connections are used on lap windings only.

Rewinding Procedure

Taking Data

During the process of stripping an armature sufficient information should be recorded to enable the winder to rewind it properly. The following procedure is used in many shops:

Count the slots and commutator bars. Record the lead throw by marking the slots and commutator bars of a coil as shown in Figures 6-44, 6-45, and 6-46. The marks shown in the diagrams are made either with a file or center punch. These record both the coil pitch and the lead throw. This is an important operation, since wrong lead throw will cause sparking and poor operation. Take the coil pitch at the same time. If the coil is wound in slots 1 and 8, record the pitch as 1 and 8. If the armature is form wound, several coils will have to be lifted. Record the end room by measuring the distance the coils extend beyond the ends of the slots.

Determine the number of coils per slot and kind of winding, that is, hand, form, loop, right-hand, left-hand, clockwise, and so on. Count the number of turns in each coil. If this is too difficult, cut the coil and count the cut ends of the wires.

If it is a one-coil-per-slot winding, it may be necessary to count all of the turns in a slot and then divide by 2 in order to get the number of turns in each coil. If it is a two-coil-per-slot winding, divide the total number of turns in a slot by 4 to obtain the number of turns per coil. On large armatures, preserve one coil in order to have the size for the construction of a form for new coils. Determine the size of the wire by means of a wire gauge or micrometer. Also record the wire covering, such as single-cotton-enamel, Formvar, or whatever has been used. Record the kind of insulation in the slot.

Caution. Try not to disturb the laminations. Do not break end-fiber insulators. Make sure that all the insulation is removed from the slots. Unsolder the leads from the commutator, and if the ends break off at the bars, use a hacksaw blade to force the broken particles of copper out of the bar. Use a blade that will make a cut in the bar no larger in size than the diameter of the new wire. A tool for this purpose is shown in Figure 6-47.

Stripping the Armature

Usually the wedges are tight in the slots and removal is difficult. Place the teeth of a hacksaw blade on the wedge, as shown in Figure 6-48, and tap it with a hammer so that the teeth are imbedded. The blade is next tapped on the end to embed its teeth more deeply in the wedge and at the same time to drive the wedge out of the slot. On large coilwound armatures, stripping is relatively simple. Cut the bands and pry out the coils one by one after disconnecting all leads from the commutator. On the smaller armature with semiclosed slots, and especially if they are hard baked, it may be necessary to place this armature in a burn-off oven to soften all of the insulation and varnish. If this is done it will be necessary to first remove the commutator from the shaft. Disconnect all wires from the commutator by either cutting them with a hacksaw blade or with a cutting tool in the lathe. It is presumed that all lead data have already been taken. Also, cut the wires from the front of the armature slots using the tools as above. This should allow ample room to remove the commutator from the shaft using either a pulley remover or hydraulic press. It is important that exact measurements be taken of the distance from the commutator to the end of the shaft (Figure 6-49). Alignment of commutator to slot must also be known (Figure 6-10).

After the commutator is removed, the armature is heated sufficiently to soften or char the insulation, using the burn-off oven. If an oven is unavailable, it may be possible, after cutting the wires on one end of the armature, to pull them out from the other end. The commutator may be put back before or after winding the armature, depending on the method of winding and connecting.

Caution. Press the commutator on the exact distance measured before removal. The commutator must fit firmly to prevent movement during rotation. Use a press for reinstalling the commutator.

Soldering the Commutator

After reinsulating and rewinding the armature and placing the leads in the commutator, the next step is to solder the leads with either a gas or an electric soldering iron. Electric irons are generally used on small armatures and gas irons on the large ones. The size of the iron used depends on the size of the commutator. Leads can also be welded to the commutator or soldered by means of a torch.

The procedure is as follows: Place soldering flux over each wire in the commutator bar. (A good type of flux is made by pulverizing resin and adding alcohol to make a paste. Commercial soldering paste can be used if it is wiped off with alcohol after soldering.)

Place the tip of the soldering iron on the commutator, as shown in Figure 6-50, and wait until the heat from the iron is transferred to the area of the commutator bar that is to be soldered. This heat transfer occurs when the paste starts bubbling.

Place solder on the commutator near the iron and allow it to melt and flow into the commutator slot before removing the iron. Flow the solder entirely around the leads. To prevent the solder from flowing down the back of the commutator and causing short circuits, raise one end of the armature so the solder flows forward. To prevent the solder from flowing from one bar to another, the iron is held as shown in Figure 6-51.

Banding the Armature

Bands are used on armatures to hold the commutator leads in place. A cord band is used on small armatures to prevent the leads from flying out of the slots while the armature is rotating. Large armatures have steel bands for the same purpose. Large armatures having open-type slots use steel or tape bands to prevent the coils from flying out of the slots.

Cord Bands The procedure for placing a cord band on an armature is shown in Figure 6-52, and the following directions should be observed: Use the proper size of banding cord; heavy for larger armatures, light for small armatures. Start at the end nearest the commutator and wind several turns in layers, allowing about 6 in. of the beginning to be free. After winding several turns, loop the start as shown at *3* on the diagram, and wind several more turns over the loop. Bring the end of the cord band through the loop and then pull on the free end. This will pull the end under the cord band and secure it there, at which point the cord can be cut off. Use enough pressure in winding so that the band will be tight.

Steel Bands Some open-slot types of armature require steel bands to prevent the coils from flying out of the slots while the armature is rotating. Steel bands are placed on the front and back ends of the coils. These bands are put on the armature in a different manner than cord bands. The procedure is illustrated in Figure 6-53 and is as follows: Place the armature in a lathe and place mica or paper insulation in the band slot around the entire armature to insulate the band from the coil sides. Hold the insulation in place by tying a turn of cord around it. Place small strips of tin or copper under the cord, equidistant around the armature, in order to secure the band after it is wound. Use the same gauge steel band wire as on the original band.

Steel bands must be put on the armature with much more pressure than is needed for cord bands. It is therefore necessary to utilize a device called a *wire clamp* to provide the required pressure. This device consists of two pieces of fiber fastened together by means of two screws and two wing nuts. The steel-band wire is fed through this clamp to the armature. Secure the clamp to a lathe or bench so that it can be held stationary while the armature is being banded. Feed the wire to the armature through the clamp while slowly turning the armature. Take care not to put too much pressure on the wire; otherwise, it will break. After one band is placed on the coil, turn the copper or tin strips over and solder the entire band. Proceed to the next band.

Tape Bands

Many shops are now using a woven glass tape treated with a polyester or epoxy resin rather than a steel banding wire. The tape is applied to armatures or rotors at about the same tension as with steel wire, using a tape tension device for applying the tape. It is preferable that the armature be hot before applying the tape to eliminate voids between layers. Approximately 50 lb. of tension can be used, and as many as five layers can be applied in an overlapping manner. The tape is held in place by smoothing down with a hot soldering iron. It is sealed and fused at the end while under tension before it is cut off. The iron is also used to fuse layer to layer. After banding, the armature is dipped into a compatible varnish and dried. It is then baked for several hours to cure. Figure 6-54 shows a tension device for applying glass band tape.

Testing the New Winding

After the rewinding and connections are completed, it is important that both winding and connections be tested for shorts, grounds, open circuits, and correctness of connections. This must be done before varnishing the winding so that any troubles that are found may be corrected more readily. Detailed instructions for making these tests will be found later in the chapter under Troubleshooting and Repairs.

Balancing the Armature

Armatures should be tested for mechanical balance just before and after they are varnished. Undue vibration and unusual noises may be due to imbalance in an armature and should always be investigated immediately. Therefore, it is important that the armature be balanced before it is installed in the motor. Balancing ways are used for this purpose and may be of the type shown in Figure 6-55. These are built in various sizes. The method of balancing an armature using this machine or others similar to this is as follows. Place the armature on the balancing ways and roll it gently. When it comes to a stop, the heavier point will be on the bottom. To compensate for this heavy point it is necessary to counterbalance it with weights diagonally opposite the heavy point. This should be directly on top. The top slot or slots should be marked. Make this test several times. If the marked slot does not come out on top, the armature may be balanced. If the marked slot always comes to rest at the top, then it is necessary to counterbalance the heavy point on the bottom. This is accomplished by placing a lead, brass, or copper strap under, above, or in place of the wedges in the marked slot or under the bands of the armatures. Experience will determine the amount of metal necessary to balance the armature. This method of balancing is called *static balancing.* Another method is called *dynamic balancing* and requires a machine usually complicated in design.

Baking and Varnishing

After the armature has been wound, soldered, banded, and tested, the next operation is varnishing. This process makes it moistureproof and prevents vibration of the coils of wire in the slots. Vibration has a tendency to impair the insulation on the wires and cause shorts. Moisture also will cause the insulation on the wires to deteriorate.

Armatures may be varnished with either baking varnish or air-drying varnish. Air-drying varnish is applied to the armature when baking is undesirable or inconvenient. Baking varnish is more effective because of the moisture that is eliminated only by baking.

When using baking varnish, place the armature in a baking oven at a temperature of 250° F for about three hours to remove all moisture and allow the baking varnish to run. Remove the armature from the oven and dip it into the varnish, allowing it to drip for ½ hour. Tape the shaft and commutator to prevent the varnish from adhering; otherwise, scraping will be necessary after the varnish hardens. Place the armature back in the oven at the same temperature for three more hours. When the varnish has hardened, the commutator may be turned down in the lathe.

Troubleshooting and Repair

Testing

Before attempting to wind the armature, the usual procedure is to test the commutator. This is done to facilitate repairs in case the commutator is defective. The commutator is tested for grounded bars and shorted bars.

Test for Grounded Commutator A commutator is grounded when one or more bars contact the iron core of the commutator. Use the test leads and lamp connected as shown in Figure 6-56. Attach one test lead permanently to the shaft of the armature and the other test lead to a commutator bar. If the bar is properly insulated, the lamp will not light. There should be no sparking or arcing between the bar and the ground. Place a test lead on the next bar and test in the same manner as before, continuing until all bars are tested. If the lamp lights when a bar is touched, a ground is indicated.

Test for Shorted Commutator The test illustrated in Figure 6-57 is made to reveal defects in the mica between bars. Place one test lead on a commutator bar and the other test lead on an adjacent bar. No light should be visible on the test lamp. If a light is observed a short exists between the bars contacted by the test leads. Move each lead one bar over, and test as before. Continue in this manner until all bars have been tested.

Testing the Winding After an armature is wound and the leads connected to the commutator, tests should be made in order to reveal defects that may have occurred during winding. These tests are to determine grounds, shorts, opens, and reverses in the windings and are made by using either a growler or millivoltmeter.

Test for Grounds VISUAL INSPECTION. After rewinding an armature, the first step is to determine whether or not the winding is grounded. A simple test lamp is all that is necessary. This can be done as shown in Figure 6-58, before the leads are connected to the commutator. If the test is to be made on an armature whose coils are connected to the commutator, the test circuit becomes that of Figure 6-59. If the lamp lights and the coils are not connected to the commutator, a grounded winding is indicated and the condition should be remedied before further tests are made. The exact position of the ground must be found in order to remove the cause. The winding usually grounds at the corners of the slots, where there is a sharp bend in the coil, or inside the slots, if there are sharp laminations out of place. If the coils are connected to the armature and the lamp lights, either the armature winding or the commutator may be grounded.

The procedure for locating the ground is as follows: Inspect the coils at the slot ends and notice if the slot insulation has shifted and caused the coils to touch the iron core, as shown in Figure 6-60. In a new winding the insulation may be shifted back to position. However, if this cannot be done, a new piece of insulation should be inserted at the bad spot. If the ground cannot be located by inspection, the growler or meter test should be made.

BAR-TO-BAR METER TEST. The circuit of Figure 6-61 is used with a low-voltage source of direct current, such as a battery or 115-volt line, with one or several lamps in series with it, as shown in Figure 6-62. Tie several turns of cord around the commutator and put the test leads under the cord, as shown in Figure 6-63. Place one lead of a d-c millivoltmeter on the shaft and the other lead on a commutator bar. The meter needle should deflect if there is a ground. Move the meter lead from one bar to another until the meter shows little or no deflection. The coil connected to this bar is the grounded one. Figures 6-64 and 6-65 show schematic diagrams of this test circuit.

Caution. On a two-pole motor, the current leads may be placed on opposite sides of the commutator or any fraction thereof. Meter readings are taken on bars between these leads. On a four-pole motor, the leads should span one-fourth the number of bars; on a six-pole motor they should span one-sixth the number of bars; and so on. Allow only enough current to flow through the armature to permit a deflection of approximately three-fourths of full scale.

This is accomplished by varying the number of lamps switched into the circuit or the battery voltage used.

A GROWLER TEST. A growler, shown in Figure 6-66, is a device that is used to detect and locate grounded, shorted, and open coils in an armature. It consists of a coil of wire wound around an iron core and is connected to a 120-volt a-c line. The core is generally H-shaped and cut out on top so that the armature will fit on it, as shown in Figure 6-67. When alternating current is applied to the growler coil, voltage will be induced into the armature coils by transformer action.

The procedure for testing an armature for grounds by using the growler is as follows:

Place the armature on the growler and turn on the current. Place one lead of an a-c mllivoltmeter on the top commutator bar. Place the other meter lead on the shaft, as shown in Figure 6-68. If a reading is noticed on the meter, turn the armature so that the next commutator bar is on top, and test as before. Continue in this manner until a bar is reached that gives no deflection, thus indicating that the grounded coil is connected to this bar.

THE TRIAL TEST. A grounded coil may be located without using either the growler or the bar-to-bar test. For lap windings the method is as follows: Disconnect two leads from commutator bars on opposite sides of the commutator and separate them, as shown in Figure 6-69. Use a test lamp and determine which half of the winding is grounded. This is done by touching one test lead to the shaft and the other to the disconnected leads. Whichever causes the lamp to light is the grounded side of the winding, and the other half is eliminated.

Disconnect one commutator lead from approximately the center of the grounded side of the armature, as shown in Figure 6-70, and test as before. This procedure immediately eliminates three-fourths of the winding. Continue in this manner until the grounded coil is located by the process of elimination.

REPAIR OF A GROUNDED COIL. After the grounded coil has been located, it becomes necessary to determine its cause and to repair it if possible. The usual cause is a breakdown in slot insulation or a lamination pressing into the coil at some point. If the source of trouble is visible, it may be possible to remedy the trouble quickly by inserting new insulation where needed or properly positioning the lamination. If the trouble is not visible, it is necessary to rewind and reinsulate part or all of the winding or to eliminate the offending coil from the circuit. The first method is used if the entire winding is desired in the circuit. Other factors, such as time, expense, type of shop, will determine the use of the second method.

The second method involves the following steps: Disconnect each lead of the grounded coil from the two commutator bars. Connect a jumper between these bars to short them. Figures 6-71 and 6-72 show how to remove a loop-wound coil from the circuit. Figures 6-73 and 6-74 show, respectively, how to remove a lap and a wave coil from the circuit.

Although this procedure allows the grounded coil to remain in the armature, it results in electrical removal of the coil from the armature circuit. The disconnected coil leads are taped and allowed to remain in their original position without touching the commutator. If the coil is grounded in two places, cut it through to prevent induced currents. To determine whether or not there is a double ground, place the armature on a growler and test for shorts.

Tests for Shorted Coils GROWLER TEST. Shorted coils in a new winding usually can be attributed to carelessness and excessive pounding on the coils, especially if a tight winding is made. These shorts occur when two turns of one coil make electrical contact, when one coil makes electrical contact with an adjacent coil, and when coil sides in the same slot are shorted (short on the half).

The procedure to test for short circuits in an armature follows: Place the armature on the growler and turn on the current. Hold a thin piece of metal, such as a hacksaw blade, over the top slot of the armature, as shown in Figure 6-75. The blade should be held so that it is directly over the slot and along the length of it. If the coil in this slot is shorted, the blade will vibrate rapidly and create a growling noise. If the blade remains stationary, it is an indication that no short exists in the coil under test. After several top slots have been given the hacksaw blade test, turn the armature so that the next few slots are on top. Test as before and continue this procedure for the entire armature.

If the armature is very large, the growler can be placed on top of it and tested in the same manner as before. Some shops have the growler mounted sideways, with provision to move it up or down. The armature in this case is mounted on horses adjacent to the growler during test.

An internal growler such as used for stators may also be used for armatures. These are made with or without a built-in feeler. The growler with the built-in feeler has a flexible blade attached to the growler so that a hacksaw blade or similar instrument is not necessary. This type is especially desirable in smaller stators where there is no room for a separate feeler. Figure 6-76 shows an internal growler with separate feeler used on a larger armature. A short circuit in the coil under the growler will cause the hacksaw blade at the other side of the coil to vibrate.

An armature having cross connections or equalizers cannot be given the hacksaw blade test. This type of armature will cause the blade to vibrate at every slot, which would seem to indicate that possibly every coil is shorted. This is not the case, however, and it will be necessary to give this type of armature a meter test.

A shorted coil on either a lap- or wave-wound armature will cause the blade to vibrate over two slots, thus identifying the slots in which the shorted coil slides are located. These slots should be marked with a piece of chalk. If vibration occurs over more than two slots, the possibility exists that more than one coil is shorted. On a four-pole wave winding, the blade will vibrate at four spots if the short is *between two adjacent bars*. On a six-pole wave winding, there will be six points at which the blade will vibrate.

On a lap or wave winding, it is a simple matter to trace the leads of the defective coil and see where they are connected to the commutator. In the case of the wave winding it is a little more difficult, and therefore a meter must be used for tracing. This is especially true if two commutator bars are shorted.

Figure 6-77 shows a growler with test prods and meter for testing for grounds, shorts, or opens. The test for shorts is described above.

BAR-TO-BAR METER TEST. Direct current is generally used for this method of finding the shorted coil. Directions are as follows: Place the armature on horses and connect a source of direct current to the commutator, using the circuit of Figure 6-78. Place the leads of a d-c millivoltmeter on adjacent bars, beginning at bars *1* and *2*, and permit enough current to flow through the armature to give about three-fourths of full-scale deflection on the meter. If the coil connected to these bars is in good condition, a normal deflection will be observed on the meter. Move the leads of the meter to the next two bars—*2* and *3*—and observe the reading. The meter needle should deflect the same amount as before. If the reading is less or zero, a shorted condition exists in the coil connected to these bars.

Caution. A slightly lower reading will result if a coil has less wire than others. In the loop winding and other windings that are put in the slots as a unit, the meter readings will be slightly different, as readings are taken around the commutator. The reason for this is that the coils become larger as they are put one on top of the other. To determine if the lower reading indicates a short, place the armature on the growler and test it for shorts. If it tests perfectly on the growler, then the lower reading means less wire or a shorter coil. On a four-pole wave winding, a shorted coil will be indicated by approximately one-half the normal reading and will be revealed on opposite sides of the commutator.

Eliminating a Shorted Armature Coil If there are more than one or two shorted coils on an armature that has seen many years of service, the best procedure is to rewind the armature. This is advisable because the armature coils have probably been heated to such a degree that the insulation is brittle and charred, and handling on the bench would cause more shorts. If one or two coils are shorted and the rest of the armature seems in good condition, these coils can probably be cut out of the circuit without seriously impairing the efficiency of the motor. The method employed for cutting out shorted coils depends on the type of armature.

Cutting a Shorted Coil Out of a Loop-wound Armature Assuming that the shorted coil has been located, the next step is to cut the turns of the coil at the end of the armature opposite the commutator. Be sure that every turn in the coil is cut to prevent induced currents from circulating in the shorted coil and causing damage to other coils.

Cutting the coil will cause an open circuit in the winding. Since the bars that connect to the defective coil are known, the open can be repaired by connecting these bars together with a jumper. Figures 6-79, 6-80, and 6-81 show the circuits formed by this method for a loop, a lap, and a wave winding. Figure 6-82 is another view of Figure 6-81.

Another method of cutting out a coil consists of cutting the coil, as was just shown, and twisting together the turns of first one side and then the other. Make sure that the wires do not have any insulation on them before they are twisted. With this procedure it is not necessary to put a jumper on the commutator, nor is it necessary to touch the commutator for any reason.

These methods of cutting out coils are not strongly recommended because the coil may be located on the bottom of the slot and therefore very difficult to reach for cutting purposes. In addition, damage may be done to other coils in the process of cutting out the defective one.

Therefore, such methods are suggested only for extreme conditions when the time element or the need for a temporary repair makes them useful.

Cutting Out a Shorted Coil on a Medium-sized Lap Winding. On this type of armature it may be possible to reach the coil that must be cut, but it may be impossible to cut out only the defective coil. The procedure is exactly the same as in the case of the loop winding shown in Figure 6-79. In all these cutting operations, experience determines the proper procedure to be used. A beginner will have trouble in handling this assignment, but very little time will be required by an experienced man.

Cutting Out a Shorted Coil on a Wave-wound Armature. In a four-pole, wave-wound armature the leads of any coil are connected approximately on opposite sides of the commutator. Therefore, if a shorted coil is cut open it will be necessary to place a jumper between the two bars that were joined to the defective coil. This means that a jumper must be placed in bars on opposite sides of the commutator, as shown in Figures 6-81 and 6-82.

When a four-pole, wave-wound armature is given a bar-to-bar meter test, a shorted coil will be indicated on the meter on opposite sides of the commutator. This does not mean that two coils are shorted, but that the defective coil is in the circuit twice, since in a four-pole wave winding the current flows through two coils in series before reaching an adjacent bar.

Test for Open Circuits Open circuits in an armature may be caused by a poor connection of leads in the commutator bars or by a broken wire in an armature coil. In either case, such a condition will cause sparking at the brushes. Poor connections and broken wires can often be detected visually. When this is not possible other means must be used to locate the open.

Bar-to-bar Test. Set up the armature and test with the millivoltmeter across bars, as shown in Figure 6-83. No readings will be indicated on the meter until the meter leads are bridging the two bars to which the open coil is connected. At this point the meter needle will jump violently, and precautions must be taken to prevent it from bending or breaking.

Repair of an Open Coil of a Lap Winding. The method of repair of an open coil depends to a great extent on the time allotted for the repair, the type of armature that is being repaired, and the kind of work in which the particular shop specializes. Of course, if one or more coils are open, the proper procedure is replacement. Usually rewinding of the armature is necessary. The next best method is to jump the two commutator bars that test open by soldering a piece of wire into the slots of the two bars. The circuit formed is shown in Figure 6-84. This is the only method that can be used in many cases. Another way of jumping two adjacent bars is to scrape away some mica between them and wedge a piece of wire in the slot. The wire is then soldered to the bars.

Repairing an Open Coil of a Wave Winding. When a wave winding is tested with the meter, the procedure is the same as that used for the lap winding. Since each coil on a four-pole, wave-wound armature is connected to bars on opposite sides of the commutator, an open coil is jumped, as illustrated in Figure 6-85. A method which requires less effort and time, but which necessitates the removal of two coils instead of one, is often satisfactory. The procedure, shown in Figure 6-86, is to jump the two adjacent bars that test open. This does away with the long jumper from one side of the commutator to the other.

Growler Test for an Open Coil. To locate an open coil with a growler, set up the armature on the growler in the usual manner. Test the top two adjacent bars with an a-c millivoltmeter. Rotate the armature and continue testing adjacent bars. When the millivoltmeter bridges the two bars connected to the open coil, the meter pointer will not be deflected. All other bars will give a deflection. This test for an open coil can be made without the meter by shorting the top two bars with a piece of wire as shown in Figure 6-87. Absence of a spark indicates that the coil is open. The open may be either at the commutator bar or in the coil itself. This procedure may be used to determine the location of the leads of a shorted coil. However, the hacksaw blade test is the most satisfactory method of determining a shorted coil.

Test for Reversed Coils Reversed coils occur only on armatures that have been newly rewound, and result from placing the leads in the wrong commutator bars. The method of locating the reverses differs with the various types of windings.

BAR-TO-BAR TEST IN A LOOP WINDING. Set up the armature for a bar-to-bar test. When the meter leads are placed on the two bars which connect to a reversed coil, as shown in Figure 6-88, a reversed reading will be indicated on the meter. When the meter is placed on the two bars in front of the reversed coil and the two bars behind the reversed coil, double readings will show up. As Figure 6-89 illustrates, if two loops are reversed in a loop winding, a double reading is obtained; next a reversed reading; and then a second double reading. All others should be normal.

BAR-MAGNET TEST. To check for a reversed coil on other than loop windings, a bar magnet is moved over each slot, inducing current in the coil lying in that slot. If a meter is connected to the two bars of that coil, as shown in Figure 6-90, the pointer will move. If there is a reversed coil on the armature, the induced current will flow through the meter in the opposite direction and cause a reversed reading.

Another method is shown in Figure 6-91. If direct current is passed through the winding and a compass is held alongside each coil in succession, the compass needle will reverse when the compass reaches the reversed coil.

Commutator Repairs

The various parts of a commutator are shown in Figure 6-92. They include a number of commutator bars, an equal number of mica segments, and an iron core consisting of two end rings and a connecting shell on which the bars and mica segments are placed.

The commutator bars are made of high-grade copper and are shaped as shown in Figure 6-93. They are wedge-shaped, the larger width being on top. Toward the bottom, the bars are partly cut out on both sides in the shape of a V. Rings fit these V cuts to hold the commutator together. Individual commutator bars are seldom replaced because the job would be impracticable.

Mica segments are used between bars to prevent adjacent bars from touching, and it is very often necessary to replace them. The segments are cut from sheet mica of the proper thickness and are placed between the bars. When these are replaced, the segments must be the same thickness as the original mica; otherwise the commutator will be either too loose or too tight.

The end rings are made of iron and are called *V rings.* These are insulated with mica which are called mica V rings. The rings fit into the V cuts on the commutator and hold all the bars together. On one type of commutator the V rings are tightened against the bars by means of a large nut that screws on the shell. The nut may be on either end of the commutator. Details of commutator construction are shown in Figures 6-92 to 6-98. Some commutators are tightened by means of large screws that extend from one ring to another. Still other types of commutators are riveted together and cannot be reinsulated.

When a commutator is disassembled, the holding nut is unscrewed and the bars are tapped lightly with a hammer. This will cause the front V ring to come off the shell; at the same time the bars will loosen and separate. Usually the mica segments will stick to the bars, and it will be necessary to loosen them with a knife. Small particles of mica may have to be scraped from the bars, although this may cause rough spots. If so, a medium grade of sandpaper is used to smooth the sides of the bars. One complete mica segment must be preserved in order that its thickness can be measured with a micrometer. A segment of mica is usually from 0.020 to 0.040 in. thick. The mica comes in sheets about 2 ft. wide by 3 ft. long and is called *segment mica.* The mica end rings must also be saved so that they can be measured for thickness and used as templates for new mica rings.

Cutting New Mica Segments After the thickness of the mica has been determined, cut the required number of segments by placing a commutator bar on a sheet of mica and marking off rectangular strips, as shown in Figure 6-99. This may also be done by measuring the length and width of one bar and then laying off these measurements on the sheet of mica. As a safety measure, it is best to make the dimensions about $\frac{1}{32}$ in. more than the actual measurements. Next cut off the strips with a paper cutter or shears.

To cut the V's in the mica segments, proceed as shown in Figure 6-100. Place about six strips of mica between two bars, and place the combination in a vise, being careful to line up both bars so that they lie in similar positions. Use a hacksaw and cut out the mica along the dotted lines as shown in the illustration. Do not let the hacksaw blade touch the bars because it will cut too deeply into the mica and at the same time weaken the bars. Reverse the position of the bars and micas in the vise and cut out the other half. Do not disturb the position of the bars and strips in turning them.

The hacksaw blade will leave a rough edge on the mica. Smooth this with a knife file while the bars and strips are still in the vise. The mica should be filed down to the same level as the V's in the bars as shown in Figure 6-101; otherwise, the commutator will not tighten sufficiently. Remove the segments and bars, and place each mica segment face down on a piece of fine sandpaper and rub it lightly to remove any remaining rough edges. Repeat this process with the bars. This is just one method of cutting mica segments. Some mechanics cut one segment at a time with shears. The method depends on the individual.

Making New Mica V Rings Besides making new mica segments it may also be necessary to renew the mica V rings. The old rings may be used as a template for this purpose, or the iron V ring may be used.

In the first method, as much of the old mica ring as possible must be preserved. If the commutator has never been reinsulated, the ring will be in one piece. The V ring is actually two separate rings, an outer and an inner ring, that fit together as shown in Figure 6-102. To duplicate this ring, it is necessary to use a molding machine and press. Since this equipment is not usually available in the average repair shop, the outer and inner rings are made separately.

The method for making mica rings is as follows: Cut the original V ring along the line indicated in Figure 6-102, thereby separating the inner from the outer ring. Assume that the inner V ring is to be made. Cut the old ring, and then heat it over a gas flame or with a torch to soften it and prevent it from cracking. (Do not apply the flame directly to the mica.) The ring can then be laid flat and will assume a shape like that shown in Figure 6-103.

The flattened V ring is placed on a piece of molding mica, and several outlines of it are inscribed. These are then cut from the molding mica with a pair of shears. It may be necessary to apply heat to the mica during this operation to prevent it from peeling and cracking. (Molding mica that requires no heat is also available.) Heat the mica very gently and then mold with the fingers to fit the iron V ring. Make the thickness of the ring the same as the original. Several pieces of mica may have to be used to make up the required thickness. The same procedure is followed in making the outer ring.

A second method is to use the iron V ring as a template. Assuming that the outer mica ring is to be made, place a clean piece of paper over the ring and press on the paper, as shown in Figure 6-104, to form an outline whose dimensions will provide the size of the mica strip to be molded.

A third method involves the use of a formula. Figure 6-105 shows that a cut-apart V ring is the top portion of a cone. A simple procedure in laying out a V ring is to find the size of the cone which will contain the ring.

Make a diagram like that in Figure 6-105, showing a cone with the shaded part representing the ring. If the cone is cut through as indicated by the line and rolled flat, a sector of a ring will be found. If the distances x and y are determined and circles inscribed using these distances as radii, then the problem can be solved.

The procedure for finding these distances follows: Measure the distances A and B shown in Figure 6-106 on the iron V ring with a ruler. The cone can also be resolved into two triangles, R and S, which are alike except for size. A simple formula can be obtained from this relationship.

In two similar triangles,

$$\frac{a}{x} \text{ of triangle } R = \frac{b}{c} \text{ of triangle } S$$

or

$$\frac{a}{x} = \frac{b}{c} \quad \text{or} \quad x = \frac{a \times c}{b}$$

Using the distance x as a radius, draw a circle. Lay out another circle inside this one using the distance y equal to $x - c$ as the radius. The ring formed by these two circles will represent the layout of the V ring.

Reassembling a Commutator After the rings are made and the mica segments cut, the next step is to assemble the commutator.

This is done in the following manner: Place the mica rings in position on the iron V ring and apply heat to mold them to fit. Put a bar in position on the V ring. Alongside the bar place a mica segment, then a bar next to the segment, and so on. Make certain that there is a mica segment between every two bars. Be careful that the mica rings stay in position while the assembly is taking place. After all the bars and mica segments have been put together, place the top V ring in position and tighten the nut or through bolts. The tightening operation is performed while the commutator is being heated with a torch, Bunsen burner, or other source of heat.

The commutator must be tight and all bars aligned when the job is completed. If the bars are not in alignment, the commutator will have to be loosened and the bars twisted to the proper position. Some shops have clamps that are placed around the commutator while it is being tightened.

After the assembly, the commutator is given a ground and short test. To determine if the commutator is tight enough, tap the bars with a light hammer. A properly assembled commutator will produce a ringing sound, while a loose commutator will cause a hollow sound.

Shorted Bars If shorted bars occur in a newly insulated commutator that has not yet been connected to the coils, it is a simple matter to reinsulate between the bars. However, if they are connected to the winding, it will be more difficult. When a shorted armature comes into the shop, determine whether or not the short is in the winding or in the commutator by lifting the leads from the suspected bars. These bars are then tested with test lamps to see if they are shorted.

The usual procedure is to assume that there is a partial short due to carbonized mica or dirt between bars. To eliminate this possibility, grind down a hacksaw blade on the grindstone so that it has a hook end, as shown in Figure 6-107, and scrape away some of the mica. Sometimes it may be necessary to scrape rather deeply into the mica to remove the short. Carbonized mica is black and gritty, while good mica is white when scraped. Scrape the mica until the white mica can be seen. If this operation removes the short, then the hole which was made by the scraping must be plugged. This is accomplished by inserting a filler called *commutator cement,* which consists of powder made of pulverized mica and glue mixed to produce a paste. This filler is forced between the bars with a knife or blade and allowed to harden.

If a hole has been gouged in the mica, plug it with a new piece of mica and cover this with cement. This cement is a conductor while it is still wet and should not be disturbed until it dries thoroughly.

REINSULATING A SHORTED COMMUTATOR WHILE IT IS CONNECTED TO THE WINDING. If the short cannot be eliminated by scraping the mica, remove several bars and put new mica segments in place. This is done in the following manner on a commutator that can be taken apart from the front end:

Unsolder the leads from the shorted bars. Unscrew the nut that holds the commutator together. Tap the bars lightly with a hammer to loosen the end ring and several bars. Remove the end ring and pull out the shorted bars with a pair of pliers, as shown in Figure 6-108. Use these bars to cut out a new mica segment. Replace the new mica and bars and reassemble.

If there is only one short and the commutator opens at the rear, an easy repair is to lift the leads from one bar and make sure they are soldered together and taped so that they cannot touch the commutator. Jump the two shorted bars. The circuit of this operation is shown in Figure 6-109. Another method consists of lifting the leads of the coil connected to the shorted bars and taping them individually. The shorted bars are jumped. This eliminates one coil from the winding. For other types of commutators, removal of the entire commutator from the shaft may be necessary.

Grounded Bars Usually the ground takes place at the front mica ring. This occurs because part of the front ring is exposed, allowing oil, grit, or dirt to accumulate on it. The ground is easily detected since usually a large hole will have developed and part of the mica ring will have been burned away at the grounded spot. The best way to clear this is to remove the front ring, cut off the defective part of the mica ring, and replace it as indicated in Figure 6-110. New mica segments may have to be installed at the same time. Make sure that the mica pieces overlap one another to prevent the possibility of a recurrence of the ground. If the commutator does not open at the front, it is removed by placing the armature in a mandrel or hydraulic press and pressed out. When it is impossible to remove the commutator without harming the winding, the old commutator is turned down completely in the lathe. Commutator measurements must be recorded beforehand so that a new commutator can be built. This is often done on smaller armatures. When the new commutator is constructed, it is desirable to put a cord band on the front mica ring and paint it with a good grade of insulating varnish or shellac. To a large extent, this will keep oil and dirt from penetrating under the bars and causing shorts and grounds.

High Bars High bars, such as shown in Figure 6-111, can be found by running the fingers over the bars. This condition is caused by loosening of the commutator due to excessive heat, shorted bars, poor assembly, and so on. To remedy this condition, tap the bar lightly with a hammer until it assumes the correct position, and then tighten the nut. Turn down the commutator in a lathe, or stone it if it is in a motor.

COMMUTATOR STONES. Commutator stones, made in various grades of coarseness, are used to smooth a rough commutator. The coarser grades are used on very rough commutators and the finer grades for finishing purposes and on commutators that are not extremely rough. For high commutator bars a medium grade should be used. While the armature is turning, the stone is held in the hand and pressed against the commutator until a smooth surface is formed. Then a fine grade of sandpaper is held against the commutator to finish the job.

Low Bars A low bar, as shown in Figure 6-112, is also recognized by running the fingers over the commutator. This condition may be caused by a blow from some heavy object. The remedy is the same as before: turn down in a lathe, stone, and then sandpaper the commutator.

High Mica If the mica segments are higher than the adjoining commutator bars, a condition called *high mica* exists. This condition may be due to the fact that the commutator bars are wearing faster than the mica segments and may be caused by the use of improper carbon brushes. Where the mica is flush with the bars, a hard grade of brush should be used so that it will wear away the mica at the same rate as the bar.

The remedy for this condition is to undercut the mica so that it is below the surface of the bars. This operation can be performed by using a machine consisting of a small electric motor with a small saw wheel attached. While the armature is in a lathe, a cut is taken on each mica segment so that it is about $\frac{1}{32}$ in. below the surface of the bar. The saw wheel must be the same thickness as the mica. Undercutting can also be done by utilizing a small file especially made for the purpose. Care must be taken to ensure that none of the mica is left on the sides of the bars, as shown at the right of Figure 6-113. If there is mica at the sides, it can easily be removed by cutting it away with a ground-down hacksaw blade. Figure 6-114 illustrates how a mica undercutter is used for a fractional horsepower motor.

CHAPTER 7

Direct-current Motors

A d-c motor is a machine which, when supplied with electric current, can be used for such mechanical work as driving pumps, running machine tools, and so on. Direct-current motors are also widely used in applications that require control of speed. Some of these are printing presses, electric trains, elevators, and drives. Direct-current motors are made in sizes varying from $\frac{1}{100}$ h.p. to thousands of horsepower. A typical d-c motor is shown in Figure 7-1.

Construction

The main parts of the d-c motor are the armature, field poles and frame, end plates or brackets, and brush rigging. The armature is the rotating part of the motor and consists of a laminated steel core with slots in which coils of wire are placed. The core is pressed on a steel shaft that also holds the commutator. This latter conducts current from carbon brushes to the coils in the slots. Figure 7-2 shows an armature with straight slots, and Figure 7-3 shows skewed slots.

The frame of the d-c motor is made of steel or cast iron, generally circular in form and machined so that the field pole can be mounted inside it, as shown in Figure 7-4. Many motors are also made with a laminated steel frame. The field pole is usually fastened inside the frame with screws or bolts, but on some small motors the field poles are part of the frame. On large motors, the poles are laminated as shown in Figure 7-5 and bolted to the frame. The field pole holds the field coils or windings. These consist of coils of insulated wire that are taped before being placed on the field pole.

Two end plates, fastened to the frame with bolts, bear the weight of the armature and keep it equidistant from the pole pieces (see Figure 7-6). The end plates contain the bearings in which the shaft of the armature revolves. These may be either sleeve bearings, as shown in Figures 7-7 and 7-8, or ball bearings, as shown in Figure 7-9.

On all d-c motors, current must be conducted to the armature winding. This is accomplished by connecting leads from the winding to the commutator, and in turn feeding the commutator with current. The commutator can be supplied with current by allowing carbon brushes to ride on it and contact it while it is turning. The brushes are held in a stationary position by brush holders, which are generally mounted on the brush rigging shown in Figure 7-10. The rigging is usually mounted on the front plate and so constructed that the brush position may be changed. On small motors, the brush holders are usually cast as part of the plate. The brush holders on all motors are insulated from the end plate to prevent grounds and to prevent short-circuiting the brushes.

Types of D-C Motors

There are three types of d-c motors: the series motor, the shunt motor, and the compound motor. These types are alike externally. They differ in the construction of the field coils and in the connections between the field coils and the armature. The series motor contains field coils composed of a few turns of wire connected in series with the armature as shown in Figure 7-11. This motor has high starting torque and a variable-speed characteristic. The greater the load the lower the speed. The series motor is generally used in cranes, winches, trains, and so on.

The d-c shunt motor contains a field composed of many turns of wire. This is connected in parallel with the armature, as shown in Figure 7-12. The motor has medium torque and constant-speed characteristic and is used on applications that require constant speed, such as drill presses, lathes, and so on. Shunt motors may have a light series field added and are called *stabilized shunt motors.* A stabilized shunt motor is a d-c motor in which the shunt field is connected in parallel with the armature circuit and which also has a light series field added to prevent a rise in speed or to obtain a slight reduction in speed with increase in load. These motors are connected like a compound motor.

In the compound d-c motor shown in Figure 7-13, each field coil is a combination of the series and shunt fields and is made in two sections. One section (series field) is connected in series with the armature, and the other section (shunt field) is connected in the shunt circuit. This motor combines the characteristics of the series and the shunt motor.

Construction of the Field Coils

Series field coils are wound with comparatively few turns of heavy wire whose diameter depends on the horsepower and voltage of the motor. The wire can be wound on a wooden form that consists of a centerpiece the size of the coil and two sidepieces to hold the coil in place. The construction of the form is given in Figure 7-14(a). The centerpiece is usually slightly tapered to facilitate removal of the coil from the form. The proper shape of the coil is retained during its removal from the form if strips of tape or cord are placed on the centerpiece before the coil is wound. It can then be tied up easily after winding, as shown in Figure 7-15. The form is placed in a lathe chuck or coil-winding machine and wound with the same number of turns and the same size of wire as the original coil. The size of the form may be obtained from the original coil or by measuring the dimensions of the core and allowing for the thickness of the tape. Figure 7-16 shows a field after it has been taped with a layer of varnished cambric and a layer of cotton tape. Field coils can also be wound on a coil winder head, as shown in Figure 7-14(b).

Shunt fields consist of many turns of fine wire arranged as shown in the cutaway view of Figure 7-17. Inasmuch as there may be thousands of turns on a shunt-field coil, it is inadvisable to try to rewind this type of coil by counting the number of turns. The usual method is to weigh the old coil and to wind the new coil with the same weight and size of wire. The shunt coils are wound and taped in the same manner as the series fields. Figure 7-17 also shows a finished coil.

The compound-field coil is a combination of a series field and a shunt field, as illustrated in Figure 7-18. The same type of form is used for the compound field coils. First, the shunt-field portion is wound on the form. This must correspond to the original coil in every detail. To form the layer of insulation shown in Figure 7-19, several turns of varnished cambric are placed around the coil while it is still in the form, or the coil is removed and taped with varnished cambric. In the latter case, the coil is replaced on the form after being taped. Next, the correct number of turns of wire for the series coil is wound. The cord on top of the insulation or tape is then tied and flexible leads are soldered to the coil ends and taped. This is an important operation and must be done carefully. Usually the shunt-field leads are smaller size of wire than the series-field leads. The coil is taped with varnished cambric and then with a layer of cotton tape. The completed winding is shown in Figure 7-20. Figure 7-21 illustrates how a field coil is placed on the field core. On large motors, the series field is usually wound and taped separately and then placed alongside the finished shunt field. This type of construction is shown in Figure 7-22. On very large motors rectangular wire is used on the series field to conserve space.

An interpole field is used on many d-c motors to prevent sparking at the brushes. This field is smaller than the main fields and is attached to the frame between them. Like the series field, it is wound on a form, usually fiber, with comparatively few turns of heavy wire. Figure 7-23 shows an interpole field and its core. The fiber form and coil are placed over the interpole core and fastened in position by wedges.

Caution. The shunt field must be properly insulated from the series field to prevent short circuits between fields.

While taping the field coil, tie down the flexible leads to prevent them from being ripped from the coils. The tape on the coil must not tear or rip while it is being placed on the core. Grounds may be caused by careless work.

Connecting Field Poles

In d-c motors, the field coils are connected so that alternate polarity is formed. Thus, in the two-pole motor of Figure 7-24, one of the poles is north and the other is south; in a four-pole motor, the poles must alternate, as shown in Figure 7-25. The field poles are connected in series except on very large motors and on motors that have been reconnected from higher to lower voltage.

To form alternate polarity in the field coils, the current should flow through the first pole in a clockwise direction, through the second pole in a counterclockwise direction, through the third clockwise, and so on. It is extremely difficult to determine this direction if the fields are taped, and three methods may be used to obtain correct field coil polarity. These are (1) trial and error, (2) compass, (3) use of iron rod or nail.

The trial-and-error method should be used only on small two-pole motors. The field coils are connected as shown at *A* in Figure 7-26 and the motor assembled. If it does not rotate, reverse the two wires of one field coil as shown at *B*, and the motor will run. This method assumes that the armature and field coils are in good condition. The shunt motor can be tested in the same manner.

The compass method may be used on any number of poles. If it is a compound motor, test one field winding at a time. For testing the field coils of a four-pole motor, the four fields are connected in series, as shown in Figure 7-27. Low-voltage direct current is applied to the fields if the series fields are being tested; otherwise, 115 volts can be used. A compass is placed near a pole on the inside of the motor or alongside the field coil as shown in the illustration. A notation is made of which end of the needle points to the pole. When the compass is moved to the next pole, the other end of the needle should be attracted. If the same end of the needle is attracted, reverse the leads of this pole. This procedure is followed until all poles have been checked. The fields should alternate in polarity.

The procedure outlined above cannot be followed if the armature is in the motor. In this case one end of a piece of soft iron is held against the field pole, with the other end extending outside the motor. To test for polarity, hold the compass against the outside end of the soft iron. Before it is touched to the next pole, the soft iron should be brought down sharply on the bench to disturb any residual magnetism which might tend to upset the compass needle. Continue in this manner until all poles are tested. As before, alternate polarity should be obtained.

A third method of testing polarity is to use an iron rod or nail. The field coils are connected in series and supplied with low-voltage direct current. The head of a nail is placed against one pole, as shown in Figure 7-28. If the polarities are correct, the other end of the nail is attracted to the next pole; if incorrect, it is repelled.

Connecting D-C Motors

Series Motor

The series motor is connected as shown in Figure 7-29. This is a two-pole series motor. The fields are connected in series and then in series with the armature. Three diagrams clarify.

Shunt Motor

The shunt motor is connected as shown in Figure 7-30. The shunt fields are connected in series for alternate polarity and across the line leads. The armature leads are also connected to the line so that the armature and the fields are in parallel.

Compound Motor

The compound motor is connected as shown in Figure 7-31. The shunt fields are connected in series for proper polarity and then across the line. The series fields are connected and tested for proper polarity. It is of the utmost importance that the polarity of the series field correspond to that of the shunt field on the same pole. A method that accurately determines this condition is described on page 213. The armature connection completes the procedure.

The motor shown in Figure 7-31 is one of *four different types of compound motors.* Although this connection is the one used most often and the one which should be used unless otherwise specified, it is essential that the other types be familiar to the student. The four types are long-shunt cumulative, long-shunt differential, short-shunt cumulative, short-shunt differential.

In a long-shunt cumulative motor, the current flows through the series-field and shunt-field coils of a pole in the same direction. This is indicated in Figure 7-32. Such a motor is said to be *cumulatively compounded.* When the shunt field is connected across the line, it is given the name of *long shunt.* The complete name of the motor is a *long-shunt cumulative motor.*

If the shunt-field connection of a compound motor is reversed with respect to the series field, the current will flow through it in the opposite direction. This is shown in Figure 7-33. This produces bucking fields and the motor is known as a *differentially connected motor*. Motors of this type are used infrequently and only on special work.

A *long-shunt differential motor* is defined as one in which the shunt field is connected across the line so that the series and the shunt fields have opposite polarity in the same pole.

When the shunt field of a compound motor is connected to the armature terminals instead of across the line, the motor is known as a *short-shunt motor*. This motor can also be either cumulative or differential.

If the shunt field is connected across the armature so that the current flows through it in the same direction as the series field, the motor is known as a *short-shunt cumulative motor*. This type is shown in Figure 7-34.

If the shunt field is connected to the armature so that the current flows through it in the opposite direction to the current in the series field, the motor is known as a *short-shunt differential*. This type is shown in Figure 7-35.

Interpoles

Nearly all shunt and compound motors of ½ h.p. or more have commutating poles or interpoles located between the main poles. These interpoles have one winding of heavy wire and are connected in series with the armature, as shown in Figure 7-36. The purpose of the interpole is to prevent sparking.

There are usually as many interpoles as main poles, although half as many may be used without causing inefficient operation. Although the interpoles are connected for alternate polarity, just as the main poles, they also have a definite polarity with respect to the main poles. The polarity of the interpoles depends on the polarity of the main poles and the direction of rotation of the motor.

Rule for Interpole Polarity The polarity of an interpole in a motor is the same as the main pole behind it. This means that if a motor viewed from the commutator end is rotating clockwise, the polarity of the interpole must be the same as that of the main pole which precedes it in the direction opposite to rotation. Figures 7-37 to 7-39 show two- and four-pole interpole motors connected for counterclockwise and clockwise rotation.

Figure 7-40 shows a schematic diagram of a compound-interpole motor.

A two-pole, compound-interpole motor connected for counterclockwise rotation is shown in Figure 7-41. The procedure for connecting this motor follows: Connect the shunt-field coils in series for proper polarity and bring the two lead wires out of the motor. Note the polarity of one pole. Perform the same operation for the series field coils, and bring two wires out. Connect the interpoles in series for alternate polarity; then connect them in series with the armature, bringing out one interpole lead and one armature lead. Six leads have been brought out of the motor, two shunt-field leads, two series-field leads, and two armature-interpole leads. (Sometimes one shunt-field and one series-field wire are connected together inside the motor and one lead from the two brought out, making a total of five out of the motor.) Connect the six leads as shown in Figure 7-41 so that a compound motor results.

Since the motor is to be connected for counterclockwise rotation, the interpole polarity should be the same as that of the main pole behind it. Therefore, in testing the interpoles for polarity, make sure that not only is alternate polarity formed but that the polarity is correct with respect to the main pole. This is the reason for noting the polarity of one main field.

If the motor runs in a clockwise direction, it will be necessary to reverse the direction of rotation. This is done by reversing wires x and y shown in Figure 7-42. The polarities of all the fields remain the same. See page 214, Test for Correct Interpole Polarity.

Reversing D-C Motors

Direct-current motors are reversed by changing the direction of current flow through the armature or through the field. In series motors the usual procedure is to reverse the current through the armature. Figure 7-43 shows this method. All that is necessary is to interchange the leads on the brush holders. Figure 7-44 shows the series motor reversed by changing the current in the field circuit. In this case the field leads are interchanged.

A shunt motor has the direction of rotation changed in the same manner as a series motor. Figure 7-45 shows a two-pole shunt motor which is reversed by interchanging the armature leads. To reverse a shunt-interpole motor, it is necessary to reverse the current flow through both the armature and the interpoles as a unit. This method is shown in Figure 7-46. Reversing the armature leads without the interpole will cause the motor to have incorrect interpole polarity, which will make the motor run excessively hot and will produce sparking at the brushes.

Reversing a Two-pole, Compound-interpole Motor Figure 7-47 shows a two-pole, compound-interpole motor with six leads brought out of the motor. The interpoles are connected in series with the armature, and two wires A_1 and A_2, are brought out from this as a unit. In the diagram, the armature is connected between the interpoles. (The interpoles are sometimes connected in series and then connected to the armature.) To reverse this motor, it is necessary to reverse the interpole and armature circuit as a unit. Wires A_1 and A_2 must be reversed as indicated in Figure 7-48.

Reversing a Four-pole, Compound-interpole Motor A four-pole, compound-interpole motor is reversed in the same manner as a two-pole motor. Figure 7-49 shows a four-pole motor which is reversed by interchanging leads A_1 and A_2.

Caution. If the leads at the brush holder are reversed, the brushes will spark and the armature will overheat. Under these conditions the motor will not operate properly. On all interpole motors, the armature circuit (armature and interpole) must be reversed as a unit for opposite rotation.

Troubleshooting and Repair

Testing

A new d-c motor should be tested before it is installed, and the same tests can be performed when the condition of a motor on the job is being determined and when a repaired motor is being given a final check. Proceed as follows:

1. Test for grounds in the fields, armature, and brush holders.
2. Test for opens in the field circuit, in the armature circuit.

3. Test to identify the six leads of a compound motor.
4. Test for cumulative or differential connection.
5. Test for correct interpole polarity.
6. Test for correct position of the brush holders.

1. *Ground Test* Before a motor can be given a ground test, all external leads must be disconnected from it. This applies especially to a motor that is being tested on the job. The following procedure applies to a compound motor, but any type of d-c motor is tested in the same manner: Use a test set with a lamp and place one test lead on the frame of the motor; with the other test lead touch each motor lead in succession, as shown in Figure 7-50. The test lamp should not light. If it does, a ground is indicated. Determine whether the ground is in the field circuit (the shunt or series field) or in the armature circuit.

If a ground is indicated on the series fields, the interpole, or the shunt fields, it will be necessary to remove the fields from the frame and reinsulate them with tape. Figure 7-51 shows positions where grounds are most likely to occur. A grounded field coil may be burned and several wires broken, necessitating rewinding of the field. A grounded field circuit does not mean that all the field coils are grounded. Usually only one is defective. To locate the defective coil the connections between coils are broken and each pole is tested alone as shown in Figure 7-52.

Motors that are permanently installed are required by the Electrical Code regulations to have the frame grounded to a pipeline that connects to the earth. This is a safety measure in case the windings ground. If the frame is not grounded, the operator might receive a serious shock when touching the motor. With the frame grounded, a fuse will burn out and indicate that something is wrong with the motor.

2. *Test for Opens* Different tests are used for the series, shunt, and compound motors.

2a. OPEN CIRCUITS IN A SERIES MOTOR. On small series motors only two wires are brought out of the motor for connection to the line. The field and armature connections are made internally. If the two wires are connected to the test leads, as shown in Figure 7-53, the lamp should light and indicate a complete circuit. If the lamp does not light, the trouble may be caused by (1) brushes not making contact with the commutator; (2) a broken wire in the field; (3) a broken connection between fields; (4) a wire disconnected or broken on the brush holder. The same test may be used on large series motors with external leads to field and armature.

2b. Open Circuits in a Shunt Motor. There are two circuits in a shunt motor, one through the shunt field and one through the armature. On small motors the connections are made internally and only two wires are brought out. Therefore, to test such a motor for opens, it must be disassembled in order to reach the field and armature wires.

If the wires are accessible, as indicated in Figure 7-54, test each circuit separately. The lamp should light brightly when the armature circuit is tested. The shunt field should produce a dim light. If it is not known which of the four wires is the shunt field and which is the armature, they can be determined by this test. If the armature circuit shows an open, the trouble may be the brushes, the connections to the brushes, or the armature windings; if the field tests open, then the trouble is either the field coil or its connections.

2c. Open Circuits in a Compound Motor. For testing purposes the compound motor is considered as having three circuits, one through the shunt field, one through the series field, and one through the armature. Figure 7-55 shows six leads brought out of a compound motor, two from the shunt field, two from the series field, and two from the armature. If the armature leads are tested with the test lamp, the lamp should light, indicating a complete circuit. The same holds true for the series-field circuit and the shunt-field circuit. Thus, three complete circuits are formed. If the open is in the armature circuit, the trouble is in the brushes or connections to the brushes or the interpole. If the trouble is in the series or shunt field, test for a complete circuit from one coil to another, as shown in Figure 7-56.

The following procedure is used to locate an open field coil on the four-pole motor, as illustrated in Figure 7-56. This method can be applied to a motor with any number of poles. Remove the insulation on connections between field coils, and connect a test wire to one field lead. Move the other test wire successively from one connection to the next until the lamp lights. In Figure 7-56 for example, move the test lead from *1* to *2*, to *3*, and so on, until the lamp lights or a spark is obtained. If the lamp lights or the test lead sparks at point 2, then coil *1* is open; if the lamp lights at point *3*, then coil *2* is defective, and so on.

3. *Test to Identify the Six Leads of a Compound Motor* The leads of a compound motor are always marked before it is shipped from the factory. Typical markings are shown in Figure 7-57. The armature leads are marked A_1 and A_2, the shunt-field leads F_1 and F_2, and the series-field leads S_1 and S_2. If the lead markings have disappeared, it is necessary to test the six leads for remarking before the motor can be properly connected. They can be identified in the following manner:

Use the test lamps, as shown in Figure 7-58, to determine the three circuits of the armature, the series field, and the shunt field. Three pairs of leads are obtained from the procedure. One pair of leads will cause the test lamp to light dimly. These connect to the shunt field. Both of the remaining pairs will cause the lamp to light brightly.

Remove the carbon brushes and the lamp will not light when applied to one pair. These leads connect to the armature. The remaining pair are the series-field leads. This procedure is illustrated in Figure 7-58.

This is but one way of identifying the leads. There are many other methods: for example, the motor may be taken apart and the leads traced. This *must* be done on a five-lead compound motor. Sometimes the shunt-field leads can be immediately identified by the fact that they have a thinner lead wire than the others. The armature wires can occasionally be traced directly to the brush holder, thus eliminating this circuit. Common sense and a knowledge of circuits are essential in this kind of testing.

4. *Test for Cumulative or Differential Connection* Compound motors are almost always connected for cumulative operation. This connection is sometimes impossible to determine unless the motor is tested when it is disconnected from the load. Test in the following manner: Connect the leads to produce a compound motor, as shown in Figure 7-59, and operate it from a d-c source. Note the direction of rotation. Stop the motor and disconnect one shunt-field lead, thereby changing it to a series motor. Run the motor for an instant and note the direction of rotation. If the direction of rotation is the same in both cases, the motor is cumulatively connected. If it runs in the opposite direction after the shunt field is disconnected, it is connected differentially. If it is

desired to connect it cumulatively and this test proves it to be connected differentially, reverse either the shunt-field leads or the series-field leads. Quite often this test is performed by connecting the leads to produce a compound motor as described above and shorting out the series field before running it to note the direction of rotation. This is done to avoid an error in case of a large inrush of current. The rest of the test is as explained above, except that the short is removed from the series field.

5. *Test for Correct Interpole Polarity* The compass cannot often be used in checking the interpoles on a job, especially if the armature cannot be removed from the motor. The following method may be used on motors in which the brush holder can be shifted from one position to another. No compass is needed, nor is it necessary to remove the armature from the motor.

Connect the line leads to the armature and interpole circuit. Disconnect all other wires. Mark the positions of the brushes and shift the brush holder so that the brushes are halfway between the marks. This is shown in Figures 7-60 and 7-61. Turn on the current for an instant and note the direction of rotation of the armature. If the armature turns in the same direction as the brushes are shifted, the polarity of the interpoles is right. If it rotates in the opposite direction, the polarity is wrong and the interpole connections must be reversed. To make this test, the brushes can be shifted either clockwise or counterclockwise. After the test has been made, shift the brushes back to their original position. The shunt-field leads are then connected and the motor operated as a shunt-interpole motor for the direction in which the motor is to run. If the motor rotates in the proper direction, disconnect the shunt field and connect the series field in the circuit so that it runs as a series-interpole motor in the same direction as before. A low voltage must be applied. Now reconnect the shunt field. Remember that the interpole and armature as a unit are used for reversing purposes.

6. *Test for Correct Position of Brush Holder* The number of carbon brushes riding on the commutator depends on the number of poles in the motor. A two-pole motor has two brushes, a four-pole motor has four brushes, etc. These brushes must be equally spaced around the commutator and must be located in the correct position. Each brush must contact at least two bars at a time.

In doing so, the brush short circuits the coil connected to these bars.

If an armature coil cuts magnetic lines of force, current will be induced into the coil. If this coil is shorted by the brushes, the induced current will burn it out or produce considerable sparking. There is one place on a motor where the coil will cut comparatively few lines of force, and this point is between the main field poles. If a coil is shorted by the brushes when it is at this point, the coil cannot burn out because current is not being induced into it. Therefore, the brushes must be placed in such a position as to short circuit an armature coil while it is midway between poles or at this neutral point.

To locate the brushes properly, proceed as follows: Assume a two-pole interpole motor, although the method applies to motors having any number of poles. The entire procedure takes place while the motor is assembled. Mark one armature coil slot with chalk and trace its leads to the commutator. Turn the armature in the motor so that the marked slot is under the interpole. With the armature held in this position, move the brush holder so that one brush is over the commutator bars connected to the coil. Fix the brush holder in this position.

Run the motor for a short time with the brushes in this position. Then shift the brushes back and forth very slowly and notice whether the motor runs more quietly or without any sparking. The location of the brushes one bar away from the determined position may cause better operation; if so, leave the brushes in the new position. Practice and experience will enable the repairman to locate the exact position.

A popular method of determining the proper brush position consists in spacing the leads of a low-reading voltmeter to contact adjacent commutator bars. The motor is operated and the leads are moved back and forth until no reading is visible on the voltmeter. This position is the correct neutral point. The brush holder is then moved so that a brush is in this position.

Several more ways to set brushes on neutral are:

1. To put normal current in the armature and interpole circuit without any field current. When the brushes are in neutral, the armature will not turn.

2. To use a field kick, that is, put a voltmeter across the brushes;

then apply current to the field only and note the kick on the voltmeter. In neutral position the kick will be zero or minimum.

3. To run the motor (loaded) in both directions; in neutral position the speeds should be identical.

Repairs

The symptoms encountered in defective d-c motors are given below. Under each symptom are listed the possible troubles. The numbers in parentheses after each trouble indicate the correspondingly numbered remedies to be found in the following pages.

1. If the motor fails to run when the switch is turned on, the trouble may be:
- **a.** Open fuse or protective device (1)
- **b.** Dirty or clogged brushes (2)
- **c.** Open armature circuit (3)
- **d.** Open field circuit (4)
- **e.** Shorted or grounded field (5)
- **f.** Shorted armature or commutator (6)
- **g.** Worn bearings (7)
- **h.** Grounded brush holder (8)
- **i.** Overload (9)
- **j.** Defective controller (10).

2. If the motor runs slowly, the trouble may be:
- **a.** Shorted armature or commutator (6)
- **b.** Worn bearings (7)
- **c.** Open armature coils (11)
- **d.** Brushes set off-neutral (12)
- **e.** Overload (9)
- **f.** Wrong voltage (13).

3. If the motor runs faster than name-plate speed, the trouble may be:
- **a.** Open shunt-field circuit (14)
- **b.** Series motor running without a load (15)
- **c.** Shorted or grounded field (5)
- **d.** Differential connection in a compound motor (16).

4. If the motor sparks, the trouble may be:
- **a.** Poor brush contact on the commutator (17)
- **b.** Dirty commutator (17)
- **c.** Open circuit in the armature (3), (11)
- **d.** Wrong interpole polarity (19)
- **e.** Shorted or grounded field (5)
- **f.** Reversed armature leads (22)
- **g.** Wrong lead swing (18)

h. Brushes set off-neutral (12), (18)
i. Open field circuit (4)
j. High or low bars (20)
k. High mica (21)
l. Unbalanced armature (24).

5. If the motor is noisy in operation, the trouble may be:
   a. Worn bearings (7)
   b. High or low bars (20)
   c. Rough commutator (17)
   d. Unbalanced armature (24).
6. If the motor runs hot, the trouble may be:
   a. Overload (9)
   b. Sparking (17), (11), and Section 4 above
   c. Tight bearings (23)
   d. Shorted coils (5), (6)
   e. Too much brush pressure.

(1) *Open Fuse or Protective Device* Tests for a burned-out fuse have been described in previous chapters. The following notes will also be of value.

Some types of cartridge fuse can be taken apart and a new fuse wire inserted. Plug fuses are constructed so that by looking at the mica window it can be easily determined whether or not the fuse is good. The fuses can be tested without removing them from their cutouts. This is done by first connecting a lamp across the line, before the current goes through the fuses. Next the test lamp is brought to the other side of the fuses; if no light is obtained, one or both fuses are blown Breakers can be snapped back into the on position. Overload protectors on starters can be reset.

(2) *Dirty or Clogged Brushes* Carbon brushes should press against the commutator with a pressure usually between 1 and 2 lb. per sq. in. of surface. This pressure is applied by means of a spring, which is generally located behind the brush. For the spring action to be effective, the brush must be free to move in the brush holder. However, there must be as little space as possible between the brush and the brush holder. If too much room is allowed, the brushes will chatter while the armature is turning.

If the brush becomes so jammed in its mounting as to render the spring useless, the brush will not press on the commutator. Current will therefore be kept from flowing through the commutator and the winding and will produce, in effect, an open in the armature circuit.

The brush holders should be no more than $\frac{1}{16}$ in. above the commutator; otherwise the brushes will chatter while the armature is turning. Figure 7-62 shows various positions of a brush. The proper distance can usually be regulated by means of a setscrew. It is also important that the brushes fit the curvature of the commutator. This is done by placing a strip of sandpaper over the commutator with the rough side against the brush and moving the sandpaper back and forth while pressure is applied to the brush.

(3) *Open Armature Circuit* An open armature circuit may result from numerous causes, such as (a) poor brush contact, (b) a broken wire leading to the brush holder, (c) a defective connection between the interpole and the armature, (d) a broken interpole wire, (e) two or more open coils in the armature, or (f) a dirty commutator. These faults are located either by visual inspection or by means of test lamps. Some of these troubles are illustrated in Figure 7-63. If there are open coils in the armature, repair by rewinding or by bridging commutator bars.

A dirty commutator should be cleaned with a dry cloth and then sandpapered. If the commutator is undercut, the dirt between the bars should be scraped out with hacksaw blades ground to fit into the slot.

(4) *Open Field Circuit* Open circuits in either the series or shunt fields will prevent the motor from starting; but if a shunt-field coil opens while the motor is running, it may cause the motor to "run away" if the motor is not fully loaded. On compound fields, a short circuit often takes place between the series and the shunt coils, causing the wires to burn and open-circuit. Figure 7-64 shows several places where opens may occur. Sometimes the opens take place in the leads connecting to the fields. These leads are broken off easily if they are not tied securely to the coil. The open may also be in the lead extending out of the motor or be due to a poor connection of the field poles. It is located either by inspection or by testing.

To repair an open field, remove it from the core and unwind or cut away the tape covering. If the break is on the top layer of the coil, remove the few turns and then attach the lead to this point. A few turns less on the coil will have no harmful effect on the operation of the moton. If many turns must be removed, splice new wire at the break and add the same number of turns to the coil as are removed. Occasionally the break may be one in which the two ends of the wire can be spliced without removing any turns. If the break cannot be located, rewind the entire coil.

(5) *Shorted or Grounded Field* A shorted field coil will either cause a fuse to burn out or produce a weak magnetic field that will not turn the armature. A completely burned field can be found by visual inspection, but a shorted field can be detected only by testing. Often a shorted field may cause the motor to run faster than normal and spark badly if no load is applied.

Three ways to test for a shorted field are (a) resistance measurement test with an ohmmeter, (b) drop-in-voltage test, and (c) transformer test.

RESISTANCE MEASUREMENT TEST WITH AN OHMMETER. Since all field coils in a given motor are alike, the resistance should be the same for each. Figure 7-65 shows the test circuit. The resistance of each coil is checked with an ohmmeter, and if the reading is lower on one field than on the other, a short is indicated. The shorted coil must be rewound.

DROP-IN-VOLTAGE TEST. If the field coils of a four-pole motor are connected in series to a 120-volt line, each coil will receive one-fourth of 120 volts, or 30 volts. Therefore, if the voltage across each coil is measured with a voltmeter, as shown in Figure 7-66, the reading should be 30 volts. The usual method of expressing this is to say that there is a 30-volt drop across the coil. If one field coil has a lower voltage drop than the others, a short is indicated.

TRANSFORMER TEST. Small field coils are tested as shown in Figure 7-67. The transformer consists of a laminated iron core, with a coil around one end. The field coil is placed over the iron core so that it rests on the transformer coil and 115 volts of alternating current is applied to the transformer. If the field coil is shorted, current will be induced into it and cause it to be repelled from the transformer coil. The field coil will jump upward if many turns are shorted.

Another method of detecting a shorted field coil is to connect the field-coil circuit to the line for a few minutes. Normally, all the field coils should become warm; if a coil feels cool, it is the shorted one.

One grounded coil will have no effect on the performance of a motor other than to cause a shock if touched. Two separate grounds in the motor are equivalent to a short and may cause a fuse to burn out. If the frame of the motor is grounded according to the Electrical Code, one grounded field may blow a fuse. Repair of a grounded coil involves reinsulating and retaping the grounded part. Care must be exercised in this operation since some of the turns may have become open or badly burned. Be sure that the grounded area is carefully gone over.

(6) *Shorted Armature or Commutator* If there are many shorted coils in an armature, or if more than one coil is grounded, the armature may not rotate. In some motors, the armature will revolve a half turn

or turn over very slowly. To test for shorted coils, place the armature on the growler and test with a hacksaw blade. Before doing so, however, clean the mica between the bars of the commutator to eliminate this as the possible cause of the shorts.

A shorted armature coil manifests itself by heating and smoking. Smoke issuing from a motor is nearly always a sign of shorted or burned coils. Sometimes the smoke is pronounced and at other times it is hardly noticeable. The odor of burning coils is quite evident. If this condition is allowed to exist for a short time, adjacent coils will be harmed. On the other hand, if it is caught in time, the winding may be saved. Whenever smoke is seen issuing from a motor, turn off the current and then locate the defective coil by feeling the armature for the hot coil. Cut it out of the circuit as explained in Chapter 6.

If the shorted coil is due to shorted bars, lift the wires from *one* of these bars, solder the wires together and tape them. Next solder across the top of the shorted bars. If the motor runs without smoking, the coil need not be cut through. If the coil smokes, this will be necessary. Shorted bars can nearly always be identified by discoloration due to the heat.

(7) *Worn Bearings* If the bearings are so worn that the armature rests on the field poles, the armature probably will not rotate. If it does, it will be noisy in operation. Try to move the armature shaft up and down to detect this condition as explained in Chapter 1. Worn bearings are easily recognized by the noise produced and by the presence of smooth worn spots on the rotor core. The only remedy is the installation of new bearings.

(8) *Grounded Brush Holder* One grounded brush holder may cause the fuse to burn out if the frame is grounded. This is especially true if the motor operates on 230 volts. Use a test-lamp set to test for grounded brush holders. All wires must be disconnected from the brush holder and the brushes lifted from the commutator before this test is made. One test lead is held on the end plate while the other is touched to each brush holder in turn. A light indicates a grounded brush holder. To remedy, remove the brush holder from the brush rigging and reinsulate with fiber washers or mica at the grounded spot.

(9) *Overload* If an excessive load is placed on a motor, it may not turn over. A very hot motor is a sign of overload. To determine if a motor is overheated, disconnect the belt or other connecting mechanism and try the motor. If it operates perfectly, in all probability the trouble lies in the load. Either decrease the load or install a larger motor. See Chapter 4 for a detailed description of this fault.

Overload does not necessarily refer to the actual load. Any condition that will cause the motor to run slowly is a form of overload; for example, tight bearings will tend to slow down a motor and are considered an overload.

Check the current flow through the motor with an ammeter and compare the reading with the name-plate current. If it is due to a heavy load, use a larger motor or cut down the load. The overload may be due to defective windings, for example, shorts, opens, or grounds. An ammeter or snap-around ammeter will read higher than normal; this obviously indicates trouble in the motor if external sources have been eliminated. In this case, the motor must be dismantled to determine the malfunctioning part.

(10) *Defective Controller* A starting box or controller that does not function properly may be the sole cause of burned-out fuses. The fault may lie in a defective controller mechanism or in faulty connections between the motor and the controller. In either case, the repairman must be well informed on controller operation and connections before attempting to make repairs. See Chapter 8, Direct-current Controllers, for the diagrams that apply.

(11) *Open Armature Coils* An open armature coil will cause vicious sparking at the commutator and will prevent the motor from running at name-plate speed. Examination will reveal badly burned spots on the commutator bars to which the open coil is connected. On a lap winding, one open coil will cause one burned spot; on a four-pole wave winding, two spots will be produced. The open circuit may be caused by loose leads in the commutator bars or by improperly soldered leads. Remove the leads from the bar, clean them, and then replace and resolder them. If the open is caused by a broken wire in the coil, jump the two bars on either side of the burned spot. When more than one burned spot appears on the commutator, jump the bars in only one place and run the motor. If the sparking is eliminated, do not jump any more bars.

(12) *Brushes Set Off-neutral* The brushes must short-circuit a coil while it is in a neutral zone. If the setscrew that holds the brush rigging in place becomes loose, it may cause the brushes to move away from the proper brush setting. When this happens, the armature will spark badly and cause the motor to lose speed. Place the brushes in the proper position.

This condition is similar to having a wrong lead swing. The remedy for it is to shift the brushes so that there is no sparking when the motor is running at full load. The correct position of the brushes in an interpole motor can be found by turning the armature so that one coil lies midway between main poles or directly under an interpole, as shown in Figure 7-68. Next, the leads of that coil are traced to the commutator, and then the brushes shifted so that the commutator bars are shorted. The voltmeter method can also be used. In a motor that has no interpoles, the brush position, determined by the direction of rotation of the motor, will be slightly different. If the motor is running clockwise, the brushes must be moved counterclockwise several bars from the position they would occupy if it were an interpole motor.

(13) *Wrong Voltage* Motors are designed to run at a specific voltage. If the impressed voltage is less than the name-plate requirement, the motor will run at a correspondingly lower speed. If a load is applied, the motor will undoubtedly refuse to turn and may even burn out a fuse. Be certain that the name-plate voltage corresponds to the impressed voltage.

If in doubt as to the value of the line voltage, measure it with a voltmeter.

(14) *Open Shunt-field Circuit* If the field circuit of a shunt motor opens while the motor is running without a load, the armature may rotate at such a high speed that there is danger of the coils flying out of the armature. The motor is said to be "running away" if a condition like this arises. In order to explain this action, the principle of the generator must first be discussed.

A generator is a machine that changes mechanical energy to electrical energy. It consists of a number of coils of wire rotating in a magnetic field. In so rotating, the coils cut the lines of force in the field and cause a voltage to be generated in the coils.

This condition exists not only in a generator but also in a motor. Since all that is necessary to generate electricity is a coil of wire revolving in a magnetic field, and since these three factors (coils of wire, rotation, and a magnetic field) exist in a motor, a motor also generates electricity. This is called *counter electromotive force* (counter e.m.f.), or *counter voltage*, because it is generated in the opposite direction from the impressed voltage. Tests have proved that increasing the strength of the magnetic field increases the counter e.m.f. Also, the faster the coils cut the lines of force, the more voltage will be generated. For example, if a counter e.m.f. of 100 volts is desired, it can be obtained either by rapidly rotating an armature in a weak field or rotating the armature at a slower speed in a strong field.

The voltage generated in a motor is opposite in polarity and nearly equal to the voltage impressed on the motor. Thus, if 120 volts is applied to a motor, the counter e.m.f. will be about 110 volts in the opposite polarity, leaving only 10 volts to force current through the armature. This is sufficient to keep the motor running.

First, the counter e.m.f. will be slightly less than the impressed voltage at all times. Second, the counter e.m.f. depends on the strength of the field, or the number of lines of force, and on the speed. If the field circuit is broken, current cannot flow through the field coil; therefore, the number of lines of force will be reduced to practically zero. Actually, a few lines of force remain, those due to residual magnetism. Consequently, an armature rotating in a magnetic field of few lines will generate very little counter e.m.f. Since this must build up approximately equal to the impressed voltage, the armature will tend to increase its speed in order to generate the required amount of voltage. When the shunt field opens, this operation takes place automatically.

(15) *Series Motor Running without Load* The load should never be removed from a series motor while it is running. If it is removed, the speed of the motor will increase until it is dangerously high. Figure 7-69 shows that the same amount of current flows through the fields as through the armature. Since a motor consumes more current while pulling a load than when running without a load, the strength of the field in a series motor will be low when there is no load, and high when there is a heavy load on the motor. To generate the required counter e.m.f. with a weakened field, the armature must turn correspondingly faster.

(16) *Differential Connection in a Compound Motor* If a cumulatively connected motor is connected differentially by mistake, the motor will run at a higher speed if it is not loaded. Inasmuch as differentially connected fields have polarities which oppose one another, the resultant field strength will be weak. Previous discussion has shown that a weakened field causes an increase in speed.

Differentially connected fields are detected by observing the direction of rotation with the motor connected first as a compound motor and then as a series motor. If the direction is the same with both connections, it is connected cumulatively; otherwise, it is connected differentially. To change a differentially connected motor to a cumulative connection, the polarities of either the series or the shunt field are reversed.

(17) *Poor Brush Contact on the Commutator* Sparking at the commutator is a common occurrence, and one of the chief causes is poor brush contact on the commutator. This may be due to (a) worn brushes, (b) clogged brush holder, (c) insufficient spring pressure, (d) loose pigtail connection, (e) brushes shaped improperly, (f) a rough, grooved, or eccentric commutator, or (g) dirty commutator.

Continual service will cause a brush to wear to such an extent that the spring pressure is no longer effective. This condition is illustrated in Figure 7-70. Vicious sparking will result. Replace with new brushes. Quite often, the heat produced at the brushes will cause the spring to lose its tension. Inspection of the spring will reveal this fault; a defective spring can be stretched without returning to its original position.

If dirt and grease become lodged between the sides of the brush and the brush holder, the brush cannot press tightly against the commutator, and sparking results.

Many brushes are equipped with pigtails as shown in Figure 7-71. These are small, flexible leads that connect to the brush holder and conduct current from the brush holder to the brush. (In nonpigtail brushes this is done by means of the spring.) If the pigtail connections become loose, sparking results. To tighten a pigtail in the brush, drop a piece of molten solder into the space between the pigtail and the brush with a soldering iron. Another method is to drill a hole in the brush the size of the pigtail, insert the pigtail, and then secure it by forcing a brad into the hole. Care must be taken not to crack the carbon.

Failure to fit a brush properly against the commutator will result in sparking. The brush is shaped by placing a piece of fine sandpaper on the commutator with the rough side facing the brush and moving the sandpaper back and forth while pressure is placed on the brush. After it has assumed the shape of the commutator, remove the sandpaper and blow away the carbon particles.

A rough and eccentric commutator will cause a distinct knocking and may be detected by placing a finger on it. The remedy is to turn down the commutator in a lathe. A dirty commutator is another cause of sparking. The commutator must be clean and free from foreign matter such as grease, oil, grit, and so on. The best way to clean a commutator is to wipe it off with a cloth. On undercut commutators, scrape out the dirt between the bars. Very often small particles of carbon dust lodge in the mica between bars and flash over while the armature is turning. This may become so bad that a ring of fire forms around the entire commutator. Cleaning the mica will remedy the condition.

(18) *Wrong Lead Swing* If the coil leads of an armature are incorrectly placed several bars away from the right ones, excessive sparking will occur at the brushes. An examination of a coil in a neutral position will reveal whether or not its leads are being shorted by a brush. In the event the bars of this coil are not being so shorted, the leads obviously were put in the wrong bars. The remedy is to shift the brushes until no sparking results, or to reconnect the leads if the motor brushes cannot be moved.

(19) *Wrong Interpole Polarity* The purpose of the interpole is to prevent sparking that results from induction; however, this can be accomplished only if the polarity of the interpole is correct. Since the

reasons for sparking are so numerous, it is difficult to examine a motor that is sparking and come to the conclusion that the cause is wrong interpole polarity. Testing is the only method of determining conclusively that incorrect interpole polarity is responsible. The test for correct polarity, which involves shifting of the brushes and noting the direction of rotation, was described earlier in this chapter. If the motor is so constructed that this test cannot be applied, a compass polarity test will have to be made.

A motor with wrong interpole connections will draw more than normal current and it will overheat. If the motor is allowed to run, the commutator will become so hot that solder will be thrown from the commutator slots. Even though the interpoles are not connected properly, the motor will often run without sparking, but the commutator will become abnormally hot.

(20) *High or Low Bars* High or low bars will cause excessive sparking at the commutator. If the motor turns slowly, a spark is seen every time the high bar passes the brush. If the motor turns rapidly, this condition will appear as a continuous spark, accompanied by a blackening of the commutator and by chattering of the brushes. High and low bars can be found by running a finger over the commutator. Tighten the commutator and turn it down in the lathe or use a commutator stone and sandpaper.

(21) *High Mica* High mica may be due to a loose commutator or, more usually, to faster wear of the copper bar than of the mica. Pronounced sparking accompanies this condition. High mica is recognized by a blackening of the entire commutator, and the mica will feel rough to the touch and higher than the bars. The remedy is to turn the bars down on a lathe and undercut the mica. A temporary repair is to hold a commutator stone against the bars while the motor is turning.

(22) *Reversed Armature Leads* This defect can occur only in a rewound armature and is manifested by sparking at the brushes. If everything else appears to be in good condition, the only way definitely to determine reversed leads is to retest the armature. A description of testing for reversed armature leads is given in Chapter 6.

(23) *Tight Bearings* If the shaft of the armature fits tightly in the bearings, it will be difficult to turn the armature by hand. In this case the bearings should be scraped or reamed so that they fit the shaft without binding. Another remedy is to smooth down the shaft by polishing it with a fine emery cloth until the bearings fit. Often, however, the fault lies in the assembly of the motor, that is, if the end plates are not put on the frame properly.

(24) *Unbalanced Armature* The armature is placed on balancing ways and tested for mechanical balance. If it is found to be unbalanced, use the method described in Chapter 6, page 185 to balance the armature.

CHAPTER 8

Direct-current Motor Control

In Chapter 5, Alternating-current Motor Control, it was shown that an electric controller has many functions. Some of the important functions are to start and stop a motor, to limit the starting current or the speed, to reverse rotation, to provide undervoltage protection and/or overload protection, and to provide dynamic braking. Some controllers are designed simply to start and stop motors; others perform several of these operations; and still others perform all of them.

Controllers are classified in many different types, but essentially they are either manually or automatically operated, using full or reduced voltage. This chapter is devoted to describing both manually and automatically operated d-c controllers and the ways in which they are connected in the motor circuit.

Small d-c motors of less than ½ h.p. consume very little current and therefore can be started by placing full voltage across the motor terminals. Motors larger than ½ h.p. usually require a reduced voltage for starting. However, d-c motors up to 2 h.p. at 230 volts can be started with full voltage, provided the voltage can be applied without damage to the motor or machine. Large d-c motors cause large initial currents to flow because they have a low ohmic resistance and therefore use a reduced voltage for starting. If full voltage is applied to a large motor while it is at a standstill, the excessive current flow may damage the motor, trip a breaker, or burn out the fuse. To start a large motor, it is necessary to place a resistance unit in series with the motor so that the starting current is reduced to a safe value. Such starters are called *reduced voltage starters.* As the motor accelerates, this resistance can be gradually decreased. The resistance is not required after the motor has reached the desired speed because the motor is then generating a voltage which is in opposition to the impressed voltage, thereby preventing excessive current flow. This opposing voltage is called the *counter electromotive force* (counter e.m.f.), and its value will depend on the speed of the motor, which is greatest at full speed and zero at standstill.

For example, if the armature of a 230-volt motor has a resistance of 2 ohms, the current flow at standstill will be, according to Ohm's law

$$I = \frac{E}{R} = \frac{230}{2} = 115 \text{ amp.}$$

If the motor is running and thus is generating a counter e.m.f. of 100 volts, the total voltage in the armature is 230 — 100 or 130 volts. Therefore the current is

$$I = \frac{E}{R} = \frac{130}{2} = 65 \text{ amp.}$$

The flow of current has been reduced considerably by the counter e.m.f. If the motor is running at full speed and is generating a counter e.m.f. of 200 volts, then the current is

$$I = \frac{E}{R} = \frac{230 - 200}{2} = 15 \text{ amp.}$$

In other words, this motor normally will pass 15 amp. at full speed. However, if the initial current is not restricted until the motor reaches full speed, 115 amp. will flow—enough to burn out the motor or do considerable damage. To prevent the large initial current, resistance is inserted in the motor circuit and is gradually decreased as the motor accelerates and generates the counter e.m.f. The resistance is mounted in a box, called a *starting box,* which is mounted near the motor. A typical starting box or reduced-voltage manual starter as it is often called, is illustrated in Figure 8-5.

Manual Controllers

Three-point Starting Box Connected to a Shunt Motor

A three-point starting box consists essentially of a tapped resistance element that limits the starting current of a motor to a safe value. This type of starter can be used for starting either a shunt or a compound motor. The resistance unit is tapped at various points and the connections brought to contacts on the face plate, as shown in Figure 8-1. When the handle is moved from point to point, the resistance in the circuit is decreased. A coil located on the face plate acts as a magnetic holding coil and keeps the handle in place after it has been moved to the last contact. The starter gets its name from the fact that three terminals are located on the face plate. These are marked *L, A,* and *F,* signifying, respectively, line, armature, and field, and are connected internally to the handle, resistance, and holding coil.

The operation of the starter shown in Figure 8-1, when connected to a motor, is as follows: When the handle is brought to the first contact point, current will flow from L_1 to terminal *L* and through the handle to the first contact point. From this point the current has two paths, one through all the resistance to terminal *A*, the other through the holding coil to terminal *F*. From the armature terminal, the current flows through the armature to L_2. From the field terminal, the current flows through the shunt field also to L_2, as can be seen from Figure 8-2. Because all the resistance is in series with the armature at the starting position, the initial current will be limited to a safe value. As the handle is moved up, the motor will accelerate and produce a counter e.m.f., which will also restrict the current flow.

It should be noticed that when the handle is moved to the last contact point, the starting-box resistance is entirely removed from the armature circuit, and that it has been gradually placed in the field circuit. This will have no effect on the performance of the motor because the resistance of the starting box has a very low value in comparison to the resistance of the shunt field. Note also that the holding coil is connected in series with the shunt field. Therefore, current will flow through it when the field is excited, energizing it and causing it to become a magnet. Thus the holding coil retains the handle in position.

Should the shunt field open for any reason, the current will stop flowing in the holding coil. Spring action will cause the handle to fall back and open the circuit to the armature. The holding coil therefore acts as a safety device, because under ordinary conditions a shunt motor with an open field circuit will tend to "run away." Because of this safety measure, the holding coil is given the name of *no-field release.*

Three-point starting boxes can also be connected to compound motors. Figures 8-3 and 8-4 illustrate this connection. The only difference between this connection and the one for the shunt motor is the addition of the series field. A manual-reduced voltage starter is shown in Figure 8-5.

Four-point Starting Box Connected to a Compound Motor

There is very little difference between the three-point and four-point starting boxes. The main difference is that the holding coil is connected across the line in series with a resistor in order to limit the current in the holding coil, as shown in Figures 8-6 and 8-7, instead of being connected in the shunt-field circuit. The four-point box has four terminals on the face plate instead of three. The line leads are L_1 and L_2, the armature is A and the field is F.

When the handle is brought to the first contact point, current will flow from L_1 to the handle and to the first contact point. From here the current has three paths, which can be followed in Figure 8-7: One path is through the resistance to the armature terminal, to the armature and series field, and out to L_2. Another path is from the field terminal to the shunt field and out to L_2. A third circuit is through the holding coil, the holding-coil resistor, and back to L_2. Because the holding coil is connected directly across the line and thus cannot hold the handle in place should the voltage fail, it is given the name of *no-voltage release.*

An advantage of this box over the three-point box is that a variable resistance can be placed in the shunt-field circuit in order to increase the motor speed. A disadvantage is that the speed may increase to a dangerous degree if too much resistance is added, because this is similar to running with the field circuit open. A diagram of a four-point box with an additional resistance in the field circuit is shown in Figure 8-8. In the diagrams, the terminals have been located at convenient points on the face plate in order to simplify the diagram. In actual starters the terminals are generally placed in a row either on the bottom or top of the face plate.

Four-point Speed-regulating Rheostat

This rheostat is a device for regulating the speed of a motor. The connections of a four-point rheostat are similar to the previous four-point box, except that the field resistance is incorporated in the same box as the armature resistance, as shown in Figure 8-9. The size of resistance wire in the armature circuit must also be larger than the previous box because the handle has a ratchet that permits it to be held stationary on any contact point by the holding coil. Because the resistance may be in the circuit at all times, it must be heavy enough to pass the armature current without heating excessively.

In operation, when the handle is brought to the first contact point, the holding coil becomes energized and attracts the pivoted arm so that it holds in the first notch of the ratchet. This maintains the handle in place without the necessity of holding it by hand. At the same time the current flows through all the armature resistance to the armature and series field and back to the line. The current also travels through the solid copper bar located above the armature resistance contacts to the shunt field and back to L_2.

As the handle is moved up to point 5, all the armature resistance is cut out and the field resistance is about to be cut in. This will increase the speed of the motor until the last contact point is reached. It should be remembered that the handle can be left in any position desired.

Four-point Starting-box and Speed-regulating Rheostat

This rheostat is a combination starting box and speed regulator. This type of starter has a special handle (shown in Figure 8-10)—actually two arms, one under the other. When the handle is moved up, both arms are interlocked. After the handle is brought to the last contact point, the holding coil maintains in position the arm which contacts the armature resistance points. If it is desired to increase the speed above normal, the handle is moved in a counterclockwise direction. This moves only the arm contacting the field resistance and cuts in resistance in the field circuit, as shown by Figure 8-11.

When the arm is in the OFF position the shunt-field resistance is shorted by means of an auxiliary contact located on the face plate. This contact is movable, so that when the handle is rotated to the uppermost position the auxiliary contact opens the shorted field resistance and allows it to be used in the field circuit. At the same time the holding coil is connected in the circuit. The object in shorting the field resistance is to prevent its use until all the armature resistance has been cut out.

In operation, the handle is moved to the first contact point, and a circuit is formed from L_1 to the handle, through all the resistance, through the armature circuit, and back to L_2. Also a circuit is completed from the first contact button through the auxiliary contact to the field terminal, through the shunt field, and back to line. After the motor accelerates and the handle is brought to the last contact, the auxiliary contact permits the field resistance to enter the circuit and also closes the holding-coil circuit which holds the handle in position. If increased speed is desired, the arm which contacts the field resistance is moved in a counter-clockwise direction, inserting resistance in the field circuit, and in turn causing an increase in speed. When the main switch is opened, a coiled spring at the base of the handle returns it to the OFF position.

Another combination starter and speed regulator which operates on the same principle as the previous box but whose construction is somewhat different is shown in Figure 8-12. The handle of this starter consists of two arms, a main arm, and an auxiliary arm. The main arm rides on two sets of contact buttons, one set for the field resistance and the other for the armature resistance. Only the armature resistance is in the circuit as the handle is moved upward. The auxiliary arm during this operation is in such a position that it short-circuits the shunt-field resistance, causing it to be inoperative during the period in which the armature resistance is cut out.

When the main arm is brought to the last contact point, the auxiliary arm connects the armature terminal directly to the line and also allows the field resistance to be put into the circuit. The auxiliary arm is held in this position by its holding coil. If the speed of the motor is to be increased above normal, the main arm is moved in a counterclockwise direction, thereby inserting resistance in the field circuit. If the main arm is brought back to the starting point, the holding coil will be disconnected, the auxiliary arm released, and the entire motor disconnected from the line.

Reversing Motors Connected to Three- and Four-point Starting Boxes

In Chapter 7, Direct-current Motors, it was mentioned that there are two methods of reversing the direction of rotation of a d-c motor, namely, by reversing the current through either the armature or the field. The conventional method is to reverse the current through the armature. In the manually controlled starters, a double-pole, double-throw switch, connected as shown in Figure 8-13, is used for this purpose. Other devices are also used, but essentially they are alike in that their primary purpose is to reverse the current in the armature circuit. Figures 8-14, 8-15, and 8-16 are diagrams of a series motor reversed by connecting a double-pole, double-throw switch in the armature circuit.

A shunt motor is reversed in the same manner, that is, by connecting a reversing switch in the armature circuit, as shown in Figures 8-17 and 8-18.

The connection diagram for a compound motor is similar to that of the series motor with the addition of the shunt field which is connected across the line. When a compound motor is to be connected to a reversing switch, it must first be connected as a series motor and then connected with the shunt field across the line, as illustrated in Figure 8-19. If six leads are brought out of the motor, care must be taken to connect the motor for cumulative operation. If five leads are brought out, the lead, which is the combination series- and shunt-field wire, should be brought to one line. If an interpole motor is reversed, both the armature and interpole must be reversed as a unit. A precaution to be observed when reversing a motor is to allow it to come to a full stop before attempting to operate it in the opposite direction.

Connecting a Reversing Switch in the Armature Circuit of a Shunt Motor Connected to a Three-point Box A diagram of the connection of a double-pole, double-throw switch and a three-point box to a shunt motor is shown in Figure 8-20. This is similar to the circuit of Figure 8-17, except that a three-point box is in the circuit. To reverse this motor, the main switch is first opened. This causes the motor to come to a complete stop and also allows the handle of the box to drop to its OFF position. The reversing switch is then thrown, the main switch closed, and the handle slowly raised.

Compound Motor—Three-point Box To connect a compound motor for reversing, connect it exactly as shown in Figure 8-20, except for the addition of the series field as shown in Figure 8-21. Note in this diagram that the armature and interpole are reversed as a unit. If only the armature is reversed, sparking will occur at the brushes and the motor will overheat.

Shunt Motor—Four-point Box To connect a shunt motor to a four-point box and reversing switch, it is only necessary to connect it as shown in Figure 8-20 with a three-point box and then add the wire for the additional line terminal on the four-point box, as shown in Figure 8-22.

Compound Motor—Four-point Box If a compound motor is to be connected to a four-point box and reversing switch it should be connected as shown in Figure 8-23.

Reversing Small Motors by Means of a Drum-type Switch In appearance, a drum switch resembles the drum controllers used on cranes, but it is much smaller in size. It is totally enclosed, with a handle on top, as shown in Figure 8-24, and it has an outlet on the bottom to permit conduit connections. When the motor is not rotating, the handle is in the center position. When rotation is desired, the handle is moved to the right. To reverse the motor, the handle is first brought to the center until the motor stops and then is moved to the left.

Removing the switch cover will reveal the terminals to which the line and motor connections are made. If the contacts are inspected, it will be found that there are two stationary sets arranged as illustrated in Figure 8-25. These consist of four contacts on both sides of the switch, attached to and insulated from its frame. The movable contacts shown in Figure 8-26 are attached to an arm that runs through the middle of the switch and are so placed as to contact the stationary points when the handle is moved in either direction.

When the motor is at rest, the movable contacts do not touch the stationary contacts. However, when the motor is running, one possible position of the contacts is as shown in Figure 8-27. For reverse rotation, the contacts are as shown in Figure 8-28. To connect this switch to a series motor, as shown in Figure 8-29, the armature wires are connected to contacts *3* and *4* and the series field to *5* and *7*. The line wires are connected to *2* and *8*. Figure 8-29 shows the connection for clockwise rotation, and Figure 8-30, the connection for counterclockwise rotation.

For a shunt motor, the armature is connected exactly as before. The shunt field, however, is connected to contacts *1* and *7*. Contacts *5* and *7* are connected together. Figures 8-31 and 8-32 show the current paths for forward and reverse.

The compound motor is a combination series and shunt motor, and therefore the connection diagrams of Figure 8-33(a) and (b) show both the series and shunt fields connected as in the previous diagrams.

Overload Relays

To protect the motor and line from accidental or prolonged overloads, either the starting box, the motor, or both can be equipped with a device that will automatically disconnect the motor from the source of current when such a situation occurs. If too large a current flows for too long a time, damage is done to a motor, or line disturbances take place. This necessary protection can be provided by fuses, by magnetic or thermal circuit breakers, or by overload relays.

Fuses are often used in the line circuit supplying electric motors. Fusible power disconnect switches provide protection against short circuits. If fault currents are a frequent occurrence in the circuit, circuit breakers should be used. A circuit breaker can be quickly reset after the fault has cleared.

Magnetic Circuit Breakers A magnetic circuit breaker provides a quick and effective means of opening the motor circuit if an excessive current flows. It consists of a coil of wire sufficiently heavy to carry the motor current and is connected in series with the line. It is located in a position close to the main contact arms, as shown in Figure 8-34.

If an overload occurs, enough current will flow through the coil to energize it and cause a plunger located in the center of the coil to rise and trip the main contact arms, thus opening the circuit. These circuit breakers can be adjusted to operate between certain ranges of current. Magnetic circuit breakers of many different designs are used, but the principle of operation is the same for all. Some circuit breakers are constructed so that breaking will occur only after the overload has been sustained for a certain length of time. Breakers of this type make use of a unit called a *dashpot* or employ thermal elements.

Thermal Circuit Breaker A thermal circuit breaker operates on a principle entirely different than that of the magnetic circuit breaker. Coils are not utilized in this type of breaker, but rather a bimetallic or other thermal unit is used to break the circuit. The principle of operation of the bimetallic unit depends on the expansion rates of different types of metal when they are heated. When two metals having different coefficients of expansion are welded together and heated, the unit will deflect and trip two normally closed contacts, which in turn will open a holding coil circuit causing the main contacts to open.

Magnetic Overload Relay Magnetic overload relays are used on both manual and automatic starters. On some of the older manually controlled starters, such as the three- and four-point starting boxes, the overload relay takes the form of a magnetic coil which is connected in series with the main line, as in the case of the circuit breaker. The circuit breaker is so designed that when a normal or slightly above normal current is flowing, there will be no effect on the overload coil. However, if an overload condition arises, causing an excessive current to flow, the coil will become sufficiently energized to lift a small arm, which in turn will short circuit two contacts. If these contacts are connected directly to the terminals of the holding coil of a three-point box, as shown in Figure 8-35, current which normally flows through the holding coil will now by-pass it. This causes the coil to become de-energized, releasing the handle of the box and shutting off all current to the motor.

A plunger type of overload relay is shown in Figure 8-36. When the current through the coil reaches the value set by the adjustable screw, the plunger is drawn up and opens two contacts. This type of relay can be used on both the manual and automatic controllers.

If it is used on manual starters, it is connected as shown in Figure 8-39. Relays are equipped so that they may be reset either automatically or manually. On automatic or semiautomatic starters, an overload relay can be used to open the contacts of a magnetic switch or contactor shown in Figure 8-37. The overload relay open-circuits the holding coil of the magnetic contactor, causing the arm to fall back and open the line circuit. Contactors are discussed in detail on page 238.

The magnetic switch or contactor is usually shown in one of the simple forms illustrated in Figure 8-38 when it is included in a circuit diagram. Figure 8-39 shows a controller diagram using a magnetic contactor and overload relay.

The operation of this circuit is as follows: When the switch is turned on, current will flow from L_1 through the snap switch, the holding coil, the overload coil contacts, and back to L_2. The holding coil will be energized, closing the contactor. If a sustained overload existed, the overload coil plunger would rise and open the relay contacts. This would open the holding coil circuit, deenergizing the coil and allowing the handle to drop. If the starting box handle is on the uppermost contact point at the time of overload, opening the magnetic switch will cause the handle to drop. Note that a snap switch is used to close the magnetic contactor in the diagram. A START-STOP pushbutton station may also be used if the contactor is supplied with an auxiliary contact for three-wire control.

Thermal Relays Most overload relays used on modern controllers are thermally operated. One type of relay consists of two strips of metal, having different degrees of thermal expansion, welded together. If this bimetallic strip is heated, it will deflect sufficiently to trip two normally closed contacts which in turn will open circuit the holding coil of a magnetic contactor, causing the main contacts to open. The bimetallic unit is usually heated by placing it near a heating coil or heating unit which is connected in series with the line. If an excessive current or prolonged overload occurs in the motor circuit, the heating unit becomes hot and transfers its heat to the bimetallic unit, which in turn bends and opens the contacts. An advantage of the thermal relay is that it provides a time delay which prevents the circuit from being opened by momentary high starting currents and short overloads. At the same time it protects the motor from prolonged overloading.

These relays are manually reset or automatically. An illustration of one type of bimetallic overload relay is shown in Chapter 5, page 145.

Another type of thermally operated overload relay is the solder ratchet type. The relay spindle is heated by motor current flowing through the heater element surrounding the spindle. The overload relay trips when the melting (eutectic) alloy has reached a fixed predetermined temperature. A sustained current, greater than the rating of the heater element, will raise the temperature of the spindle above the melting point of the eutectic solder which holds the ratchet wheel to the spindle. The ratchet wheel is then free to turn, allowing the relay to trip and open its contacts. About two minutes are required before manual resetting. An illustration of this type of overload relay is shown in Chapter 5, page 146.

The usual method of denoting a thermal overload relay is to show a normally closed contact next to an overload heater symbol, as illustrated in Figure 8-40. A diagram showing an application of a thermal relay is presented in Figure 8-41.

D-C Magnetic Contactor

D-C contactors are compact magnetic switches suitable for remote control of lighting circuits, power (motor) circuits which have separate overload protection, battery charging circuits, and other similar applications requiring a safe and convenient means of interrupting such circuits. Contactors do not have overload relays.

Magnetic contactors may be single, double, or triple pole in construction. In any case, only one coil is necessary to close the contacts of the switch. Figure 8-42(a) shows the main parts of a single-pole magnetic contactor of the clapper type which consist of a holding coil, movable arm, main contacts, and auxiliary contacts. In addition, a blowout coil is located near the main contacts and is used to quench the arc that usually occurs when the main contacts are broken. This coil is wound of heavy wire and is connected in series with the main line. The magnetic field that is produced by current flowing through it reacts against a similar field surrounding the arc and causes the arc to move upward, thereby breaking it.

It can be seen from Figure 8-42(a) that the main contacts will make if the holding coil is energized. Only a small current is necessary to energize the coil sufficiently to attract the arms. It is obvious, therefore, that any size of magnetic contactor can be closed by sending just a small amount of current through the coil. An advantage of the magnetic contactor is that it can be controlled by a START-STOP station located at a remote point. Figure 8-42(b) shows another method of denoting a contactor. Another type of contactor utilizes a solenoid and plunger for closing the contacts. Permanent magnet blowouts are used on some contactors and are usually mounted in the arc hood. Two-pole contactors usually consist of two contacts connected in series for one pole and a single contact for the other pole. These contactors generally do not have overload relays. A wiring diagram of a typical double-pole contactor is shown in Figure 8-42(c).

Pushbutton Stations A magnetic contactor is usually controlled by means of a pushbutton station. The common station consists of two buttons, a START and a STOP button. The construction is such that when the START button is pressed, two normally open contacts are closed, and when the STOP button is pressed, two normally closed contacts are opened. Spring action returns either button to its normal position when pressure is removed. Figure 8-43 shows several ways of illustrating a START-STOP station.

To control a magnetic contactor by a pushbutton station, it is only necessary to connect the holding coil to the stations so that when the START button is pressed current will flow through the coil, and when the STOP button is pressed the circuit through the coil will be opened. The auxiliary contacts will maintain the current through the coil when the START button is released. Figures 8-44 and 8-45 show a circuit diagram of a magnetic contactor connected to a START-STOP pushbutton station.

In the circuit of Figure 8-46, when the START button is pressed, a circuit is formed from L_1 through the STOP button, the START button, the holding coil M, to L_2. This energizes the holding coil and causes the main and auxiliary contacts to close. The main contacts close the circuit to the motor, while the auxiliary, or maintaining, contacts maintain the current through the holding coil when the START button is released.

If the STOP button is pressed, the circuit through the holding coil is opened, causing the main contacts to open, thereby stopping the motor. Note that the auxiliary contacts are connected across the START button.

Magnetic Starters (Full Voltage)

Magnetic Starters differ basically from contactors in that they are designed primarily for starting motors and consist of a contactor and an overload relay, usually of the manual reset type. These starters can be used only on smaller motors, up to approximately 2 h.p., and where full voltage can be applied without damage to motor or machine. On this type of starter, overload, undervoltage, and no-voltage protection are provided. On a sustained overload the relay will trip and open the solenoid circuit, disconnecting the starter from the line. Voltage failure or a severe voltage dip will also de-energize the solenoid circuit. This starter is illustrated in Figure 8-47(a) and (b).

Quite often it is necessary to control the motor from more than one location, and this is easily accomplished by using several pushbutton stations. Figure 8-48 shows two START-STOP stations controlling a magnetic switch.

Three START-STOP pushbutton stations are connected as shown in Figures 8-49 and 8-50. It should be remembered that the STOP buttons must always be in series with one another and in series with the holding coil, so that in an emergency the motor can be stopped from any station. Any number of START-STOP stations can be added to control a magnetic starter if they are connected properly in the circuit. The important point to remember is that START buttons are connected in parallel and STOP buttons in series.

Reversing Starters (Full Voltage)

A d-c motor can be reversed by reversing the current flow through the armature circuit or the field circuit. In a compound motor, this entails reversing the current through the shunt and series fields. It is therefore much simpler to reverse the current in the armature circuit. Note in Figure 8-51 that the armature is connected in such a manner that when contacts *R* are closed, current will flow through the armature in one direction, and when contacts *F* are closed, current will flow through the armature in the opposite direction, thereby reversing the direction of rotation. A

FORWARD-REVERSE-STOP station is used with this starter. It is important that the motor be brought to a full stop before the reverse button is pressed. On this type of starter the contacts are mechanically interlocked so that it is impossible for the *R* and *F* contacts to close at the same time.

Magnetic reversing starters are also constructed with electrical interlocks to give additional protection against the *R* and *F* contacts closing at the same time. Figure 8-52(a) shows the control circuit of an electrically interlocked magnetic switch. Figure 8-52(b) shows a control circuit using front and rear contacts of the FORWARD and REVERSE buttons.

Magnetic reversing starters also come equipped with a timing relay which prevents the motor from being reversed before it comes to a full stop. In Figure 8-53 the timing relay *TR* opens the normally closed *TR* contacts. When the STOP button is pressed, the *TR* relay prevents them from closing until a specific interval of time has elapsed. The operation is as follows: When the REVERSE button is pressed, current flows from L_1, the STOP button, REVERSE button, forward interlock, reverse coil, to L_2. All normally open *R* contacts close, including the reverse holding contacts and the reverse timing contact. Normally closed *R* interlock opens. When the reverse timing contacts close, coil *TR* is energized, opening the normally closed *TR* contacts, thereby making both the FORWARD and REVERSE buttons inoperative while the motor is running. When the STOP button is pressed, timing contacts *TR* remain open until the *TR* relay has timed out. This prevents reversing the motor until it has come to a full stop.

Jogging In the event that it is desired to run the motor for a very short interval of time, an additional button is added to the station. With this button it is possible to run the motor only while the button is depressed. When pressure is removed from this button, the motor will stop automatically without pressing on the STOP button. With this arrangement the motor can be made to run momentarily. Just as in other stations, the STOP button must be in the holding-coil circuit in case it should be necessary to use it. A circuit having a START-JOG-STOP station connected to a magnetic switch is shown in Figures 8-54 and 8-55.

The operation of the circuit of Figure 8-54 is as follows: Pressing the START button completes a circuit from the positive line through the START, JOG, and STOP buttons, the overload contacts, the holding coil, to the negative line. The holding coil becomes energized, the main contacts close, and the motor starts. The auxiliary contacts also close, maintaining the current in the holding coil after pressure is removed from the START button. Pressing the STOP button opens all contacts, and the motor stops. If the JOG button is pressed, a circuit is formed from positive through the JOG contacts, the STOP button, overload contacts, and coil to negative, closing the main and auxiliary contacts. The maintaining contact circuit will open when the JOG button is pressed and will thereby be made inoperative. Thus, the maintaining circuit is broken when the JOG button is depressed.

Figures 8-56 and 8-57 show connections to a small d-c motor using a JOG selector pushbutton station. The JOG button has a sleeve which can be turned to RUN or JOG. When the sleeve is turned to the JOG position, the front contacts are opened, as shown by the dotted line, thereby disconnecting the maintaining or sealing contacts. If the JOG button is now depressed, the motor will run only while pressure is held on the button. With the sleeve in the RUN position, the front contacts of the JOG button are closed, allowing the RUN button, when depressed, to complete the control circuit. This energizes coil *M*, which in turn closes the *M* contacts, sealing in coil *M*. JOG relays, described in Chapter 5, are also used in some starters and provide jogging by preventing the *M* coil from sealing in by means of contacts across the START button.

Reduced-voltage Starters

Motors larger than ½ h.p. usually require resistance in the circuit at the start to limit the starting current to a safe value. As the motor accelerates, this resistance is automatically removed from the circuit in one or more steps, depending on the size of the motor and the type of controller. There are many methods of automatically removing the resistance from the motor circuit. The ones listed below will be described in detail:

1. Counter e.m.f. starter.
2. Lockout starter.
3. Definite magnetic time starter.
4. Definite mechanical time starter.
5. Drum starter.

Counter e.m.f. Starter

When the armature of a motor increases in speed, the counter voltage generated in the armature also increases, thereby reducing the current in the armature circuit. This reduction in current decreases the voltage drop at the armature starting resistance, thereby increasing the voltage across the armature terminals. Therefore, if a coil designed to operate at 50 volts is connected across the armature terminals, as shown in Figures 8-58 and 8-59, it will become operative only when voltage across the armature is 50 volts or higher. The coil can be made to operate a contactor which will shunt part or all of the resistance connected in series with the armature, as illustrated by Figure 8-60. This shows the position of the accelerating contact when the motor starts.

The operation of the circuit in Figure 8-58 is as follows: When the START button is depressed, the holding coil is energized and the main contacts are closed. This completes a circuit through the starting resistance and the armature. The shunt field is also energized. As the motor accelerates, the voltage across the armature will reach a value where it will be sufficient to energize the coil of the accelerating contactor, thereby closing the accelerating contacts. This cuts the resistance out of the armature circuit and connects the armature across the line.

Counter e.m.f. starters are also made with several steps of resistance and several accelerating coils instead of one. A three-unit type is shown in Figure 8-61. Each coil operates at a different voltage. As the voltage across the armature increases with acceleration, each coil is energized in succession, and its contacts short a starting resistance until finally the armature is connected across the line.

On some controllers, the accelerating coil is placed in series with the holding coil after the accelerating contacts have closed; on others, a resistance is inserted in series with the accelerating coil to limit the current through it. Some counter e.m.f. starters have one large coil which operates several accelerating contacts. On this latter type, the accelerating contact arms are placed at varying distances from the core of the magnet. Each arm is closed in succession as the voltage across the coil increases and the arms in turn cut out resistance from the armature circuit.

Figure 8-62 is a diagram of a counter e.m.f. starter using relays to activate the shorting contactors across the resistors. The operation is as follows: Pressing the START button energizes contactor coil *M*. This closes the main contacts and the sealing contacts. The motor operates through resistors R_1 and R_2. Accelerating coil *1*, connected across the armature, is energized as soon as the armature counter e.m.f. reaches a predetermined value and closes accelerating contacts *1* which in turn close the circuit through coil *1A*. Coil *1A* closes contacts *1A* across R_1, eliminating this part of the resistor from the armature circuit. The armature will now speed up, the counter e.m.f. will increase and energize accelerating coil *2*, which will indirectly close *2A* and place the armature circuit across the line.

Lockout Starter

The accelerating contactors that are used in this type of controller are called *series-lockout* contactors because the accelerating coils are connected in series with the armature and are so designed that the contacts will stay open if the current through the motor is large, as at start, and will close after the motor accelerates and the current decreases. Lockout contactors are designed with either one or two coils. In either case, the coils are connected in series with the armature.

This type of controller is also known as a *current-limit starter* because the acceleration of the motor is controlled by the amount of current flowing through it.

Two-coil Lockout Contactor Figure 8-63 illustrates one type of two-coil, series-lockout contactor. The coils of this contactor are connected in series and in series with the armature. The upper coil is the closing coil that tends to close the contacts, and the bottom coil is the lockout coil that tends to hold the contacts open. The coils are designed so that the magnetic field, or "pull," of the lockout coil will predominate if heavy current flows through the motor. For example, when the motor starts, the contacts will be kept open by the initial current flow. As the motor accelerates and the current decreases, the pull of the upper coil will predominate and the contacts will close. This action is explained as follows:

Figure 8-64(a), (b), and (c) illustrate this type of controller with one step of resistance. When the START button is pressed, the main contacts close, completing a circuit through the closing coil, the lockout coil, the resistance, and armature circuit. The initial current energizes the lockout coil to such a degree that the contacts are prevented from closing. As the motor accelerates, the current decreases to a value where the pull of the closing coil will predominate over the lockout coil and the contactor will close. This will short both the lockout coil and the resistance. A simple diagram of this circuit is shown in Figure 8-65. The shunt field is connected across the line throughout the operations of the controller.

Controllers of this type are also made with two and three steps of resistance instead of one. One set of contacts is needed for each step. Figures 8-66 and 8-67 show a two-step controller.

If the motor is overloaded to any degree, the pull of the lockout coil may cause the contacts to open and place the resistance in the circuit. The motor will run this way until the overload is withdrawn or until the motor accelerates to a point where the current value drops. On the other hand, if there is a light load on the motor, the pull of the closing coil will close the contacts and cause the motor to accelerate too quickly.

One-coil Lockout Contactor A one-coil contactor is similar to the two-coil contactor in that two magnetic circuits are established when current flows through the coil. When excessive current flows through the coil, a strong magnetic field will be established which will tend to keep the contacts open. On the other hand, when a normal current flows through the coil, the magnetic field will close the contacts.

Figure 8-68 illustrates this type of contactor. Note the two magnetic paths, one through the tailpiece *B* and the other through the metallic connection *C* around which a copper sleeve is placed. If a heavy current flows through the coil, a strong magnetic circuit is set up through the tailpiece, attracting it to the extension of the coil base and thereby keeping the contacts open. When the current flow drops, the magnetic path at *C* will become stronger and cause the contacts to close. The copper sleeve limits the flux passing through *C* when a heavy current is flowing, and consequently most of the flux passes through the tailpiece.

There are several other types of single-coil lockout contactors, but all operate on the same principle of magnetic difference between two points.

From Figures 8-69(a), 8-69(b), and 8-70 it can be seen that when the START button is pressed, the main contacts close and a circuit is formed from positive through the lockout coil, resistance, and armature circuit to the negative line. After the initial high current has decreased and the motor has accelerated, the current through the coil will be such as to permit the accelerating contacts to close, cutting out the resistance. The current path is then through the lockout coil and armature circuit to negative.

Figures 8-71 and 8-72 show a series-lockout controller having two steps of resistance. Its operation is as follows: Pressing the START button closes the main contacts. A circuit is now formed from positive through R_1, through lockout coil A, to R_2, the armature, and to negative. When the initial current drops low enough, contacts A close, shorting R_1 and placing lockout coil B in its place. The circuit is now through B, A, R_2, and the armature. After the armature has accelerated sufficiently, the current will fall off again and contacts B will close, shorting out R_2 and placing only coil B in series with the armature.

Definite Magnetic Time Starter

Like other reduced-voltage starters, the definite magnetic time starter also must cut out the starting resistance in steps so that the motor can accelerate gradually. However, the accelerating contactors for this kind of starter operate on a different principle from that of the others.

The coil of the contactor has an iron core that is surrounded by a copper sleeve. When the coil is de-energized, the decaying flux will induce a current in the copper sleeve and cause the core to lose its magnetism slowly. This action will permit the core to retain its hold on the armature for several seconds or until the motor has had time to accelerate. On these contactors, the contacts are normally closed. When the coil is energized, the contacts open; when the coil is de-energized, several seconds elapse before the contacts close. The amount of time that the contacts remain open can be determined by adjusting the spring tension on the contactor.

Figures 8-73 and 8-74 are wiring diagrams of a starter employing this type of acceleration. An advantage of this starter over the others is that the acceleration does not depend on the speed or current flow of the motor. Its operation, based on Figure 8-73, is as follows:

Pressing the START button energizes the accelerating coil, causing the accelerating contacts *A* to open and the auxiliary accelerating contacts *1A* to close. This energizes the coil *M*, which closes the line contacts *M* and auxiliary contact *1M*, and opens normally closed auxiliary contact *2M*. Closing of the line contactor establishes a circuit through the resistance and armature. Contact *1M* provides the holding effect of the line coil, while contact *2M*, having been opened, de-energizes the coil *A* of the accelerating contact, which drops back after a definite time and thereby shorts the resistance from the circuit and places the motor across the line.

Definite Magnetic Time Starter with Jogging This controller can be used for jogging by providing a JOG button in the control circuit. Figure 8-75 shows the same starter as in Figure 8-74 with the JOG button added. When the JOG button is pressed, the accelerating coil is energized and the accelerating contacts are kept open. The auxiliary contacts close and supply current to the line coil only while the JOG button is depressed. The holding circuit for this coil is broken when the JOG button is released.

Definite Magnetic Time Starter with Two Steps of Resistance For larger motors, two steps of resistance are provided in the controller. Figure 8-76 shows a magnetic time starter having two accelerating contactors. The operation is essentially the same as that of the magnetic time controller except that two accelerating contactors are used instead of one. Contactor A_1 shorts out R_1 while A_2 shorts out R_2. When the START button is pressed, coil A_1 is energized and interlock A_1 closed. This in turn energizes coil A_2, which closes interlock A_2. Coils A_1 and A_2 open contactors A_1 and A_2, while interlock A_2 energizes coil *M*, which in turn closes the main contacts. A circuit is now completed from positive through the resistance, the armature circuit, to negative. Coil *M* opens interlock *M*, which in turn opens the circuit through coil A_1, causing contactor A_1 to close, shorting out R_1. Interlock A_1 is opened when coil A_1 is de-energized; the circuit to coil A_2 is opened; and, after a set time, R_2 is shorted and the motor is placed across the line.

Definite Magnetic Time Starter with Dynamic Braking It is important in many instances that a motor be brought to a quick stop rather than be allowed to keep running until it stops of its own accord. This can be accomplished by either mechanical braking or electrical braking, or both. Elevators, cranes, and trains are equipped witth a mechanical brake that will quickly stop the motor. To prevent excessive wear on the brakes and also to help stop the motor quickly, the controllers used for some of this machinery are so designed as to make use of the generating action of the motor for braking purposes. This is called *dynamic braking*.

It was explained previously that a motor generates an e.m.f. opposite in direction to the impressed voltage. If, to stop a motor, the main switch is opened, the motor will continue to rotate but will gradually slow down. While the motor is coming to a stop, it will generate voltage if the shunt field remains energized. If the armature is connected to a resistance during this period, the generated voltage will drive a current through the resistance and back through the armature in a direction that will tend to give the motor a torque in a direction opposite to its rotation, thereby causing it to come to a quick stop.

To accomplish this, the main contactor on a controller equipped for dynamic braking is constructed with two sets of contacts, one set of normally open contacts for the main line supply, the other set normally closed for dynamic braking. When the START button is pressed, the holding coil is energized, the main line contacts are closed, and the dynamic braking contacts are opened, as shown in Figure 8-77. When the STOP button is pressed, the main contacts open and the brake contacts close. The current generated by the motor now flows through the resistance and into the armature, as shown in Figure 8-78. This will produce a torque in the opposite direction and cause the motor to come to a quick stop.

Figure 8-79 shows a diagram of a definite magnetic time starter with dynamic braking added. Note that the only differences between this and Figure 8-74 are the addition of a resistance, connected across the armature, and the connection of the shunt field directly across the line.

Definite Mechanical Time Starter

A d-c motor can also be accelerated by mechanical definite time mechanisms. This can be accomplished by dashpot timing acceleration and geared timing acceleration.

Dashpot Acceleration One type of dashpot mechanism consists of a solenoid through which an iron plunger can be made to rise when the coil is energized. Under ordinary conditions, the plunger will rise very quickly. However, if the plunger is made to ascend slowly, it can be put to use in cutting out resistance units from a motor circuit in a specified time and produce gradual acceleration.

To do this, the lower part of the plunger is attached to a piston which must rise in a cylinder filled with oil or air. When the solenoid becomes energized, the piston will be moved upward by the plunger. Its upward movement will be slow because it must force the air or oil from one compartment to another in the dashpot cylinder. This slow motion is used for shorting the starting resistance in steps, as shown by Figure 8-80. Figure 8-81 shows a wiring diagram of a starter employing this type of acceleration. Its operation is as follows:

Pressing the START button completes a circuit through the contactor coil *M*; the main contacts close. Then a circuit is formed from positive through the main contacts, all the resistance, the armature, series field, to negative, with the result that the motor starts slowly. An auxiliary contact on the main switch closes and energizes the solenoid, which causes the plunger to rise slowly, closing contacts *1* first because they are the shortest distance apart. All the others close in succession, cutting out resistance and accelerating the motor gradually.

The reduced-voltage starters shown in Figures 8-82 and 8-83 use a fluid dashpot timing mechanism. These starters provide time-limit acceleration. The operation is as follows: Pressing the START button energizes the line contactor coil and accelerating coil. The line contacts close, placing resistance in series with the armature, limiting the inrush of current. At definite time intervals controlled by a time-limit dashpot device, one or more increments of resistance are shorted by the closing of the accelerating contactor.

The starter shown in Figure 8-84 is intended for heavy duty where starting demands are frequent. Pneumatic timing mechanisms are used with this starter. Pressing the START button energizes coil *M*, closing the main line contactor and placing resistance in series with the armature. After definite time intervals, coils *1A* and *2A* become energized, closing contacts *1A* and *2A*, thereby eliminating the starting resistance from the armature circuit. Figure 8-85 is another diagram showing timed acceleration.

Adjustable-speed motors are usually equipped with a field accelerating relay. This relay provides full field during normal acceleration to base speed, and it also limits the current drawn by the armature in going beyond base speed under field-weakened conditions. The coil of the relay is connected in series with the armature as shown in Figures 8-86 and 8-87. When the current drawn by the armature during acceleration or under field-weakened conditions becomes excessive, the field accelerating relay coil closes the contacts across the field rheostat thereby placing the shunt field directly across the line. The shunt field now has full strength and prevents excessive armature current during acceleration. Figure 8-87 also has a field failure relay, which is connected in series with the shunt field. The contacts of this relay are connected in series with the holding contacts across the START button. Field failure would de-energize the relay coil, in turn opening the *FL* contact and causing the main contact to open, thereby stopping the motor. In operation (see Figure 8-87), pressing the START button energizes coil *M*, thus closing all *M* contacts. The armature receives current through the resistance, the shunt field is energized, and the motor runs. In series with the armature, *FA* receives full current and causes contacts *FA* to close, thus putting the shunt field across the line during acceleration. Note also that field failure relay is in series with the shunt field. Coil *M* also closes time delay contact *M*, in turn energizing accelerating coil *1A*. This relay closes contact *1A*, cutting out part of the resistance in the armature circuit. Accelerating coil *1A* also activates time delay *1A*, thus energizing accelerating coil *2A*. This coil closes contact *2A*, eliminating the accelerating resistance.

Geared Timing Acceleration A geared timer is similar to a dashpot timer in that it has a plunger which is moved upward when a solenoid coil is energized. The timer is so constructed that several contact fingers will make in succession as the plunger rises. However, the amount of time between the closing of each finger is governed by a simple adjustable pendulum similar to the escapement of a clock. When the plunger rises, the accelerating fingers try to close. This exerts a torque on the gears of the mechanism and causes them to rotate. The escapement allows the gears to turn only at a certain rate, so that the accelerating fingers will close at definite time intervals and in sequence. This type of controller is shown in Figure 8-88(a) and (b).

The upper half of the solenoid is energized through a normally closed interlock when the START button is pressed. As the line contacts close, the interlock opens and inserts the lower half of the coil in the holding circuit. The accelerating fingers of the multifingered contactor close in sequence and connect the motor across the line.

Geared Timer with Dynamic Braking Another type of starter, similar in many respects to the diagram of Figure 8-88, but with dynamic braking, is shown in Figure 8-89. The dynamic braking circuit makes use of the starting resistance for braking purposes. When the START button is pressed, the solenoid coil is energized and immediately closes the main contacts and opens the dynamic braking contacts *4*. This allows the current to flow from positive through contact *1*, all the resistance, through the motor, to negative. Timing of the geared mechanism closes contacts *2* and *3* in sequence and puts the motor across the line. When the STOP button is pressed, contacts *1*, *2*, and *3* open and contact *4* closes, putting the starting resistance across the armature, stopping the motor. The dynamic braking relay keeps the solenoid coil from closing until the motor has completely stopped.

Drum Controller

Drum controllers are manual switches used for trains, hoists, cranes, machine tools, and other applications where it is necessary to cut out resistance from the motor circuit. The general type of drum switch is usually made for reversing and accelerating. However, these switches are also designed to include other operations such as braking and field acceleration. In appearance, the drum controller is similar to the drum type of reversing switch which was described earlier in this chapter, except that it is larger and contains more contacts. Inside the switch there is a cylinder on which is located a series of contacts, each insulated from one another and from the cylinder. These contacts are called the *movable contacts*. There is also a series of stationary contacts located inside the controller, but not on the rotating cylinder, so arranged as to make contact with those on the cylinder as it is rotated. On top of the controller is a handle which can be moved clockwise or counterclockwise for either direction of rotation of the motor. The handle may be held stationary in any desired position in either the forward or reverse direction by means of a roller and a grooved wheel. At each successive position of the handle the roller drops into the grooved wheel and keeps the cylinder from moving either way until moved by the operator.

Arcing usually occurs when the contacts are moved from one position to another. To reduce arcing, blowout coils are provided in many controllers. Shields made of asbestos or other flame-resistant material are placed between contacts to prevent arc-overs. These arc shields also prevent short circuits caused by arcing. The shields are removable and easily replaced.

A simple type of drum controller having two steps of resistance is illustrated in Figure 8-90. The diagram shows the controller rolled flat. There are two sets of movable contacts and one set of stationary contacts. For forward direction, one set of the movable contacts makes contact with the stationary set. For the reverse direction, the other set of movable contacts is in the circuit. Note that there are three forward positions and three reverse positions to which the handle can be set.

The controller operation is as follows: In the first position, movable fingers *a, b, c,* and *d* of Figure 8-90 contact the stationary contacts *7, 5, 4,* and *3.* The current travels from *7* to *a,* to *b,* to *5,* and through the armature to *4.* From *4* the current flows through *c,* and *d* to *3,* through all the resistance, to the series field, and to negative, giving the connections shown in Figure 8-91. On the second position, part of the resistance is cut out. The third position removes all the resistance from the circuit and places the motor across the line. The shunt field is across the line at all times.

Troubleshooting and Repair

The procedure in locating trouble on d-c controllers is similar to the procedure used for a-c controllers, and a review of Chapter 5, Alternating-current Controllers, will be found helpful in locating trouble on d-c magnetic controllers. Typical troubles that occur in manual d-c controllers are given below.

1. If the motor does not start when the handle is moved several points, the trouble may be:

a. Open fuse, breaker, or relay

b. Open resistance unit; test by placing a 115-volt test lamp across adjacent contact points; the lamp should light; if it does not, the resistance between the two points is open

c. Poor contact between the arm and the contact points; arcing may occur

d. Wrong connection on starter (This may occur on four-point boxes when the starter is first connected; if the two line terminals are not connected properly, the motor will not start, but the handle will hold if brought to the last point.)

e. Broken wires may cause open circuits in the armature or field circuits

f. Low voltage

g. Excessive load

h. Loose or dirty terminal connections

i. An open holding coil in a three-point box; this will cause an open field circuit.

2. If the handle does not hold when it is brought to the last point, the trouble may be:

a. An open holding coil, due to burn-out, broken leads, or poor contacts

b. Low voltage

c. Shorted coil

d. Wrong connection

e. Overload contacts open.

3. If the fuse blows when the handle is moved up, the trouble may be:

a. Grounded resistance units, contacts, or wires

b. Handle brought up too quickly

c. Open shunt-field circuit on starting box; in a three-point box, the trouble may be in the holding coil

d. Resistance shorted out.

4. If the starting box overheats, the trouble may be:

a. Overloaded motor

b. Handle brought up too slowly

c. Shorted resistance units or contacts.

5. If a magnetic switch is used in conjunction with the manual starter, consult the troubles as listed at the end of Chapter 5.

CHAPTER 9

Universal, Shaded-pole, and Fan Motors

The motors discussed in this chapter are used in a variety of appliances that are in common use today.

Universal Motors

A universal motor is one which can be operated on either direct current or single-phase alternating current at approximately the same speed. This motor is most popular in the fractional horsepower size and is used on household appliances such as vacuum cleaners, food mixers, drills, and sewing machines.

Universal motors are series wound and have high starting torque and a variable speed characteristic. They run at dangerously high speed without a load, and, because of this, they are usually built into the device they drive.

There are several types of universal motors in use today. The most popular type is similar to the small two-pole series motor with two concentrated field poles. Another type of universal motor has a field winding distributed in slots, much the same as the split-phase motor. These motors are generally made in sizes varying from $\frac{1}{200}$ to $\frac{1}{3}$ h.p., but are obtainable in much larger sizes for special applications.

Since the universal motor is similar in many respects to the d-c series motor, it is advisable that the student first review Chapter 6, Direct-current Armature Winding, and Chapter 7, Direct-current Motors, before studying this chapter.

Construction of the Universal Motor

The main parts of the concentrated-field universal motor are (1) frame, (2) field core, (3) armature, (4) end plates.

The *frame* is a rolled steel, aluminum, or cast-iron shell similar to that in Figure 9-1 and large enough to hold the field core laminations snugly. The field poles are generally held in the frame by means of through bolts. Very often the frame is constructed to form an integral part of the machine it supports.

The *field core,* shown with other components of the motor in Figure 9-2, is constructed of laminations which are tightly pressed together and held by rivets or bolts. As shown in Figure 9-3, the laminations are designed to contain both field poles of a two-pole motor.

The *armature* is similar to that of the small d-c motor. It consists essentially of a laminated core having either straight or skewed slots and a commutator to which the leads of the armature winding are connected. Both the core and commutator are pressed on the shaft.

As in other motors, the *end plates* are located on the ends of the frame and held in place by screws. The plates house the bearings, usually of the ball or sleeve type, in which the armature shaft revolves. Many universal motors contain an end plate which is cast as part of the frame. Only one plate can be removed from this type of motor. Brush holders are usually bolted to the front end plate, as illustrated in Figure 9-4.

Operation of the Universal Motor

The universal motor is so constructed that when the armature and field coils are connected in series and the current applied, the magnetic lines of force created by the fields will react with the lines of force created by the armature and cause rotation. This is true regardless of whether the current is alternating or direct.

Rewinding the Field Coils

Nearly all universal motors are two-pole machines and therefore have two field coils. Just as in the d-c series motor, the field-pole windings consist of relatively few turns of wire. Thus, there may be a few hundred turns on each coil in contrast to several thousand on a shunt-field coil.

If new field coils are to be made, proceed in the following manner:

Remove the old coils from the core. These are usually held in place by one or two pins, shown in Figure 9-5, which are forced through a small hole in the field core and must be removed first. Some field coils are secured to the core by a thin iron clamp that extends from one side of the coil to the other, as shown in Figure 9-6. Sometimes a piece of fiber is wedged from one field coil to another, as shown in Figure 9-7. The shape of the field coils is illustrated in Figure 9-8.

Remove the tape from the coils; then record the wire size and the number of turns in each coil. The insulation of the wire is usually enamel or Formvar. Use the same size of wire with the same kind of insulation.

Flatten the coil to a rectangle, like that shown in Figure 9-9, to make a form for the new coil. Before taking measurements for the form, remove all the tape covering so that the new coil will be the same size as the old coil. If the coil is made slightly smaller, there will be difficulty in putting the coil on the core. On the other hand, if the coil is made large, it may take up too much room and perhaps prevent assembly of the end plate on the frame.

Cut a piece of wood to the dimensions of the inside of the coil. This will be the form on which the new coil will be wound. To facilitate removal of the coil after it is wound, taper the sides slightly and place one turn of insulating paper around it. To hold the coil in position while winding, bolt two sidepieces to the form, as in the assembly shown in Figure 9-10. Place the form in the lathe or winding machine and wind the proper number of turns of the right size of wire on the form. Tie the coil before removing it, using the slits cut in the sidepieces as guides. Field coils may also be wound on coil winder heads, as shown in Figure 7-14(b).

Splice flexible leads to the ends of the coil wire. Be sure to tie the leads to the coil to prevent them from being pulled out accidentally. Tape the coil with one layer of varnished cambric and one layer of cotton tape, wrapping the coil as shown in Figure 9-11. Shape the coil so that it is like the original, and then paint or varnish it. After it dries, place it on the core and secure it in the original manner.

If the coil fits tightly, be careful not to scrape the corners on the core; otherwise the wires may ground or break. It is good practice to place insulation at the corners of the coils to eliminate this possibility. Do not pull on the leads while putting the coils in place because this can loosen or break the connections.

Connecting the Field Coils and Armature

The field poles of a universal motor are connected in series for opposite polarity, just like the poles of any d-c motor. The methods of testing the field poles for correct polarity are the same as those used on d-c poles, namely, the nail test shown in Figure 9-12 or the compass method. These are preferred, but another way, as explained in Chapter 7, is to connect the two fields in series without regard to polarity and then reverse the leads of one pole if the motor does not run.

As in the case of all two-pole series motors, both fields are connected in series as described above and then in series with the armature, as shown in Figure 9-13. Figure 9-14 shows that one line wire is brought from the armature and the other line wire from the field.

Another method of connecting the universal motor is to connect the armature between the two field coils, as shown in Figure 9-15. The end of the first field coil is connected to one side of the armature, and the other side of the armature is connected to the next field pole.

Reversing the Universal Motor

In a universal motor of the concentrated-field type, the direction of the rotation is changed by reversing the flow of current through either the armature or the field coils. The usual method is to interchange the leads on the brush holders. Figure 9-16 shows this motor connected for clockwise rotation, and Figure 9-17, for counterclockwise rotation.

On many universal motors, especially those in which the brush holders cannot be shifted, reversing the rotation will cause severe arcing and sparking at the brushes, because most of these motors are made for specific application and are wound for operation in only one direction. Reversing the direction will cause the brushes to be off the required sparkless plane. The only way in which these motors can be reversed without causing sparking is to relocate the leads on the commutator. This will be more fully discussed later.

Winding the Armature

Armatures for universal motors are wound in the same manner as those for small d-c motors. Just as in any armature or stator, the first step in rewinding is to secure sufficient accurate information concerning the old winding to enable the repairman to rewind the armature with the correct turns, coil pitch, lead throw, and size of wire.

Taking Data Before data on an armature are taken, there are a few pertinent facts about universal armatures that will help in gathering the necessary information. These are as follows:

All two-pole universal armatures are lap wound with the beginning and end leads of a coil connected to adjacent commutator bars, as in Figure 9-18. Most universal armatures are also loop wound, as in Figure 9-19. After one coil is wound, a loop is made and then the next coil is wound. Nearly all universal armatures contain two coils in each slot, and there are twice as many commutator bars as slots. It also means that there are two loops for each slot. There are also one- and three-coil-per-slot universal armatures, but in this section discussion will be confined to two-coil-per-slot armatures.

Proceed in the following manner in taking data on a universal armature: Count and record on a data sheet the number of slots and commutator bars. Align the center of a slot with a string or straightedge and see if it lines up with a bar or mica. Record this on the data sheet by making a drawing such as Figure 9-20. Find the pitch of the coils by counting the slots between the top completely exposed coil, and record it on the data sheet as 1 and 6 or 1 and 5, as the case may be. Figure 9-21 illustrates a 1-and-6 pitch. The pitch of the armature coils is always approximately one-half the total number of slots for a two-pole motor.

Lead Throw All the data so far recorded have been obtained without removing any wires from the armature. The remainder of the information is gathered during the process of stripping the armature. The lead throw is the information to be secured next.

This should be as exact as possible, although it may be difficult to achieve accuracy because of the varnish on the windings. This information is important if sparkless operation is desired.

The following method is used to determine the correct lead throw:

Carefully unwind several coils, starting with the top coil, and mark on the commutator exactly where the beginning and end leads of at least two adjacent coils are located. In order to unwind the top coil it will be necessary to pick up all of the leads over this coil. Thus, as a coil is unwound to a loop, mark the slots of the coil and the commutator bar lightly with a center punch. Record whether this is the loop of the first or second of the two coils in the slot. Figure 9-22 illustrates this procedure. The leads of the coils to be taken out are still attached to the bars and are removed as each coil is unwound. As coil *7* is removed, the beginning lead of this coil can be seen attached to commutator bar *3*. This is three bars to the right of the slot in which coil *7* is wound. The commutator bar, as well as the slots of coil *7*, should be marked. This information should be recorded on the data sheet accompanied by a diagram like that in Figure 9-22. In this method it is assumed that the coils can be unwound. On some armatures the varnish on the coils may make this impossible.

When this armature is to be rewound, the first coil is started in the marked slots and the first lead is put in bar *3*. All loops follow in sequence.

Figure 9-22 shows that the wires are unwound in a clockwise direction, indicating that the coils were wound in a counterclockwise direction. Also, it will be noted that the coils progress to the left. This information, too, is recorded.

The number of turns per coil is obtained as the coils are unwound, and the size of wire is measured with a wire gauge or micrometer.

Usually the armatures are varnished and baked to such an extent that it is extremely difficult to unwind the coils. This is especially true of the topmost coils. In this event the first four or five coils, or more, are cut off in order to reach a coil that can be unwound. If the coils are burned or charred, unwinding is usually a simple operation. It is only necessary to unwind a sufficient number of coils to obtain the data; all other coils can be cut and pulled out. All wedges must be removed before the coils are unwound.

Using the Growler to Obtain Lead Throw If the armature is not completely shorted or open, a simpler method can be used to obtain the lead data. The procedure is as follows:

Place the armature on a growler, as illustrated in Figure 9-23. If a coil is shorted, a hacksaw blade will vibrate when placed over the slot in which the shorted coil is located. If two bars are shorted, the same effect will be produced over two slots. This is the principle used to obtain lead throw.

Short-circuit two bars with a piece of wire, and then with a hacksaw blade locate the slot which causes the blade to vibrate. Turn the armature so that this slot is on top. Short-circuit the next two bars and see if the hacksaw blade vibrates on the same slot. If it does, mark the three bars that were used for this test, and also mark the slots of the coils which caused the blade to vibrate.

Stripping the Armature After recording all the data, the entire armature is stripped and all the old insulation removed. This is done by either unwinding all the coils or by cutting the wire on both ends with a hacksaw and then pushing the wire through the slots. New insulation of the same thickness is used, but it is cut to extend above the slots about ¼ in. and on both ends of the slot about $\frac{1}{16}$ in.

It is important that the commutator be tested for shorts and grounds before the new winding is put on and also that slots be cut in each bar to hold the loops. Be sure that the width of the slots in the commutator is the same as the diameter of the wire with which the armature is wound.

Winding Procedure The method of rewinding the armature of a universal motor is similar to that presented in Chapter 6. Briefly, the procedure is as follows:

Start with any slot, wind the required number of turns into the slots of the proper pitch, and make a loop. Wind the same number of turns into the same slots as the first coil and make another loop. Wind the next two coils into the next slot. Vary the lengths of the loops so that the leads can be identified when they are placed in the commutator bars. Identification may also be provided by using sleeving of different colors on the leads.

Some slight differences will be found in different motors; for example, on some armatures the coils are wound in a clockwise direction, and on others they are wound counterclockwise. In addition, the coils may progress in a right-hand direction or in a left-hand direction. In some armatures the coil leads are on the front of the winding and on others on the back or pulley side. Also, the leads on some armatures will be found on the left side of the coil, while on others they are located on the right side. The best policy to follow is to rewind an armature exactly as it was originally wound. If the armature coils were originally wound in a clockwise direction, as in Figure 9-24, rewind them that way. If the coils were wound counterclockwise, then rewind them in that direction, as shown in Figure 9-25. If the leads or loops were originally located on the right-hand side of the coil, as illustrated in Figure 9-26, rewind them that way. This also applies to loops placed on the left-hand side of the coil, as in Figure 9-27.

Sometimes, as shown in Figure 9-28, the armature leads are located at the back of the armature, and in this case the leads are brought through the slots so that they can be connected to the commutator.

Position of Leads in Commutator It is important that the position of the leads in the commutator be exactly the same as in the original winding. If the leads are placed one or two bars from the correct position, severe sparking will occur. The position of the leads is usually determined by the direction of rotation of the motor and will be different for one direction of rotation from the position for another. However, some universal motors are designed to operate equally well in either direction, although most of them are made for operation in one direction.

If the motor is designed for clockwise rotation, the leads of a coil are usually placed two or three commutator bars to the right of the coil, as shown in Figures 9-29 and 9-30. For counterclockwise rotation, the leads are usually connected several bars to the left of the coil, as shown in Figures 9-31 and 9-32. For rotation in either direction, the leads should be midway between those for clockwise and counterclockwise rotation.

If the armature coils were originally wound in a clockwise direction but are rewound counterclockwise, the motor will run in the opposite direction and spark badly. Reversing the brush leads will reverse the motor and also stop the sparking.

Distributed-field Compensated Motor

This type of universal motor, the essential parts of which are shown in Figure 9-33, has a stator core similar to that of the split-phase motor and an armature similar to that of the concentrated-field motor. There are two types of distributed-field universal motors. One type is called the *single-field compensated motor* and has one stator winding. The other is called the *two-field compensated motor* and has two stator windings.

The two-pole, single-field compensated motor has a stator winding like the main winding of a two-pole, split-phase motor. The fields are wound into the slots of the stator in the same manner. The field poles must be of opposite polarity and connected in series with the armature. Motors of this type are also constructed with four or more poles. To reverse this motor, interchange either the armature or field leads and shift the brushes against the direction in which the motor will rotate. The extent of the brush shift ordinarily amounts to several bars.

The two-field compensated motor has two windings in the stator, a main winding and a compensating winding. These are like the running and starting windings of a split-phase motor and are located 90 electrical degrees from one another. The compensating winding is used to reduce the reactance voltage present in the armature when it is operating on alternating current. This voltage is caused by the alternating flux, and its effect is to reduce the voltage in the armature with a consequent loss in speed and power.

Stripping and Winding When a compensated universal motor is stripped, it is essential that the slots be accurately marked so that the new winding will be located pole for pole in the same slots as the original winding. If the new winding is located one slot out of the way, severe sparking will occur. The only remedy for this is to shift the brushes or rewind.

When this motor is rewound, the main winding is usually placed in the slots first, and the compensating winding is put over this 90 electrical degrees away. Skein or form winding is generally used for the stator coils. A connection diagram of a two-pole compensated motor is shown in Figures 9-34 and 9-35. Note that the main field, compensating field, and armature are in series.

Two poles are usually found in small motors, and four or six poles are used in the larger universal motors. The main poles are usually wound with only one or two coils per pole, and the compensating poles have three or four coils per pole. A layout diagram of a 12-slot, two-pole motor is shown in Figure 9-36. To reverse this motor, either the main winding leads or the compensating winding and armature as a unit are interchanged. The brushes do not have to be shifted.

Speed Control of Universal Motor

The speed of a universal motor can be regulated by inserting resistance in series with the motor, by using a tapped field, or by means of a centrifugal device.

Resistance Method The speed of small universal motors such as those used on sewing machines is varied by a small variable resistance connected in series with the motor, as shown in Figure 9-37. The amount of resistance in the circuit is varied by means of a foot pedal and may consist of a carbon pile or resistance wire.

Another type of speed control on small universal motors, which is illustrated in Figure 9-38, consists of two carbon blocks which are manually pressed tightly together for high-speed operation. As these blocks are slowly moved apart, they allow less current to flow and consequently slow down the motor. These motors start on very slow speed because the speed switch separates the carbons at start. As the switch is moved, it causes the carbons to increase their pressure, thereby allowing more current to flow. When the carbon blocks are separated entirely, a fixed resistance remains in the circuit, as shown in Figure 9-38. The capacitor is used to reduce arcing.

Tapped Field The speed of some universal motors is controlled by tapping one field pole at various points, as illustrated in Figure 9-39, thereby varying the field strength and consequently the speed.

The field pole is wound in several sections, with different sizes of wire and taps brought out from each section. Another method is to wind Nichrome resistance wire over one field pole and bring taps out from this. The lowest speed is obtained when the entire winding is in the circuit; medium speed, when part of the field is out of the circuit; and high speed, when this winding is eliminated.

Centrifugal Device Many universal motors, such as those used for home food mixers, have a number of speeds. Selection is usually made by a centrifugal mechanism located inside the motor and connected as shown in Figure 9-40. The switch can be adjusted by means of an external lever. If the motor runs above the speed set by the lever, the centrifugal mechanism will open two contacts and insert resistance in the circuit, which will in turn cause the motor speed to decrease. When the motor slows, the two contacts close and short the resistance so that the motor runs faster. This process is repeated so rapidly that the variation in speed is not noticeable.

The resistance is connected across the two governor contacts, as shown in Figure 9-40. Since sparking will occur with the opening and closing of these contacts, a small capacitor is connected across them in order to reduce the sparks and prevent pitting of the contacts. As many as sixteen different speeds can be obtained in this manner.

Troubleshooting and Repair of a Universal Motor

Testing Both the field winding and the armature must be tested for defects before and after assembly. The fields must be tested for grounds, shorts, opens, and reverses in the same manner as d-c fields are tested. All these tests are described fully in Chapter 7 on d-c motors. In the case of universal motors with distributed-field windings, the method described in Chapter 1, Split-phase Motors, is to be followed. Because the armature of the universal motor is like the d-c armature, the tests are the same. Refer to Chapter 6 for the methods used in determining and locating defects in d-c armatures and commutators. It should be remembered that before an armature is rewound, the commutator should be tested for for shorts and grounds.

Repair The troubles encountered in universal motors are the same as those found in d-c motors. All the troubles and their remedies listed below have been discussed in Chapters 6 and 7.

1. If the motor sparks badly, the trouble may be:
   a. Wrong lead position on the commutator
   b. Shorted field poles
   c. Open armature coils
   d. Shorted armature coils
   e. Reversed coil leads
   f. Worn bearings
   g. High mica
   h. Wrong direction of rotation.
2. If the motor runs hot, the trouble may be:
   a. Worn bearings
   b. Dry bearings
   c. Shorted coils
   d. Overload
   e. Shorted fields
   f. Brushes off-neutral.
3. If the motor smokes, the trouble may be:
   a. Shorted armature
   b. Shorted fields
   c. Worn bearings
   d. Wrong voltage
   e. Overload.
4. If the motor has poor torque, the trouble may be:
   a. Shorted coils
   b. Shorted field
   c. Wrong brush position
   d. Worn bearings.

Shaded-pole Motors

The shaded-pole motor is a single-phase a-c motor varying in size from approximately $\frac{1}{100}$ to $\frac{1}{20}$ h.p. It is used for applications requiring very low starting torque, such as fans and blowers. A typical shaded-pole motor is illustrated in Figure 9-41.

Construction of the Shaded-pole Motor

The main parts of a shaded-pole motor are shown in Figure 9-42. These are a stator or field frame, a rotor, and end plates.

The stator is usually of the concentrated-field type and has a laminated core consisting of salient field poles on which a coil of wire is placed. The poles are provided with a slot near one end in which a solid copper coil of one turn, called the *shading coil,* is placed. Many shaded-pole motors have a slotted stator like that of a split-phase motor in which the winding is placed in the slots.

All shaded-pole motors have rotors of the squirrel-cage type, such as are used on split-phase and polyphase motors.

On many of these motors only one end plate can be removed, the other being cast as part of the frame. The end plates are fiitted with either ball or sleeve bearings.

Operation of the Shaded-pole Motor

All single-phase induction motors require an auxiliary winding to provide the motor with a starting torque. On split-phase and capacitor motors, a starting winding located 90 electrical degrees from the running winding is used for this purpose. A shaded-pole motor also requires a starting winding, but in this case it usually consists of just one closed turn of heavy copper wire embedded in one side of each stator pole.

On starting, a current is induced into the shaded poles from the main poles. The shading coils establish a magnetic field which is out of phase with that established by the main fields, and a shifting field is produced sufficient to give the desired starting torque. When the motor reaches speed, the effect of the shading coils is negligible. When current is induced into the shading coils, a flux is built up which opposes the flux which produced it. Because of the nature of the sine curve and its changing instantaneous values during a cycle, the shading-coil flux will tend to keep the main-pole flux in the unshaded part of the pole during the change from 0 to near maximum. From this point to a similar point as the current drops, very little current is induced in the shaded coil, and as a result the main-pole flux will be distributed over the entire pole face. So far the magnetic axis has shifted from the unshaded part of the pole to the center of the pole. During that part of the sine curve where the current drops from near maximum to 0, current will again be induced in the shaded coil, creating a strong flux, this time in the same direction as the original unshaded-pole polarity. Consequently, in one half cycle the magnetic-axis flux has shifted from the unshaded part of the pole to the shaded part. Actually the shaded-pole flux has lagged behind main-pole flux during the half cycle. Since the flux has shifted from the unshaded part of the pole to the shaded part of the pole, the rotation of the motor will also be from the unshaded to the shaded part of the pole.

Shaded-pole Windings

The ordinary shaded-pole motor has projecting field poles on which are placed the shading turns, as shown in Figure 9-43. The coils that fit over the poles are usually wound on forms like those used for winding d-c field poles and universal-motor fields of the concentrated type. Leads are connected to the coil ends, and the entire coil is taped and placed over the pole. The field coils are usually held in position by means of a metal wedge placed between poles. If the metal wedge is made of iron or other magnetic material, the operation of the motor may be improved.

In rewinding, be sure to put back the same number of turns of the same size wire with the same insulation. Also, be certain that the new coils are the same size as the old ones, otherwise difficulty may be encountered in slipping them over the poles. It is good practice to put insulating paper on the corners or around the core to prevent the coil from grounding.

Shaded-pole motors are made for two, four, six, and eight poles, and adjacent poles are connected for alternate polarity. A connection diagram of a concentrated-field type, four-pole shaded-pole motor is shown in Figure 9-44.

Shaded-pole motors are also constructed with a stator similar to that used in split-phase motors. The stator has a distributed winding that is wound in the same manner as that of the split-phase motor. Instead of the solid copper ring used in the concentrated type, the shaded winding consists of coils of wire that are wound into slots. A typical layout of the main and shaded winding of a four-pole, 12-slot motor is shown in Figure 9-45, and a wiring diagram is shown in Figure 9-46. Note that the shaded winding is connected for alternate polarity and closes on itself. Note also that it occupies only about one-third of a pole side.

Reversing a Shaded-pole Motor

Some shaded-pole motors are constructed so that they can be reversed merely by throwing a switch. Most of them, however, cannot be reversed unless they are taken apart. To reverse this type of motor, disassemble the motor, reverse the stator end for end, and reassemble. Because the direction of rotation of a shaded-pole motor is from the main pole to the shaded pole, it can be seen that in Figure 9-47 the direction will be clockwise and in Figure 9-48, counterclockwise. This method of reversing must be used if the motor is not externally reversible.

One type of shaded-pole motor that can be reversed externally has one main winding and two separate shaded windings. The stator of this motor has slots into which the windings are placed. The main winding is usually distributed over several slots but may have only one coil per pole.

Each of the two shaded-pole windings has as many poles as the main windings, but only one shaded winding is used at a time. One shaded winding forms a pole at one side of each main pole; the other forms a pole on the other side. This is illustrated in Figure 9-49, where a complete pole consists of one main coil and two shaded coils. A typical layout of a 12-slot, four-pole motor is shown in Figure 9-50. Figure 9-51 shows a diagram of the connections for this motor. The main poles are connected in series for alternate polarity and so are the shading poles. When rotation is desired in a certain direction, the circuit of one shaded winding is closed and the other is left open, as shown in Figure 9-51.

To reverse the motor, it is necessary to open the closed shaded-winding circuit and close the other shaded-winding circuit. Thus, the position of the shaded poles is changed with reference to the main poles.

Another type of reversible shaded-pole motor has two main windings and one shaded-pole winding. Figure 9-52 shows two poles of this winding, and Figure 9-53 presents a typical layout of a four-pole, 12-slot motor. The shaded-pole winding on this motor may be of the wound type, or it may have a single closed piece of copper. For clockwise direction, one main winding is used, while the other main winding is open. For counterclockwise direction, the main windings are reversed.

The procedure for testing and troubleshooting of these two motor types is the same as for other types of motors.

Fan Motors: Speed Control

This section deals with the methods used for obtaining a variety of speeds from different types of motors when used on fans and blowers. These motors have been discussed in detail earlier in this chapter and in the chapters on split-phase, capacitor, and polyphase motors. Only the methods of varying the speeds of these fan motors will be discussed here.

Floor-type Fans

Either split-phase or capacitor motors are used for floor fans. The split-phase, two-speed motors are generally made with two running windings and either one or two starting windings, depending on the manufacturer. Schematic diagrams of two of these motors are shown in Figures 9-54 and 9-55.

A three-speed, split-phase motor is shown in Figure 9-56. The three speeds are obtained with only three windings: one running, one auxiliary, and one starting winding. The running and auxiliary windings are wound in the same slots, and the starting winding is located 90 electrical degrees away. For high speed, the running winding is connected across the line, and the starting winding is connected in series with the auxiliary winding across the line. For medium speed, the running winding is connected in series with half the auxiliary winding, and the starting winding is connected in series with the other half of the auxiliary winding. For low speed, the running and auxiliary windings are in series across the line, and the starting winding is connected across the line. Actually, a tap at the inside point of the auxiliary is brought out for medium speed. A centrifugal switch is connected in series with the starting winding. This motor is used also on wall fans.

In another type of split-phase fan motor with two speeds, only a running winding and a starting winding are necessary. A four-pole motor will be considered, although these motors are made for a variety of poles. For high-speed operation, the four running poles are connected in two circuits to produce alternate polarity in adjacent poles. For low-speed operation, the four poles are connected in series to produce the same polarity in two adjacent poles. The latter is a consequent-pole connection and will cause four additional poles to be formed between the main poles. Therefore, the motor will rotate at the slower, eight-pole speed. In both cases, the starting winding is connected across the line. There are two salient starting poles with consequent-pole connection, producing four poles for both speeds. Four leads are usually brought out of the motor. A diagram of this motor is shown in Figure 1-77.

Two-speed capacitor motors are also used for floor fans. One type is similar to the split-phase motor of Figure 9-54, except that a capacitor is included in the starting-winding circuit as illustrated in Figure 9-57.

Another type of capacitor motor used for two-speed floor fans is the tapped-field (permanent-split) capacitor motor. This motor, illustrated in Figure 9-58, does not use a centrifugal switch. For three speeds, the auxiliary winding is tapped at the center point, and a lead is brought out for medium speed, as shown in Figure 9-59. This motor is similar to the three-speed, split-phase motor, except that the centrifugal switch is removed and a capacitor substituted. This motor is used extensively for blowers in air-conditioning systems.

Wall and Desk Fans

Wall and desk fans are of many types, and their motors range from universal through split-phase, capacitor, shaded-pole, and three-phase. All operate on single-phase current.

The universal type has a resistance unit in the base to vary the speed and is connected as shown in Figure 9-60. A lever that extends outside the base is used to insert the resistance in the circuit.

Split-phase motors for use on wall fans are wound like the ordinary split-phase motor, but many do not have a centrifugal switch. A special type of autotransformer, located in the base of the fan, as shown in Figure 9-61, is used to change the speed and also to produce an out-of-phase current in the starting winding. The primary of the transformer is tapped for different speeds and is connected in series with the main winding. The starting winding is connected across the transformer secondary. These motors are usually wound for six poles.

A capacitor motor for a wall fan is shown in Figure 9-62. This contains a capacitor of approximately 1 μf in the starting-winding circuit. To increase the effective capacity and consequently the starting torque of this motor, the capacitor is connected across an autotransformer. The taps on the transformer permit a choice of various speeds.

Fans for Unit Heaters

Unit heaters are usually suspended from the ceiling of large rooms and are equipped with a fan or blower that distributes the heat generated in the heater. The fan or blower motor is usually connected to an autotransformer for speed variation and is controlled from a snap switch connected to the autotransformer unit, as shown in Figure 9-63. The motors are generally of the single-value, permanent-split capacitor type. To decrease the speed of this type of motor, the voltage in the running and starting windings is lowered by means of the autotransformer. The lower the impressed voltage is, the slower the motor will run.

Different manufacturers use different methods for varying the speed. On some motors only the running-winding voltage is varied while the voltage in the starting winding is held constant. On other motors the running winding consists of two sections connected in series across 230 volts for high speed. If low speed is desired, the two sections are connected to 115 volts through an autotransformer. Usually, these unit-heater motors are connected for three speeds.

Many fans are made with a motor of the shaded-pole type. The speed of these motors is varied by inserting a choke coil in series with the main winding, as shown in Figure 9-64. Taps on the choke coil provide the different speeds.

Figures 9-65, 9-66, and 9-67 show the connection diagrams for a multispeed shaded-pole motor used for fans, small blowers, and unit heaters. Speed control is obtained by means of tapped windings. Figures 9-65 and 9-66 show the internal connections while Figure 9-67 illustrates the external connection.

Some fan motors have a three-phase, star-connected winding but are operated on single phase. In this motor, one winding has several coils of Nichrome resistance wire, as shown in Figure 9-68, which causes the current in the winding to be out of phase with the others. Another winding is connected in series with an inductance located in the base of the fan and tapped to provide the various speeds. The third phase is connected to the line. The resistance and inductance produce the revolving field that causes the rotor to turn.

Single-speed Fan Motors

Blower and large-fan motors are often wound and connected for three-phase current and are generally single speed. One such type, shown in Figures 9-69 and 9-70, has 48 slots and 24 coils and is connected series-star for eight poles. The coils of this motor are placed in alternate slots, one coil occupying two complete slots. If designed for two-voltage operation, it is connected series-delta for low voltage and series-star for high voltage. Six wires must be brought from this motor for two-voltage operation.

Small-motor Selector Guide

The small-motor selection guide shown in Figure 9-71 outlines comparative characteristics of the principal standard types of motors which meet the needs of the vast majority of applications. The selection guide is reproduced by permission of Westinghouse Electric Company.

CHAPTER 10

Direct-current Generators; Synchronous Motors and Generators; Synchros; Electronic Control of Motors Using Electron Tubes

The difference between a motor and a generator should be clearly understood before the subject of d-c generators is studied. It was pointed out previously that a motor is a machine that, when supplied with electric current, can be used for mechanical work, such as running an elevator or driving a pump. A generator, on the other hand, is a machine that is driven by mechanical means, such as a steam engine, diesel engine, or electric motor, and produces electric current. Direct-current generators are rated in kilowatts and range in size from a fraction of a kilowatt to several thousand kilowatts. Figure 10-1 illustrates a d-c generator of medium size.

Direct-current Generators

Direct-current generators are similar to d-c motors in appearance and construction. They have the same type of armature and field poles and are generally identical. For this reason, a d-c generator can easily be converted into a motor; likewise, a motor can easily be converted into a generator.

Operation of the D-C Generator

If a conductor is moved across the lines of force in a magnetic field, as shown in Figure 10-2, a voltage will be induced in the conductors. This voltage can be measured by connecting a voltmeter across the terminals of the conductor. If several conductors are connected in series (like turns of a coil), the value of the voltage generated will be equal to the sum of the voltages generated in each conductor. The value of the generated voltage also depends on the strength of the magnetic field and the speed with which the conductors cut the magnetic field. The stronger the magnetic field, the greater the voltage; likewise, the higher the speed of cutting, the larger the voltage.

If the conductor shown in Figure 10-2 is moved downward, as shown in the illustration, the current induced in the conductor will flow in the direction indicated by the arrows. When the conductor is moved upward, the current will flow in the opposite direction. This observation shows that the direction of current flow depends on the motion of the conductor. Similarly, a change in the direction of the magnetic lines of force will also cause a change in the direction of the induced current.

Figure 10-3 shows a conductor wound like an armature coil with leads connected to a two-bar commutator. If the armature is rotated, the conductor will cut the lines of force, and direct current can be obtained from the brushes riding on the commutator.

Thus, three factors are needed to generate electricity. These are (1) magnetic lines of force (flux), (2) a conductor, and (3) cutting of the flux lines by the conductor.

The three methods of producing the lines of force necessary in generating electricity are as follows:

1. Use of permanent magnets, as in magnetos.
2. Excitation of the generator field coils with direct current from a battery or small generator (separate excitation).
3. Excitation of the field coils by current from the armature (self-excitation).

The Separately Excited Generator

When the field coils are connected to an outside source of electricity, the generator is known as a *separately excited* generator. Figure 10-4 shows a two-pole shunt generator with the field coils energized by a battery. When the armature rotates in the magnetic field, current is supplied to the load.

The Self-excited Generator

Most generators use some of the current generated in the armature to supply excitation current to the fields. This type is called a *self-excited* generator. Figure 10-5 shows the shunt field connected to the armature. At standstill, the magnetic field is due only to residual magnetism of the field core and is very weak. When the armature rotates, the conductors cut this weak flux and generate a very low voltage that will excite the field coils slightly and create additional lines of force. Because the armature now turns in a stronger magnetic flux, it will generate higher voltage and cause more current to flow to the fields, which in turn will produce more lines of force. This action continues until the field poles saturate magnetically. This process in which the voltage increases in a generator is called "the building-up process."

There are three types of self-excited generators; the series generator, the shunt generator, and the compound generator.

The Series Generator The series generator was used at one time for street lighting and is seldom encountered nowadays. The circuit of a series generator is shown in Figure 10-6. The connections are like those of a series motor with the load replacing the current source. The armature, fields, and load are all connected in series. If the load is disconnected from the generator terminals, the circuit through the generator will be open, and consequently no current can flow through the field coils and no voltage will be generated. If a small load such as a lamp is connected, a small current will flow through the generator. This will create a small magnetic flux, and a low voltage will be generated. If a heavier load is put on the generator, a greater current will flow, and consequently more lines of force will be produced and a higher voltage generated. Thus, as the load on a series generator is increased, the lines of force are increased, and these in turn increase the generated voltage. This is one of the characteristics of a series generator: The voltage at no load is zero and it increases to a maximum at full load.

The Shunt Generator The field coils of the shunt generator are connected across the armature terminals, as illustrated in Figure 10-5. The field strength, therefore, is practically constant regardless of load. However, as the load is increased, the terminal voltage will decrease because of an increased voltage drop within the armature. One characteristic of the shunt generator is therefore that a slight drop in voltage occurs as the load is increased. The voltage at no load is maximum and decreases slightly as the load is increased.

The Compound Generator There are several types of compound generators, the most common being the short-shunt cumulative generator. Like the d-c motor of the same name, this has the shunt field connected across the armature, and the current flow in the shunt field is in the same direction as in the series field. This generator can also be connected long shunt.

Diagrams of the short-shunt connection are shown in Figures 10-7 and 10-8. This generator usually supplies constant voltage regardless of load, but its regulation can be varied by changing the number of turns in the series field winding or by using a resistor across the series field to vary the current through it. This is called a *diverter*. In general, the characteristic of a compound generator is a combination of the characteristics of both the series and shunt generators.

By changing the number of turns in the series field, it is possible to obtain three types of compound generators. These are (1) an overcompounded generator, (2) a flat-compounded generator, and (3) an undercompounded generator. These generators are designed as such and have the desired series turns to obtain the characteristics described below:

1. If the turns on the series field are increased over the number necessary to give the same voltage output at all loads, the generator will be *overcompounded*. This means that as the load is increased, the generated voltage increases. At no load, normal voltage is obtained, but as the load is increased to full load, the voltage rises approximately 5 percent. This is desirable when the generator is located some distance from the load. The rise in generated voltage compensates for the voltage drop in the line.

2. If the number of turns is decreased, a *flat-compounded* generator is obtained. In this generator, the voltage produced at full load is the same value as the voltage at no load. This generator is used where the load is nearby, such as in the same building.

3. If the turns in the series winding are further decreased, an *undercompounded* generator will result. In this type, the voltage at no load is normal. As the load is increased, the voltage drops con-

siderably, until at full load it is approximately 20 percent below normal. This generator is useful where a short might occur, as in a welding machine.

Differentially Connected Generators

A diagram of a short-shunt differential generator is shown in Figure 10-9. Notice in this illustration that the current in the series field is opposite that in the shunt field. Consequently, as the load increases, the series field strength increases; but because it is in opposition to the shunt field, the resultant flux drops rapidly. The characteristic, therefore, is normal voltage at no load and a rapidly decreasing voltage as the load increases.

Interpoles

On all of the generators mentioned, interpoles are generally used. These are connected in series with the armature, as in d-c motors. The polarity of the interpoles in a generator is, however, opposite to that in a motor. The rule is as follows: The polarity of the interpoles in a generator is the same as the main pole ahead of it in the direction of rotation. Just as in d-c motors, the field poles are tested in the same manner. Either five or six wires are brought out of the generator. Figure 10-10 shows a two-pole interpole generator.

Changing a Compound Motor to a Generator

Compound motors are generally connected long-shunt cumulative. To convert this motor to a generator, it is necessary to change the long shunt to a short shunt and reverse the series-field leads. The first change is readily understandable and need not be made unless desired. The reversing of the field leads must be made for the following reason. In a generator the voltage is supplied to the fields from the armature terminals. Therefore, as shown in Figure 10-11, if the series field of a motor is not reversed, a differential generator will be produced. A short-shunt motor is shown for simplicity. In this change the direction of rotation remains the same.

Regulating the Generated Voltage

To regulate the generated voltage, a field rheostat is inserted in the shunt-field circuit, as in Figure 10-12. This arrangement makes it possible to vary the current in the shunt field, which in turn varies the lines of force. With full current in the field, maximum voltage will be obtained. As resistance is added, the generated voltage will become less.

How to Measure Voltage and Current of a Generator

A voltmeter and ammeter are used to measure the voltage and current, respectively. As illustrated in Figure 10-13, the voltmeter is always connected across the line, and the ammeter in series with the line. The ammeter is really a millivoltmeter with an internal shunt, and actually the meter measures the voltage drop across the shunt. The shunt, however, is calibrated in such a manner that the reading on the meter indicates current flow. Often the meter is supplied with an external shunt; in this case it is connected as shown in Figure 10-14. These meters are connected in the same way for a motor, that is, voltmeter across the line and ammeter in series with the line.

Connecting Compound Generators in Parallel

When a load on a generator exceeds the capacity of the generator, it is necessary either to decrease the load or to connect another generator in parallel with the first one, thereby dividing the load between the machines. A parallel connection of two generators is shown in Figure 10-15.

To connect two generators in parallel, the voltage of each generator must be exactly the same. This can be regulated by means of the field resistance and is measured by a voltmeter. Line wires of the same polarity must be connected together. An equalizer connection, consisting of a wire which connects the series field of both generators in parallel, is necessary. The reason for this equalizer connection is that if generator *1*, at the left of Figure 10-16, runs slightly faster than generator *2*, it will generate more voltage; consequently, more current will flow through the series field and cause the output of generator *1* to exceed the output of generator *2*. Generator *1* will therefore assume more of the load, and generator *2*, less. As the load on generator *2* decreases, more of the burden will be placed on generator *1* until it has taken the full load and generator *2* is running as a motor.

If an equalizer is used, the excess current of generator *1* is divided between the series fields of both generators and prevents one from assuming more of the load than the other. This action is best described with reference to the circuit at the right of Figure 10-16. Each generator now has equal flux and therefore generates equal voltage. As a consequence they share the load equally. The shunt field has been omitted in Figure 10-16 for simplicity.

Troubleshooting and Repair of a D-C Generator

Testing d-c generators is similar to testing d-c motors. The faults and troubles that occur in d-c generators, but not in d-c motors, are described below.

1. If it does not generate, the trouble may be:

a. Loss of residual magnetism: If the field poles lose residual magnetism, it is impossible for the armature to cut lines of force, and therefore no current can be generated. To remedy this condition, the shunt field is connected to a source of direct current for a few seconds.

b. Too much resistance in the field circuit: Because the building up process of a generator depends on the continued increase in the strength of the field, it is obvious that the voltage cannot build up if a high resistance in the field circuit prevents sufficient current from flowing in the field coils to increase the flux. The high resistance may be due to the field rheostat, open circuit in the field, loose connections, poor brush contact, or broken brush pigtails.

c. Wrong field connection: The residual magnetism in a generator produces lines of force from a north pole to a south pole. If the current in the field coils is in the wrong direction, as shown in Figure 10-17, lines of force will be produced opposite to the residual lines, and a cancellation of flux will result which will prevent the generator from building up. To remedy this trouble, reverse the shunt-field connections or reverse the direction of rotation of the generator.

d. Wrong rotation: Wrong direction of rotation is similar to reversed field polarity because it causes the current in the shunt field to flow in the wrong direction. To correct this situation, reverse the direction of rotation or interchange the shunt-field leads.

e. Shorted armature or field: A shorted armature or field may allow only a low voltage to build up. If completely shorted, the voltage will not increase, and the armature will smoke. If all other faults are eliminated, test the armature and field for shorts according to the method described for d-c motors.

2. If the voltage drops considerably as the load is placed on the generator, the trouble may be:

a. Differential connection

b. Shorted armature

c. Overload.

3. If the voltage does not build up to a maximum, the trouble may be:

a. Wrong brush position (Check for the neutral position, as described in Chapter 7, Direct-current Motors; for interpole generators, the neutral point is directly under the center of the interpole.)

b. Shorted armature or field coils

c. Resistance in the field circuit

d. Speed of generator too low.

All the troubles listed above are in addition to those usually found in a d-c motor. For instance, sparking at the brushes of a generator may be due to the same causes as in a d-c motor. A review of the chapter on d-c motors is essential.

Synchronous Motors and Generators; Synchros

A synchronous motor is an a-c motor in which the rotor revolves in step or in synchronism with the rotating magnetic field produced by the stator winding. This action means that if the magnetic field of a 60-cycle, four-pole motor revolves at the rate of 1800 r.p.m., the rotor will also turn at that speed.

In an ordinary induction motor, the rotor turns at a slightly lower speed than the revolving field. This is necessary in order that the squirrel-cage winding be cut by the revolving field and thereby have a current induced in it. Since slip is defined as the difference in speed between the actual r.p.m. of the rotor and that of the magnetic field, a synchronous motor has zero slip.

Synchronous motors of the type shown in Figure 10-18 are made in sizes varying from approximately 20 h.p. to hundreds of horsepower and are used wherever it is necessary or desirable to obtain constant speed. In many cases, synchronous motors are used to improve the power factor of the electrical system of a plant or factory. Many small synchronous motors are also made but are constructed differently from the large ones. The motor shown in Figure 10-18 is a brushless synchronous motor.

Synchronous Motors with Excited Rotor

Some synchronous motors have a rotor that is excited by direct current. Other synchronous motors have a rotor that needs no excitation. The first type has a stator core and winding like the stator of a three-phase induction motor. The rotor of this type has salient field poles, shown in Figure 10-19, similar to the fields of a d-c motor. The field coils which fit over the poles are connected in series for alternate polarity and have two leads brought out to two slip rings on the shaft. The field coils are excited with direct current supplied by a small d-c generator or brushless exciter. On many synchronous motors, the d-c generator is attached to the shaft of the motor to supply the excitation to the rotor fields. A three-phase power source is generally used for the motor stator.

A squirrel-cage or amortisseur winding is provided for starting purposes because this type of motor is not self-starting. The squirrel-cage winding is located around the rotor as it is in an induction motor.

Operation of the Synchronous Motor

When the main line switch to the stator winding of a synchronous motor is closed, a rotating magnetic field is established in the motor, which cuts across the squirrel-cage winding and causes an induced current to flow. The magnetic field of the squirrel-cage winding reacts with the stator field in such a manner as to cause rotation.

The motor will run and increase in speed to a point just below synchronism. At this speed, the rotor field coils are energized with direct current and definite magnetic poles are formed on the rotor. These magnetic poles attempt to lock with the revolving magnetic poles of the station and, in so doing, increase the motor speed until the rotor is running in step with the revolving field.

When used for power factor correction of an a-c line, the field windings are overexcited and cause the motor to draw a large leading current. This tends to correct a lagging power factor, because in a plant using many induction motors, a large lagging current is drawn. The leading current of the synchronous motor compensates for the lagging current of the induction motor. This machine, when utilized for power factor correction, is called a *synchronous condenser.*

Windings

The stator winding of a synchronous motor consists of a number of coils placed in stator slots and, as in a three-phase induction motor, connected either star or delta for a definite number of poles. Three leads are brought out of the stator winding for connection to the line, as shown by Figure 10-20.

The field coils, of which there must be as many as there are poles in the stator, are wound in the same manner as those used in d-c motors. The amortisseur winding is embedded in the core of the field poles and connected on each side to end rings. It is used only for starting.

The rotor winding consists of a number of field poles joined in series for alternate polarity. Two leads are brought out and connected to two slip rings in order that the winding can be supplied with direct current, as illustrated in Figures 10-20 and 10-21.

Brushless Synchronous Motor

This type of synchronous motor has no brushes, slip rings, or commutator. In the previous paragraphs it was explained that a d-c exciter was necessary to supply the direct current for the field windings in the motor. This involved the use of brushes and commutator in the exciter, as well as brushes and slip rings for the synchronous motor. In the brushless type of synchronous motor, d-c excitation is also necessary, but it is obtained from an a-c generator and rectified to direct current by the use of high-current silicon rectifiers. The silicon rectifiers allow current to flow in only one direction, thus providing rectification; they also replace all sliding and mechanical contacts. These rectifiers are commonly known as *solid state diodes* and are usually arranged in a three-phase bridge connection assembly. The rectifier assembly, exciter rotor, and rotating field structure of the motor rotate with the shaft of the motor, thereby eliminating the need for brushes, slip rings, and commutator.

Solid state rectifiers and controls are explained in detail in Chapter 11. Therefore, only elementary diagrams will be shown here, and we shall not go into the theory of rectification. Figure 10-22 illustrates a synchronous motor, showing how direct current is produced for the motor field windings. The operation is as follows: The exciter field receives a d-c input through a rectifier and provides the magnetic field for the rotor of the exciter. The rotor generates a three-phase voltage as it revolves in the magnetic field. The output of the exciter is connected to a three-phase bridge rectifier and is converted to direct current which is fed to the rotor field of the synchronous motor. The stator of the motor is connected to a three-phase power source. All the components, with the exception of the exciter field and motor stator, rotate with the shaft of the motor. The synchronous motor is brought up to speed by means of the damper or squirrel-cage winding on the rotor, and, as it approaches synchronous speed, the rotor field coils are energized with the rectified current, causing the poles to lock in with the revolving field. Additional solid state components are required for the purpose of applying the excitation at the proper speed and to short the motor field during start-up. A rheostat in the field of the exciter controls the voltage output of the exciter. This may also be accomplished by means of solid state components.

Synchronous Motors with Nonexcited Rotors

Nonexcited-rotor synchronous motors can be made for either single-phase or polyphase operations. One type comprises a stator core similar to either a split-phase or polyphase stator and a squirrel-cage rotor on which flat surfaces have been cut, as in Figure 10-23, thereby producing salient poles.

The squirrel-cage winding provides the starting torque and brings the motor to a speed at which the salient poles on the rotor can lock in synchronism with the frequency of the field current. The salient poles must equal in number the poles on the stator from which they obtain their magnetism by induction. When the motor reaches speed, the squirrel-cage winding is useless and rotation is then caused by the rotor poles locking in step with the stator magnetic poles. On some motors, the rotor poles are made of magnetized steel and retain their magnetism at all times.

Synchronous Clock Motors

A common type of synchronous motor extensively employed is that used on electric clocks. Most of these are self-starting, whereas some must be turned by hand to give them a starting torque. Self-starting motors are given the starting torque by means of shaded poles (shown in Figure 10-24) as in the case of shaded-pole motors. Usually these motors have two salient field poles and therefore should rotate at 3600 r.p.m. However, the rotor is constructed so that it has from eight to sixteen or more salient poles besides a squirrel-cage winding. Figure 10-25 shows a rotor with twelve salient poles. The motor starts when the clock is plugged in because a revolving field is set up which cuts across the squirrel-cage winding and causes the rotor to turn. When the rotor reaches synchronous speed (600 r.p.m. for a 12-pole motor), the rotor poles, which have become polarized by the stator field, lock in with the stator magnetic field and rotate at the synchronous speed.

Another type of clock motor employs a rotor consisting of several laminations with the outer edge cut in a fashion to produce salient fields, as shown in Figure 10-26.

The stator consists of a two-pole frame with either one or two coils to produce the magnetic field. The pole pieces are also cut to form salient poles of the same size as the rotor poles.

These motors do not have shading poles and therefore are not self-starting. When the clock is plugged in, a pulsating magnetic field is established which cuts the rotor poles, magnetizing the poles on the rotor but producing no torque. However, if the rotor is given a start manually, its poles will be attracted to the stator poles and will lock in step with the pulsations of the current, thereby keeping the motor running at a synchronous speed. The number of salient poles on the stator will determine the speed, which may range from 450 r.p.m. for 16 poles, 60-cycle current, to 225 r.p.m. for 32 poles. Figure 10-26 shows a synchronous clock motor with 32 poles. There are other types of synchronous motors, but on the whole they are similar to those described above.

Troubles of Synchronous Clock Motors Usually the troubles encountered on clock motors are lack of lubrication and worn bearings. Frequently a few drops of oil on the rotor bearings will put the clock in operation, but if the bearings are badly worn, the clock may operate only for a short time under this treatment. In case the bearings are badly worn, it is necessary to have them replaced by a watchmaker. If the winding is open or burnt, it must be replaced. Rewinding the coil is difficult and expensive.

Synchronous Generators

A synchronous generator is similar in construction to the excited type of synchronous motor. It consists of a stator having a three-phase winding and a rotor with salient field poles that are excited by direct current. Whether it has a squirrel-cage winding or not depends on the use to which the generator is put.

As in the case of the d-c generator, the synchronous generator may be turned over by a motor, steam turbine, or diesel engine. Three wires are brought out of the stator winding which is usually star connected. A fourth wire may be carried from the star point and used as a ground wire for lighting purposes.

In operation, the generator is first brought to speed and the field poles slowly excited with direct current. As the rotor fields revolve, lines of force cut across the stator winding and cause current to be induced therein. If the stator is connected for three phase, then three-phase current will be generated. For single phase, only two of the three wires are used, or, if star connected, one phase wire and a star point. If two phase is desired, it will be necessary to transform from three phase to two phase or utilize a two-phase generator.

A diagram of an a-c generator, also called an *alternator,* is shown in Figure 10-27. Note that it is similar to the synchronous-motor circuit of Figure 10-21. Because the frequency of an alternator depends on the speed and number of poles of the machine, it is obvious that varying the exciting voltage will have no effect on the frequency, although the generated voltage will be affected by the exciting voltage. The generated voltage varies with the load, and therefore in order to keep the voltage constant, it will be necessary either to adjust the exciting voltage manually or to use an automatic voltage regulator.

Brushless Synchronous Generator

The brushless synchronous generator is similar in construction to the brushless motor. The revolving elements used to supply direct current to the field winding of the generator are the exciter rotor, the solid state rectifier assembly, and the field pole windings on the rotor of the generator. There is no need for slip rings, brushes, or commutator since all these rotate with the shaft of the generator. The stationary field winding of the exciter is connected to a rectified a-c supply. Figure 10-28 shows an elementary diagram of a brushless synchronous generator. In operation, a three-phase exciter is converted to direct current by means of a solid state (diodes) bridge rectifier. The rectified current is fed to the rotor field of the generator. As the rotor revolves, lines of force cut across the stator winding and cause current to be induced therein. In addition to rectification there may be static voltage regulation, voltage sensing, and compensation for parallel operation. It must be remembered that a prime mover such as a motor, diesel engine, and so on, must be used to turn over the generator.

Alternators in Parallel Several conditions must be satisfied before alternators can be paralleled.

1. The output voltage of the alternators must be equal, and the frequency must be the same. Assuming that two alternators are to be paralleled, regulate the voltage of each by adjusting the excitation voltage of the d-c generator supplying current to the alternator fields and the frequency by adjusting the speed of the prime mover.

2. The polarities of the alternators must be synchronized. This operation is called "phasing out" the alternators and is performed in the following manner: Assume alternator *A* is to be phased out with alternator *B*, as in Figure 10-29. Connect three sets of lamps across the paralleling switch as shown in the illustration. If both alternators are running at the required speed and generating the proper voltage, all three sets of lamps should go on and off at the same time, thus indicating that the alternators are properly phased out. This is called the *all-dark* method. The three-pole switch is closed when all lamps are dark. If each set of lamps goes on and off alternately, it is an indication that the machines are not in phase. To remedy such a condition, interchange any two leads from alternator *B* at the parallel switch.

Another method of phasing out is to use three sets of lamps connected as shown in Figure 10-30. This is known as the *one-dark-and-two-bright* method and is a more desirable way of phasing out than the all-dark system. With both alternators running, the phasing-out switch is left open until one set of lamps is dark and the other two sets bright. The switch is then thrown to close the circuit.

Synchros

A synchro is a small rotating machine that is similar to a synchronous alternator. However, the salient field winding of the synchronous alternator is excited with direct current, while in the synchro the field is excited with alternating current. Both machines have a three-phase winding. These machines are not used as motors and therefore are not rated in horsepower, but rather in the torque that they exert. This is usually expressed in inch-ounces (in.-oz.). Synchros are used for remote signaling, control, or indication and must be used in conjunction with one or more similar machines. When one machine, the transmitter, is turned, the other machine, the receiver, turns a like amount, whether the transmitter is turned through a complete revolution or only 1 degree.

Construction of the Synchro

There are many types of synchros. The usual kind consists of a stator, shown in Figure 10-31, like that in a split-phase or polyphase inductor motor. It has a three-phase, star-connected winding in the slots. Three wires are brought out of the stator for connection to another synchro. The rotor usually consists of a core having two salient poles, as shown in Figure 10-32. It has two field coils which are connected for alternate polarity. The ends of this winding are connected to two slip rings that contact brushes connected to alternating current. Synchros are also designed with the three-phase winding on the rotor and a distributed two-pole winding on the stator. Ball bearings are used to eliminate end play and provide exceptionally smooth operation.

Operation of the Synchro

Each synchro may be thought of as a transformer. The field coil acts like the primary and is connected to an a-c source, and the three-phase winding of the stator acts like the secondary. Because there are three windings in the synchro stator, a voltage will be induced in each phase. These voltages differ, depending on the position of the rotor with respect to the stator. If the rotor is turned slowly by hand, different voltages will be induced in the three-phase winding. Figure 10-33 shows a diagram of a synchro machine. There are five external leads, three from the three-phase winding and two from the rotor winding. Note that the rotor winding is excited by 120 volts of alternating current.

One synchro is located at the sending point as a generator or transmitter, and the other is operated at the receiving point as the receiver. The two machines are connected as shown in Figure 10-34. Note that the three-phase windings are joined to each other and that the primaries are connected in parallel to the same source of excitation.

If the rotor is in the same position in both the transmitter and receiver, then the voltages generated in the corresponding phase windings of both machines will be equal. Because corresponding phases are connected to each other, the voltages induced will oppose one another and no current will flow.

If the rotor of the transmitter is moved from its initial position, the induced voltages of both machines will be unequal and opposite, as in Figure 10-35, and consequently current will flow from one stator to the other. This current will set up a torque in the receiver and cause the rotor to turn until it is in a position corresponding to that of the rotor of the transmitter. When both rotors are in the same position, no more current will flow, and the rotor of the receiver will not turn.

If the receiver turns in the opposite direction to the transmitter, it is necessary to reverse two wires of the three-phase winding. It is important that the primaries of each machine be connected to the same source of supply or they will be out of phase and will not operate properly.

Electronic Control of Motors Using Electron Tubes

Earlier chapters of this book have shown that it is necessary to control motors; that is, motors must be started, stopped, jogged, and reversed, and, within limits, it must be possible to control their speed.

The controls needed to perform these various functions on d-c motors are designed to alter the quantity or the direction of the current in the field or in the armature of the motor. In Chapter 7, on d-c controls, these functions were shown to consist mainly of resistances, switches and solenoids.

It is possible to control motors, not only electromechanically and electromagnetically, but also electronically, by means of vacuum tubes or gas-filled tubes. Some electronic devices can be made to operate a relay which in turn controls a motor. Others influence the amount and direction of current flowing in the motor circuit and thus the action of the motor itself. Both types may be found in one control device. Before showing how electronic controls operate a motor, it is important that the reader have a working knowledge of some of the various types of electronic tubes to be met in the field.

Theory of Electron Tube

The heart of all the devices used in electronic control is the electron tube. Like those used in radios, it consists of a glass or metal envelope that contains several electrodes. The simplest tube is the diode, which consists of two electrodes, an anode or plate, and a cathode. The symbol for this tube is shown in Figure 10-36.

For this tube to operate, it is necessary that electrons be freed or driven out of the cathode. This is so constructed that it can become a source of electrons when it is heated. Heating tends to release the electrons, as shown in Figure 10-37. Some cathodes are made like the filament of an incandescent lamp with an added coating of material, usually barium oxide, which frees a large number of electrons while the filament is hot. The tube will cease to function after the coating material has been evaporated by long use.

Some tubes have a cathode that is indirectly heated. In these, the cathode is a sleeve which fits around the filament. The latter is used as a heater in this case. The symbol of this type is shown in Figure 10-38.

To be useful, the electrons that are emitted from the cathode must be collected, otherwise they will simply float around in space or return to the cathode. The electrons will be collected by the anode or plate when it has a positive charge on it, as shown in Figure 10-39. The anode is connected to the positive terminal of a battery, causing the electrons to move quickly to the anode and cause a current to flow through the empty space between the anode and cathode.

The operation of this circuit is as follows: The filament is fed current from the secondary of a transformer, causing the cathode to become hot and emit electrons. The anode is connected to the positive side of the battery, and therefore the electrons are attracted to it. Thus a circuit is formed by the electrons from the cathode to the anode, through the meter to the positive side of the battery, then through the battery back to the cathode. (Note that the flow of electrons is actually from negative to positive, instead of the conventional positive to negative for current.) If the polarity of the battery is reversed, as in Figure 10-40, that is, if the negative side of the battery is connected to the anode, the electrons will be repelled from the plate and no current will flow. Electrons will merely pass from the cathode to a positive anode.

Half-wave Rectification

The chief advantage of the diode lies in its ability to convert alternating current to pulsating direct current. If the anode is made positive half the time and negative the other half, current will flow only when the anode is positive and stop when the anode is negative. An alternating current applied to the diode does this very thing. The point is illustrated in Figure 10-41. This diagram is similar to the previous one, except that the battery is replaced by the secondary of a transformer. The tube now acts as a "rectifier"; that is, it permits current to flow in only one direction. It rectifies the alternating current into direct current.

Figure 10-42 shows how the diode produces direct current. (The heater circuit has been omitted for simplicity.) During the half cycle when the anode is positive, electrons are attracted to it. At this instant, the other side of the secondary coil is negative. A circuit is therefore completed from the cathode to the anode, through the transformer coil, through the load, and back to the negative cathode. At the reversal of the cycle, the anode becomes negative, repelling the electrons and preventing current from flowing. This tube will produce half-wave rectified current; in other words, current will flow for half a cycle and then stop for half a cycle. This is known as *pulsating current,* and it is shown in Figure 10-43.

Full-wave Rectification

Pulsating half-wave current, while useful and satisfactory for many applications, can be improved by using another half-wave rectifier to form a full-wave rectifier. A full-wave rectifier circuit is shown in Figure 10-44. Diodes *A* and *B* are half-wave rectifiers so connected that when the anode of *A* is positive, the anode of *B* is negative, and vice versa. Thus, tube *A* will pass current through the circuit during one half of the a-c cycle, and tube *B* will pass current through the circuit during the other half of the a-c cycle. Current will flow through the load in the same direction during both halves of the cycle. Full-wave rectified output is less pulsating than half-wave rectified output, as shown by the curves of Figures 10-45. One tube can be used instead of two by putting two anodes in the same envelope, as shown in Figure 10-46.

Gas-filled Tubes

The tubes mentioned so far are all of the vacuum type and are designed for relatively small amounts of current. Tubes designed for larger currents usually contain a small amount of inert gas such as argon, neon, or mercury vapor. The use of gas enables the tube to handle much larger electronic currents. The symbol for a vapor or gas tube is the same as that for a vacuum tube, and a dot is added to show the presence of the gas, as shown in Figure 10-47.

Because the cathode of the gas-filled tube is designed to supply many more electrons than the vacuum type, it is made of thick metal and takes about a minute to heat. Consequently, equipment of this type is usually provided with a time-delay circuit that does not permit the anode voltage to be applied until the cathode is properly heated.

Small- and medium-sized gas-filled tubes are used as rectifiers for battery charging, and large mercury-vapor rectifier tubes are used to furnish direct current for the operation of motors. Their advantage is that in addition to permitting the heavier current to flow, they maintain a constant voltage drop across the tube and thus afford better voltage regulation than the vacuum type.

A simple application of the gas diode permits the operation of a d-c motor from an a-c line, as shown in Figure 10-48. In this circuit, alternating current is rectified to full-wave direct current, and this in turn is fed to a d-c motor. A field rheostat can be used to regulate the speed of the motor. With this connection, it is possible to obtain variable-speed advantages from the d-c motor when a d-c line is not available.

The Triode

To regulate the amount of current that the tube handles, a third element, called a *grid,* is inserted between the anode and the cathode. This tube is called a *triode* because it has three electrodes. Its symbol is shown in Figure 10-49. The filament is not counted as an electrode when it is used to heat the cathode.

The grid consists of a wire fence, encircling the cathode so that it lies between cathode and anode. It is mesh constructed so that electrons can readily get through to the anode from the cathode. However, if the grid is made sufficiently negative, as shown in Figure 10-50, the electrons leaving the cathode will be repelled and will never reach the anode. Even though the anode is positive, no electrons will reach it because the negatively charged grid repels all electrons. The amount of grid voltage necessary to "cut off" the plate current to zero will depend on the amount of anode voltage. The greater the anode voltage, the greater the grid voltage necessary to reduce the electron flow to zero.

If the grid voltage, or *bias,* as it is called, is reduced, the number of electrons reaching the anode will be increased. The smaller the grid bias is made, the greater will be the current in the anode circuit. This can be accomplished, as shown in Figure 10-51, by connecting a potentiometer across the grid-bias battery and varying the grid potential by moving a sliding contact. The value of the triode is that a comparatively small voltage between grid and cathode has the same effect on the current in the anode circuit as a large voltage between the anode and the cathode. The triode is useful as an amplifier.

The Thyratron

The thyratron is a gas-filled triode that differs in operation considerably from the vacuum-tube triode. As stated previously, a gas tube allows more current to flow through it than does a vacuum tube. Because the gas completely fills the tube, it is evident that electrons emitted from the cathode will collide with the neutral atoms of the gas in their travel to the anode. This collision will cause one or more electrons to be ejected from each of the atoms, and as a result an electron flow consisting of those from the cathode and those thrown from the gas atoms will be formed. The process of depriving gas atoms of one or more electrons is called *ionization.*

At the same time, the atoms, after having the electrons ejected, become positively charged (charged atoms are called *ions*) and are attracted to the negative cathode. Millions of electrons, which surround the cathode as a "space charge," prevent other electrons from flowing toward the anode. These space-charge electrons are neutralized by the positive ions, thereby permitting a greater electron flow.

In the vacuum triode, the anode current increases proportionately with changes in the grid voltage. In the thyratron, no anode current flows until the grid, also called the *starting anode,* is properly biased. If the grid is too negatively charged, it will repel the electrons and no current will flow. As the grid is made less negative, with the proper voltage applied to the anode, a point will be reached where the electrons will meet the anode and current will flow in the cathode-anode circuit. Once the current starts to flow, thereby ionizing the gas, it will continue to flow, no matter how negative the grid voltage is made. The only way to stop the current flow in a gas-filled tube is to reduce the anode voltage to zero or to open the anode circuit as illustrated in Figure 10-52. Because of this action, the thyratron is called a *trigger-type tube.*

The Thyratron on Alternating Current When alternating current is applied to the anode of the thyratron, as in Figure 10-53, it will automatically stop conducting when the negative half of the a-c cycle occurs. As soon as the tube stops conducting, the starting anode will regain control.

The thyratron in this circuit resembles a half-wave rectifier, except that the tube will not start to function until the voltage applied to the grid is of the proper value. This means that the current can be controlled for less than half a cycle, as shown in the time-current curve in Figure 10-54.

With this type of starting-anode control, it is not possible to have the current flow for less than one-quarter of a cycle, because if the tube does not start to conduct before the anode voltage reaches its greatest value it will not conduct at all.

Phase-shift Control By applying alternating current to the starting anode, it is possible to control the operation of the thyratron tube so that it will start conducting at any required point of the half wave, thus assuring a more precise control over the current passed through the tube than could be obtained by the circuit of Figure 10-53. This is called *phase-shift control,* and it is especially important when used for timing in welding operations and for speed control of d-c motors.

Operating a d-c Motor on Alternating Current, Using Thyratrons With the circuit illustrated in Figure 10-55, it is possible to operate a small d-c motor by using a thyratron tube. With a few more additions to the circuit, it is possible to operate larger motors. When switch S is closed, current through resistor R_2 provides the grid with a positive voltage and causes the tube to conduct. Resistance R_1 is used to prevent the tube from operating when switch S is open, and the value of R_1 determines the motor speed when S is closed. When the thyratron conducts, pulsating direct current will flow through the armature. The field is excited through the separate full-wave rectifier tube shown in the diagram.

Speed Control of d-c Motor The circuit shown in Figure 10-56 is similar to that of Figure 10-55 and includes a variable inductance and variable resistance for speed control of the motor. The variable inductance is used to shift the phase of the thyratron grid voltage so that conduction through the thyratron will stop. By varying the value of the inductance, it is possible to shift the phase of the grid voltage so that the tube may conduct during any part of a half wave. If it conducts only during a very small portion of a half wave, a slow speed will be obtained; if it conducts during most of the half wave, a higher speed will be realized. The variable resistance can vary the speed range also, depending on the value of the inductance used. On large motors, many different controls and tubes are employed, and the circuits are quite complicated.

Reversing a d-c Motor with Two Thyratrons By using two thyratrons, it is possible to reverse a d-c motor by throwing a single-pole, double-throw switch. A diagram of this circuit is shown in Figure 10-57. This diagram is similar to the previous ones and includes another thyratron. If the switch is in the FORWARD position, the motor will run in a clockwise direction. If the switch is thrown in the REVERSE position, the other tube will conduct, and current will flow in the opposite direction through the armature and cause the motor to reverse. If the switch is reversed very rapidly, the motor will come to a quick stop. In all of the thyratron circuits, an open in the grid circuit will stop the motor.

The Phototube

The basis of many electronic controls is the phototube, a device which responds to light. This tube is essentially a diode, and like all diodes it has two electrodes, an anode and a cathode, as shown in Figure 10-58. Current will flow when the anode is positive with respect to the cathode, provided that the cathode is illuminated.

In the rectifier tubes previously discussed, the cathode released electrons when it was heated; in the phototube the cathode will release electrons when light strikes it. Thus there are two requirements for the phototube action: the anode must be positive, and the cathode must have light falling on it. The more light that falls on the phototube cathode, the greater is the current flow through the tube; but at best this current will be very small, about twenty millionths of an ampere. It is so small that it cannot do much work and must be used in conjunction with an amplifying triode to close a relay which in turn can start or stop a motor.

A simple relay circuit showing the operation of the photocell is given in Figure 10-59. When the light does not fall on the phototube, it will not conduct, and the full voltage of the battery *C* is applied to the grid *G* of the vacuum tube. As a result, no current will flow between the anode and cathode of the tube. The relay, which is in the anode-cathode circuit, therefore will not be energized.

When light falls on the phototube cathode, electrons will be emitted and thereby cause a current to flow from the battery *C* through the resistance *R* (a very high value of resistance), through the phototube, and back to the battery *C*. Even though this current is very small, the resistance *R* is so large that there will be an appreciable voltage drop in this resistance, thus reducing the voltage at point *G*. The grid will become less negatively charged and current from battery *B* will flow in the anode circuit of the tube and operate the relay. The relay may be connected to a motor either to stop or to start it. The phototube circuit of Figure 10-59 uses batteries for operation, but it is possible to obtain the same result by using alternating current instead of direct current. A similar circuit using alternating current is shown in Figure 10-60.

By using a number of contacts on the relay, it is possible to have the phototube perform many functions. A typical application is shown in Figure 10-61. When the light source is interrupted by a person or object passing between the light source and phototube relay, the motor is turned on. Thus the phototube can be used for such applications as to open doors, operate counting devices, drinking fountains, and so on.

Phototube Operation of a Large Motor In Figure 10-60 a phototube operated a relay, which in turn closed a switch to operate a small motor. It is possible to go a step further and connect the relay to operate a magnetic switch which in turn will operate a larger motor. A circuit of this application is shown in Figure 10-62.

A double-pole, double-throw switch is used to permit operation either by phototube or pushbutton station. When light strikes the phototube, the large voltage drop across resistance R will make the grid of the amplifying triode less negative and cause the tube to conduct, thereby energizing the relay coil. The relay contacts close and, in turn, energize the holding coil of the magnetic switch whose contacts close the motor circuit.

When no light reaches the phototube, the triode stops conducting, the relay switch opens, and the motor stops. When the double-pole, double-throw switch is in the pushbutton circuit, the motor can only be operated manually by pushing the START button.

The circuits shown here are a few of the many circuits that are used for electronic control of motors. Most electronic circuits are more involved and require detailed analysis and study before troubleshooting is attempted.

CHAPTER 11

Solid State Motor Control

Introduction

It was explained in the previous chapter that it is possible to control electric motors not only electromechanically and electromagnetically, but also electronically, using vacuum and gas-filled tubes. This section will be devoted to a brief introduction of the theory and operation of solid state devices such as semiconductor materials, rectifiers, transistors, and silicon controlled rectifiers and the relationship of these to motor control. First, good, basic understanding of the nature of semiconductor materials is necessary for understanding the circuitry involving the various devices listed above.

Theory of Semiconductors

From the standpoint of electrical conductivity, all substances can be classified as insulators, conductors, or semiconductors. Without going into detail on the composition of matter, it can be stated that one of the properties of all matter is its ability to conduct electrical current. An *insulator* is a material that has a very high resistance to the passage of current, whereas a *conductor* can pass current very readily. Semiconductor materials, on the other hand, have an electrical conductivity greater than that of an insulator but less than that of a conductor. In other words, semiconductors are neither good conductors nor good insulators.

Semiconductor materials are usually manufactured from either of two elements, silicon or germanium. Silicon is preferred, for SCRs, because it possesses several advantages over germanium, one of which is its ability to withstand higher operating temperatures and voltages without damage to its crystal structure. Both elements are used in electronics because they are easily obtained, inexpensive, and have the electrical and mechanical qualities so necessary in many electronic devices.

Atoms and Electrons

We know that an atom is the smallest part of an element that still retains the characteristics of the element. We also know that an atom consists of a nucleus in the center, with particles called *electrons* revolving with great speed around the nucleus in one or more orbits or shells. Figure 11-1 shows a silicon atom. Notice three distinct orbits with two electrons in the first orbit, eight in the next, and four in the last. The nucleus is composed of *protons* and *neutrons*. The protons carry a *positive* charge and have the tendency to repel one another. The electrons spinning around the nucleus have a *negative* charge and likewise repel one another. Neutrons have no charge and therefore have no effect on one another.

The total number of electrons revolving around the nucleus in an atom is always equal to the number of protons in the nucleus. Consequently, the atom does not have either a positive or negative charge. However, if an atom should lose an electron, its net charge would be positive because the atom would have more protons than electrons; such an atom is called a *positive ion*. If an atom gains an electron, its net charge would be negative and is called a *negative ion*. How an atom gains or loses electrons will be explained later, but it is obvious that the charge of an atom depends on whether there is an excess or deficiency of electrons.

It was pointed out previously that electrons rotate around the nucleus in one or more paths, depending on the element or compound. These paths are called *shells* or *orbits*, and the electrons in the outer shell are called *valence electrons*. It is the electrons in this outermost orbit that have the greatest velocity and greatest energy and, since they are furthest from the nucleus, are most readily separated from the atom. Good conductors have electrons in the outer shell that can be separated from the atom with very little effort. Others are moved through a conductor by applying a voltage across the conductor. It is these electrons (*free* or *mobile electrons*) that are important in electronics. Substances from which electrons are not easily separated from the atoms are poor conductors. Atoms with fewer than four electrons in the outer shell (valence electrons) are good conductors. Atoms with more than four electrons in the outer shell are relatively poor conductors, and atoms with four valence electrons are semiconductors and are neither good nor poor conductors. Figure 11-2 shows atoms of aluminum and phosphorous.

Silicon has four valence electrons and in its pure form has high resistivity to current flow. These four outermost electrons are held in place very strongly by the nucleus and cannot be used as mobile or free electrons to carry a charge. Consequently, pure silicon is more of an insulator than a conductor.

Semiconductors

In order to utlilize silicon as a conductor, minute amounts of impurities must be added to or alloyed with the silicon. This addition will either produce a material with excess electrons or a material with a deficiency of electrons. The addition of impurities is known as "doping." Now, if we add a minute amount of arsenic, which contains five electrons in its outermost orbit, to pure molten silicon there would be an excess of electrons, because four of these electrons will form a bond with adjoining silicon atoms, leaving one electron to move randomly to other positions in the silicon crystal. These *free* electrons will become the current carriers if an external voltage is applied to the silicon crystal. When an impurity is added to pure silicon or germanium and produces a substance with numerous free or excess electrons it is called an *N type* semiconductor. The substance will now exhibit electrical characteristics necessary for the operation of a semiconductor. For example, if a voltage is applied to the ends of an N type substance, the excess electrons in the semiconductor will be repelled by the negative terminal of the voltage source and attracted to the positive terminal, as shown in Figure 11-3. This movement of electrons from the negative side to the positive side of the e.m.f. source constitutes a current flow. However, the free electrons act as negative current carriers.

Adjoining atoms in crystals bond together by sharing their valence electrons. This means that one of the four valence electrons in an atom of silicon rotates not only in its own orbit but also around the valence orbit of an adjoining atom. It is, therefore, under the influence of two atoms rather than one. This is called *covalent bonding.*

There is also a P type semiconductor. This is obtained by adding a minute quantity of aluminum to pure silicon. Aluminum contains only three electrons in its outermost shell or orbit, and when it is alloyed with silicon or germanium, which have four valence electrons, the three valence electrons of the aluminum form covalent bonds with three electrons of the silicon (or germanium), leaving one bond incomplete. This absence of an electron is called a "hole." This type of substance which has a shortage or deficiency of electrons, or holes, in its crystal structure is called a *P type* semiconductor.

When the ends of a battery are connected to a P type semiconductor, electrons flow from the negative terminal through the semiconductor and back to the positive terminal. The electrons which move in the semiconductor break out of their covalent bonds into holes. However, in breaking out of the covalent bonds, the electron leaves a hole which is filled by another covalent electron. Although electrons move from the negative terminal through the P type semiconductor, the holes in the semiconductor will move in the reverse direction. To be precise, a hole flow is in the direction opposite to an electron flow and acts as positive current carriers. P and N type semiconductors are seldom used except in combination with one another, as we will see in the following discussion.

The P-N Diode

A diode is formed when P and N type semiconductors are combined or bonded as a P-N unit. There are a number of methods used to manufacture a P-N diode, but regardless of the method used, new characteristics are produced which make the combination a useful electronic device. The region where the P section joins the N section is called the *junction* or *barrier*. A P-N semiconductor diode is shown in Figure 11-4. An interesting phenomenon occurs when the two types of semiconductors are combined as a unit. Some of the free or excess electrons from the N section diffuse or flow across the junction and combine with the holes in the P section. As a result, the P section at the junction will acquire a small negative charge because it has acquired electrons, and the N section at the junction will acquire a positive charge because of a loss of electrons. The junction region will now have equal and opposite charges, and a potential difference will exist at the junction. This is called a *potential* barrier, and its polarity is such that will prevent further passage of electrons from N to P. This is shown in Figure 11-5. The negative polarity at the junction in the P section will repel excess electrons that try to enter from the N section. Actually, it is the potential difference at the barrier that prevents complete diffusion from N to P and thus preserves their original characteristics. A very small voltage exists at the junction of the P and N semiconductors.

Reverse and Forward Bias

An external battery connected to the ends of a P-N unit, as in Figure 11-6, will cause little or no current to flow through the junction. In tracing out the circuit, notice that the external battery is connected so that the negative terminal is connected to the P section and the positive terminal is connected to the N section. This connection increases the potential barrier at the junction, permitting very little current (measured in microamperes) to flow. When the negative terminal of the battery is connected to the P section and the positive terminal connected to the N section, the diode is said to be *reverse biased.* If the battery connections are changed as shown in Figure 11-7, the potential difference at the barrier is greatly reduced, and electron current flow is increased. This is called a *forward-bias* connection, and electrons will flow as long as the forward bias is applied. When a junction is reverse biased the diode will have a high resistance, and conversely, a forward biased diode will have a low resistance. Therefore, the resistance of the diode to current going in one direction is much higher than the resistance to current in the other direction. In other words, a P-N diode conducts more readily in one direction than the other so that it can be used to convert alternating current to direct current. Figure 11-8 shows the symbol for a diode. The arrow or P section is called the *anode* and the N section is called the *cathode.*

The P-N Diode Rectifier (Silicon or Germanium)

A rectifier is a device that permits current to flow in only one direction. In the previous chapter, it was explained how this was accomplished by the use of the electron tube. Since a P-N diode permits a relatively high current flow when forward biased, it can be used to change alternating current into pulsating direct current. We learned that the diode will conduct much more readily if the negative terminal of a power source is connected to the N section (cathode) of the diode and the positive terminal is connected to the P section (anode) of the diode, as shown in Figure 11-9. Thus, a circuit is formed from the negative terminal to cathode, anode, through the load, and to the positive side of the power source. (Note that the flow of electrons is from negative to positive in the external circuit, rather than the conventional positive to negative direction.) If the polarity of the power source is reversed as in Figure 11-10, no current will flow.

We know that if a diode is forward biased it will conduct current, and if it is reverse biased it will not. When a diode is forward biased there is a forward voltage drop across the diode of about 0.5 volt if the current in the circuit is within its rated value. Therefore, a battery of more than 0.5 volt is necessary to overcome this barrier. If, however, the applied voltage is increased to a point where the current rating is exceeded, the diode may be irreparably damaged because of excessive internally generated heat. Most rectifiers have a current rating determined by the temperature rise due to the power lost, especially at times of high current flow. For this reason, high-current rectifiers are mounted on a stud and fastened to a "heat sink" to remove the heat. Low-current rectifiers do not need a heat sink and are cooled by the surrounding air.

Figure 11-11 shows a curve representing the voltage current characteristics both for forward bias and reverse bias. Note that the forward current is measured in milliamperes and the reverse current in microamperes. If a small negative voltage (reverse bias) is applied to the diode, the diode limits the current flow to a few microamperes. However, if a large enough reverse bias is applied, the reverse current increases very rapidly (point x). This will undoubtedly damage the diode unless its characteristics are such as to withstand this reverse current. One such diode is called the *Zener diode,* which will be discussed later in this chapter. Often, diodes are marked with a plus sign on the cathode side of the device or with the symbol of the arrow showing the high resistance direction. The arrow also points towards the conventional plus. Figure 11-12 illustrates some diodes.

Half-wave Rectification

The semiconductor diode has the ability to convert alternating current to pulsating direct current. If the cathode is made negative half of the time and positive the other half, current will flow only when the cathode is negative with respect to the anode and will stop when the anode is negative with respect to the cathode.

An alternating current applied to the diode does this very thing. This is illustrated in Figure 11-13. This circuit is similar to Figure 11-9, except that the d-c power source is replaced by the secondary of a transformer. The semiconductor diode now acts as a rectifier; that is, it permits current to flow in one direction only. It rectifies the alternating current into pulsating direct current. Figure 11-14 shows alternating current before rectification, and Figure 11-15, after rectification. During the positive half cycle when the anode is positive with respect to the cathode, a circuit is completed, as shown in Figure 11-13, from the negative terminal through the cathode, anode, load, and back to the positive terminal. The load will see the entire positive half cycle. At the reversal of the cycle (negative half cycle), the anode becomes negative with respect to the cathode, preventing current from flowing through the load, and so on. The diode, therefore, is used to produce half-wave rectified current from alternating current. In other words, current will flow for half a cycle and then stop for half a cycle. This is known as pulsating direct current and is shown in Figure 11-15.

Filtered Direct Current

In some applications, the pulsating d-c output obtained by using just the rectifier diode is not suitable as a power supply. The pulsations or ripples can be eliminated by connecting a capacitor across the load, as shown in Figure 11-16. This capacitor is used as a filter in this circuit.

When the rectifier is conducting during the positive half cycle, current will flow from the negative side of the line through the load, the rectifier, and back to line. At the same time, the capacitor is charged to its peak value. When the applied voltage from the line falls below the charged capacitor voltage, the capacitor discharges through the load. In the graph of Figure 11-17, note that the capacitor is charged for less than a half cycle: at the end of this time it discharges into the load, thus keeping current flow in the load at all times.

Full-wave Rectification

Half-wave rectification, while useful and satisfactory for many applications, can be improved by using two diode rectifiers to form a full-wave rectifier. Two methods will be shown: (1) a center-tap transformer with two diodes, and (2) a bridge type of rectifier network using four diodes.

A full-wave rectifier using a center-tap transformer is shown in Figures 11-18 and 11-19. During the half cycle when *A* is positive with respect to *C*, as in Figure 11-18, current will flow from *C* through the load, through D_1, and to *A*. Diode D_2 will not conduct during this half cycle. During the next half cycle, Figure 11-19, *B* is positive with respect to *C*, and current will flow from *C* through the load, through D_2, and to positive. Of course, since the current is continuous in each half cycle, it will flow from *A* or *B* to *C*, depending on the cycle. This is shown by the arrow adjacent to the secondary of the transformer. Notice that during both half cycles, the current flow through the load is in the same direction. Figure 11-20 shows a filter capacitor connected across the load to reduce the ripple voltage. Curves representing full-wave unfiltered and filtered rectification are shown in Figure 11-21.

Full-wave bridge rectification is shown in Figures 11-22(a) and (b). During the half cycle when *A* is positive and *B* is negative, current flows from *B* through D_2, the load, D_3, and to *A*. Current through load is in the direction *C* to *E*. During the next half cycle, when *B* is positive with reference to *A*, current flows through D_1, through the load from *C* to *E*, through D_4, and back to the transformer. Note that during both alternations, current flow through the load is in the same direction. A filter capacitor is shown by the dotted lines. Figure 11-22 is the same type of bridge rectifier in a different form. The bridge rectifier shown in Figure 11-22 possesses several advantages over the full-wave rectifier of Figure 11-20. It does not use a center-tap transformer, and the output voltage is twice as great as it would be if the same transformer were used with a center tap. A disadvantage of this full-wave circuit is that the drop across two diodes rather than across just one must be subtracted from the output voltage.

Zener Diodes

The symbols used to illustrate Zener diodes are shown in Figure 11-23. Ordinarily, a diode will pass current when it is forward biased. If it is reverse biased, current in the order of microamperes will flow. However, if the reverse-bias voltage is increased beyond a limiting value, called the *Zener breakdown point,* a breakdown will occur and current flow will increase very rapidly with very small increases in voltage. In other words, after breakdown occurs, very small changes in voltage across the reverse-biased diode will cause relatively large variations in reverse current. The graph of Figure 11-24 shows this. A diode that is designed to operate in this region is called a Zener diode and is often used to provide voltage regulation.

Large current changes due to small voltage changes can be made to control a voltage to close tolerances. Figure 11-25 shows a circuit using a Zener diode to keep the voltage across a load constant, even though the input voltage may vary.

The one desirable characteristic of the Zener diode is that, at the Zener region, a very small increase in voltage produces a very large increase in current flow through the Zener. Remember that the Zener diode is always reverse biased. In the circuit of Figure 11-25, note that the Zener diode is in series with R_1. If the voltage input across these two devices tended to increase, the current flow would increase. This rise in current in D_1 would not change the voltage across D_1 to any significant degree. However, the voltage drop across R_1 would rise. Any increase in input voltage would be experienced by R_1 rather than D_1, thus keeping D_1 at a constant voltage and also keeping the load at a constant voltage since it is connected directly across the diode. Similarly, if the input voltage tended to decrease, the drop across R_1 would decrease, leaving D_1 with substantially the same voltage. Since Zener diodes are reverse biased, the electron flow will be from anode to cathode.

The Transistor

Up to this point we have discussed the construction and operation of the semiconductor diode. From here we proceed to the semiconductor triode or transistor. The transistor is illustrated in Figure 11-26. Note three terminal wires. Just as the diode consisted of two layers of semiconductor material, so the transistor consists of three layers of semiconductor material. The outer layers have one type of semiconductor, and the center layer has the other type of semiconductor. If the outside layers were blocks of N type silicon, the middle layer would be P type silicon. This would be considered an NPN transistor and is shown in Figure 11-27. Figure 11-28 shows another arrangement with the N type silicon in the center. This is called a PNP transistor. The center region in comparison with the other layers is a very thin layer, about 0.001 in. in thickness and is called the *base*. The outer regions are called the *emitter* and *collector*. The symbol for the transistor is shown in Figure 11-29. Note that the terminal with the arrow is the emitter. If the arrow points towards the base it is a PNP transistor; if the arrow points away from the base it is an NPN transistor.

The basic transistor described above can be considered as two diodes connected back to back as in Figure 11-30. Since each diode has a junction, there will be two junctions, or barriers, in the basic transistor. If we connect a battery to the ends, as in Figure 11-31, you will notice that electrons will travel easily through junction *A* because it is forward biased, but the electrons will be blocked by junction *B* because of reverse biasing. If a three element NPN transistor is used, the same results will be obtained. See Figure 11-32. It is obvious that very little current will flow from *E* to *C* because of the reversed bias of junction *B*. If two batteries are used instead of one, as in Figure 11-33, again very little current will flow, because junction *B* is reverse biased. If base wire *B* is connected to the batteries as in Figure 11-34, we now have a path for current or electron flow through junction *A*.

Since the emitter-base section of the transistor is forward biased, electrons will flow from the negative terminal of the battery through the emitter, through the base, and back to the positive terminal of the battery. However, it was mentioned before that the base is extremely thin, and, consequently, electrons flowing from the emitter to the base could pass through the base to the collector if a positive charge was present at the collector.

It will be noticed in Figure 11-35 that the collector is connected to the positive side of battery *2*, which in turn is connected in series with battery *1*, producing a high positive charge at the collector. As a result, most of the electrons from the emitter will pass through the very thin base and flow through the collector to the positive side of battery *2*. Approximately 2 percent of the emitter current does not pass through the reverse-biased junction and flows from the center region (base) to the positive side of battery *1*. The flow of current in an NPN transistor is shown in Figure 11-36. This circuit is called a *common-base* configuration. Notice that almost all of the current in the forward-biased junction passes through the very thin base region and flows through the reverse-biased junction. The small percentage of the current that does not pass through the reversed-biased junction flows to the positive terminal of battery *1*.

It is this small amount of current flowing through the junction in the forward direction that permits the large amount of current to pass through the reverse-biased junction. As can be seen, the collector current is very much larger than the base current. In fact, the collector current is controlled by the base current and is directly proportional to it. It was pointed out previously that without a base connection there is practically no current flow. Now, with just a very small base current, a large current will flow to the collector. With other types of transistor circuit configurations unusually high power gains are obtainable. Figure 11-37 shows the common-emitter type of transistor circuit configuration, which is one of the most common used in solid state drives.

The NPN transistor is similar to the PNP transistor with slight differences. The polarities of the power source must be reversed if a PNP is used instead of an NPN. In either case, the emitter-base circuit must be forward biased and the collector circuit must be reversed biased.

Since the transistor is an important device in solid state motor control, it may be well to summarize some of the important facts concerning its construction, operation, and functions.

1. The two basic types of transistors are the NPN and PNP.
2. The three terminals are called the *emitter, base,* and *collector.*
3. The emitter-base junction is forward biased; the collector-base junction is reverse biased.
4. The electron current flow is opposite to the direction of the arrow on the emitter.
5. The first and second letters indicate the polarity of emitter and collector, respectively.
6. In an NPN transistor, electron current flows from emitter to collector.
7. In a PNP transistor, electron current flows from collector to emitter.

8. The base region of a transistor is very thin—about 0.001 in.
9. A small change in base current will produce a proportional change in collector current.

Comparison of a Three-element Tube and a Transistor

The transistor can be compared to the three-element tube, or triode, described in Chapter 10. The plate of the tube collects the current. The collector of the transistor does the same thing. Therefore, these elements, the plate and collector, have similar functions. The cathode of the tube emits electrons which travel to the plate. The emitter of the transistor supplies carriers to the collector. Therefore, the cathode of a tube and the emitter of the transistor have similar functions. In the three-element tube, electrons flow through the grid. In the transistor they flow through the base. The grid base controls the plate current in a tube. The bias voltage between the base and emitter controls the current to the collector. It can be readily seen that the three-element tube and the transistor perform similar functions. Figure 11-38 illustrates these comparisons.

Transistor Circuit Arrangements

There are three possible transistor circuit arrangements: (1) common base, (2) common emitter, and (3) common collector. Each arrangement or configuration has its own advantages and is used in circuits where its properties provide the necessary power gain, current gain, etc., needed for the efficient operation of the particular drive. In all of these circuit arrangements, the collector current is equal to emitter current minus the base current. Figures 11-39(a), (b), and (c) show the circuit arrangements for NPN and PNP transistors.

Resistance R_1 in all of these circuits limits the emitter-base current. Its resistance is based on the transistor specifications. *RL* is the load resistor; the amplified signal voltage appears across this resistor. The (common-emitter) transistor is used most frequently as an amplifier, because it possesses high voltage, high current, and high power gain.

The Unijunction Transistor

This type of transistor is used mainly in conjunction with a silicon controlled rectifier. The unijunction transistor (UJT) is different from the basic transistor in that it consists of a single bar of N type silicon with connections at both ends and a single P type region on the side of the bar about halfway from either end of the bar. This type of transistor is shown in Figure 11-40. Note that the ends of the N bar are marked base *2* and base *1*. The P region is called the *emitter* and is located near the middle of the bar. Note also that there is just one junction (unijunction). Essentially, the unijunction transistor is a P-N diode with a P section and a double N section.

If a voltage is applied across B_1 and B_2 with positive on top and negative on the bottom, as in Figure 11-41, the N type silicon bar will act as a resistor with a small current flow in the direction of the arrow. The voltage will divide across the N bar so that if the battery voltage is 10, the voltage across the N bar at the junction of the P region will be about +6. In order for this unijunction transistor to operate, the voltage at the emitter must be more than 6 volts positive in this case. This will make the junction forward biased, and current will flow across the junction. Thus, if the section from B_1 to the emitter is forward biased the UJT will turn on, and the resistance between B_1 and emitter will become less and less as more current flows through it. As we learned before, when a diode is forward biased, its resistance becomes very small. Therefore, when the UJT is turned on, the resistance between B_1 and the emitter will have a very low value.

There are a number of applications for the UJT, but it is used most frequently for triggering the silicon controlled rectifier. When used for this purpose, as in Figure 11-42, it is used in a relaxation oscillator circuit. In this circuit, with the battery connected as shown, and at the closing of the switch, current will flow from the negative terminal to the capacitor, to R_1, and to the positive terminal. At the same time, the UJT is connected across the power supply so that a positive voltage of some value is present at the junction. The capacitor will start to charge at a rate determined by R_1 until the capacitor attains a voltage at the emitter that will be slightly larger than the voltage in the N bar at the junction. As soon as this voltage is reached, the junction will be forward biased, permitting the charged capacitor to discharge through R_3 and

B_1 E as shown by the dotted line. The polarity of the resistor will be positive on top and negative on bottom. It is this positive pulse due to the discharge of the capacitor that is used to trigger the silicon controlled rectifier. Once the capacitor discharges, the UJT turns off and the cycle is repeated.

The Silicon Controlled Rectifier

The silicon controlled rectifier (SCR) is a solid state switch composed of four alternate layers of P and N type silicon and is capable of rectifying alternating current into adjustable direct current. It is small in size, compact, light in weight, shock resistant, and silent in operation. It has high electrical conductivity, needs no warm-up as thyratron tubes do, and has no moving parts. Various representations of the SCR are shown in Figure 11-43. Figure 11-43(a) shows the symbol, Figure 11-43(b) the construction, and Figure 11-43(c) the PNPN layers. As shown in these illustrations, the SCR has three terminals. These are called the *anode, cathode,* and *gate*. As its name implies, the SCR is a rectifier and will conduct current in only one direction.

Characteristics of the SCR

Under normal operating conditions, the SCR will conduct only if the gate voltage is positive with respect to the cathode and if the anode is positive with respect to the cathode. If the gate current is zero, the characteristics of the SCR are such that a forward anode voltage will permit a small leakage current to flow through it. This is called the *foward blocking current* and is shown in the graph of Figure 11-44(a). The leakage current remains practically constant as the voltage is increased up to a point called the *forward breakover voltage*. Anode current will increase very rapidly at this point. When the current reaches a certain level, the SCR switches on and remains on until the current falls below a level called the *holding current* or until the current is reversed, as is automatically done in alternating current. When the anode current drops below the holding current level, the SCR reverts to its blocking state.

If a reverse voltage is applied to the SCR, a small reverse leakage current flows. This is called the *reverse blocking current*. If the reverse voltage is increased to a point called the *reverse breakdown* *voltage,* the reverse current through the SCR will increase very rapidly and quickly destroy the SCR by excessive local heating of the crystals.

Firing the SCR with forward voltages less than the breakover point for zero gate current can be accomplished by making the gate positive with respect to the cathode. Figure 11-44(b) shows characteristic curves for various gate voltages.

If a gate current is applied, the forward breakover voltage is reduced considerably. If the gate current is sufficiently high, practically the entire blocking region is removed and the SCR behaves essentially like a conventional rectifier of the diode type. For normal operation, SCR's are operated considerably below the breakover point for zero gate current. Also, a gate current of sufficient magnitude is used to assure triggering at the proper point.

To summarize, an SCR will trigger without a gate current if the supply voltage is sufficiently large. Also, a gate current of sufficient magnitude is necessary if the supply voltage is held constant. Finally, an SCR will turn on at a certain anode voltage if the gate current is held constant. Under normal operating conditions, the SCR will conduct only if the gate is positive with respect to the cathode. A small current (several milliamperes) through the gate circuit triggers the SCR into conduction. The gate current is required only long enough to ensure that the anode current is built up. This takes just a few microseconds. The SCR will continue to conduct until the anode current falls below a small so-called holding current or until the anode voltage is reversed. In some a-c circuits, the SCR is cut off during each negative half cycle, and the gate regains control on each positive half cycle. Thus, the gate current, in the order of milliamperes, provides a control in which only a few microwatts can control hundreds of watts through an SCR in microseconds.

Therefore, if by means of circuitry, the SCR can be made to fire at any particular time during each half cycle of alternating current, then we have provided an excellent method of controlling the speed of a d-c motor. If the SCR is turned on or set to fire early in the half cycle, the motor will run fast. If the SCR is fired late in the half cycle, the motor will run slowly. It is apparent that by varying the time of firing, practically all speeds within range of the motor may be obtained. Figure 11-45 shows different firing angles.

Operation of the SCR

It was explained above that the SCR consists of four semiconductor materials arranged in alternate layers of PNPN. To explain its operation, we will consider an SCR as made up of two transistors, a PNP and an NPN, as shown in Figure 11-46. The anode, cathode, and gate terminals are connected as illustrated in Figure 11-47.

For the NPN transistor to conduct, the base of this transistor must be positive with respect to the emitter. If there is no voltage or a negative voltage present in the base, the transistor cannot turn on because it is reverse biased. Consequently, no current can flow between cathode and anode of the SCR.

Assume that the voltage of the anode and cathode are as shown and a positive gate pulse is applied to the base of the NPN transistor. The base-to-emitter bias is now forward, the NPN transistor turns on, and the collector current rises. The voltage drop across the NPN becomes very low when the NPN transistor turns on, making the collector practically as negative as the emitter.

Since this collector voltage is the base voltage of the PNP transistor, and since the emitter voltage of the PNP is positive, the PNP transistor will turn on. When the PNP turns on, the collector voltage will be practically the same as the emitter voltage. Since the collector of the PNP is connected to the base of the NPN, and since it is practically the same positive voltage as the PNP emitter, the base of the NPN becomes more positive, which in turn causes its collector current to increase further. This is called a *regenerative feedback action* because an increase in collector current in one transistor increases the collector current in the other. The amount of current increase will depend on the resistance of the external circuit.

It can be seen that once there is feedback from the collector of the PNP to the base of the NPN, a positive trigger voltage is no longer needed, because the positive voltage on the PNP collector holds the NPN base positive. It is also obvious that there must be a definite amount of current flow through the transistors to keep the NPN base positive. If this current—called the *holding current*—is sufficiently low, the SCR or PNPN switch will turn off.

The following points should be kept in mind:

1. A small gate-to-cathode current is necessary to trigger the SCR.
2. Once forward current starts flowing, it will continue indefinitely

unless the small holding current is reduced below its holding minimum.

3. Removing the gate current after the anode current has built up does not shut off the SCR.

4. To shut off the SCR (or to commutate it), the anode current must be reduced below the minimum holding current. The SCR is shut off automatically when the supply voltage is alternating current, because a reverse voltage is supplied to the SCR at the end of every positive half cycle.

5. Time is an important factor in turning off an SCR. If forward voltage is applied too soon after turn-off, the SCR may fire prematurely. About 10 microseconds should elapse between turn-off and reapplication of forward voltage.

6. If the anode voltage rises too quickly, enough leakage current might develop and fire the SCR prematurely.

Triggering the SCR

From the preceding information it is obvious that the ability of the SCR to change from a nonconductor to a conductor or from OFF state to ON state depends on the application of a small current to the gate terminal. This minute gate current, called a *control signal* or *trigger signal,* produces the pulse that triggers the SCR into conduction, provided the anode is positive with respect to the cathode.

If the SCR can be triggered at the same time during each positive half cycle, for example, at 90 electrical degrees, then only a definite percentage of the total power can be applied to the load, thus varying the speed of a motor. It is possible, with the proper circuitry, to vary the timing of the gate pulse and thereby obtain control over a wide range. All SCR's require triggering, and since there are numerous methods of controlling this process, some of the more important ones relating to motor control will now be discussed.

Half-wave Phase Control

We will assume an a-c power source connected to a motor in series with an SCR, as in Figure 11-48. If the SCR is triggered at the beginning of each positive half cycle, as in Figure 11-49, current will flow through the SCR and motor during each entire positive half cycle. Since the SCR is conducting when the anode is positive and nonconducting when the anode is negative (negative half cycle), the output will be half-wave direct current, and consequently the motor will receive approximately half power. Figure 11-50 shows a trigger pulse at 90 electrical degrees with the resultant firing of the SCR at this point. Since current will flow for only half of each positive half cycle, the power applied to the motor will be half that in the previous example. It can be seen that the power applied to the motor can be controlled by triggering the SCR anywhere from 0 to 180 electrical degrees. This is known as *phase control.* In other words, phase control is controlling an a-c supply to a load for a fraction of each half cycle. It is obvious, therefore, that the power applied to a d-c motor can be controlled and that speed control can be obtained merely by pulsing the SCR for a controlled fraction of each cycle.

Full-wave Phase Control

Full-wave rectified control is shown in Figure 11-51. This circuit is similar to the half-wave circuit of Figure 11-48, with the exception that full-wave d-c rectification is obtained through the use of a bridge rectifier. Assuming a trigger pulse at 60°, the circuit is as follows: From L_1, the electron flow is through rectifier D_3, SCR_1, motor M, rectifier D_2, and to L_2. During the next half cycle, electron flow starts from L_2, to rectifier D_4 SCR_1, Motor M, rectifier D_1 and to L_1. Note that the electron flow through the motor is in the same direction during each alternation of the a-c power source, making this circuit suitable for a d-c load. This is a very simplified circuit and does not include refinements necessary for the efficient operation of the motor. Figure 11-52 shows the output wave forms for this circuit.

If the load in the previous circuit were an a-c motor, it would be necessary to connect the motor in series with the a-c power source as shown in Figure 11-53(a). Figure 11-53(b) shows the wave form for this particular circuit. Note that although this is full-wave control, the output is a-c controlled.

Triggering Circuits

Resistance Triggering. A simple method of triggering an SCR, using alternating current as a power source, is shown in Figure 11-54(a). During the positive half cycle and with S_1 closed, the anode of the SCR will be positive with respect to the cathode and the gate will be positive with respect to the cathode. Current flow through the gate will trigger the SCR into conduction and cause a relatively large current to flow from L_1 through the SCR, through the load, to L_2. Gate current will now decrease because the source of gate current is the voltage across the SCR, and this voltage drops considerably while the SCR is conducting. At the start of the negative half cycle, the SCR shuts off and is nonconducting. Consequently, the load will see only a half-wave pulsating direct current. R_1 limits the peak gate current to a permissible value, while diode D_1 prevents reverse voltage from being applied between gate and cathode during the negative half cycle.

The resistance R also determines the time at which the SCR fires. Consequently, the phase angle of firing in the circuit of Figure 11-54(a) will be the same during each positive half cycle and cannot be changed, assuming all other components in the circuit are constant, unless a variable resistance R is used, as in Figure 11-54(b). In this case, a phase retard from practically full ON to 90° can be provided by varying the resistance. Gate control cannot go beyond the 90° angle in this circuit because the supply voltage and the gate voltage supplying the gate current are in phase. Therefore, the circuit of Figure 11-54(b) will provide a variable gate control which will fire the SCR for the entire positive half cycle when the variable resistance is at a minimum to half ON when the resistance is at a maximum. Wave forms for maximum and minimum power are shown in Figure 11-54(c).

Resistance Capacitor Triggering

In the circuit shown in Figure 11-55, a variable resistance is connected in series with a capacitor. With the start of the positive half cycle, the capacitor will start to charge through the variable resistor. The top of the capacitor will be positive, the bottom will be negative. Notice that the positive side of the capacitor is connected to the gate of the SCR. When the capacitor charges to a voltage sufficient to trigger the SCR, conduction will start and a relatively large current will flow through the SCR and load. The time in the half cycle at which the SCR triggers will depend on the *RC time constant,* explained in the next paragraph. The diode D_1 in this circuit permits charging the capacitor during the negative half cycle, making the top of the capacitor negative. This is necessary because the capacitor must be reset for the next positive-charging cycle. This circuit will give a full half-cycle control, enabling the SCR to fire at any time from 0 to 180 electrical degrees, because the time of firing depends on the length of time it takes for the capacitor to charge to the required voltage.

RC Time Constant

It takes a period of time to charge or discharge a capacitor in a series resistance-capacitance circuit shown in Figure 11-55. The length of time it takes for a capacitor to charge or discharge 63.2 percent is known as the *RC time constant.* In other words, if we assume a 100-volt source, the length of time it takes to charge the capacitor to 63.2 volts or discharge it to 36.8 volts is *one time constant.* The formula to compute the length of time in one time constant is

$$T \text{ (seconds)} = R \text{ (ohms)} \times C \text{ (farads)}.$$

From this formula, it can be seen that the greater the resistance, the longer it takes the capacitor to charge, and vice versa. Since current through this circuit is inversely proportional to the resistance, it is obvious that a reduction in resistance will increase the current. Consequently, the rate at which C_1 charges is dependent upon the current through it. This current is controlled by R_1.

Since, in the circuit of Figure 11-55, it is the potential charge on the capacitor that gives the gate its ability to trigger the SCR and since we can vary the time of this charge by varying resistance R_1, it is obvious that an *RC* circuit can be used to supply full half-cycle control from 0 to 180 electrical degrees.

It takes five time constants for a complete charge or discharge. In the above example, if it takes 0.01 second to charge a capacitor to 63.2 volts, it would take 0.05 second for a complete charge to 100 volts.

Unijunction Triggering

The theory of the unijunction transistor was explained earlier in this chapter, and its circuitry was shown in Figure 11-42. There are a number of uses for the UJT; however, one of its main uses is that of producing a trigger pulse by discharging a capacitor into the gate of an SCR in a relaxation oscillator circuit.

Figures 11-56 and 11-57 show elementary circuits for half-wave and full-wave motor control using unijunction triggering. In each circuit, capacitor C_1 charges through resistor R_1. When the capacitor charges to the voltage required to turn on unijunction transistor Q_1, the resistance between emitter E and B_1 drops considerably, C_1 discharges through EB_1, and R_2, and develops a voltage across R_2. The voltage is positive on the top of R_2 and supplies the gate current which causes the triggering of the SCR. In Figure 11-56 half power is developed. In Figure 11-57 full power is developed. The circuits of Figures 11-56 and 11-57 are suitable for control of shaded-pole and universal motors without feedback control. The latter term is explained later in this chapter.

In more advanced circuits, a transistor is used as a substitute for the variable resistor. We know from previous explanations on the operation of transistors that a small emitter-base current flow controls the flow of a much larger emitter-collector current. We also know that the current flow in the emitter-collector circuit is proportional to the emitter-base current flow. Therefore, as seen in Figure 11-58, the current through capacitor C_1 can be controlled by the emitter-base current through the transistor rather than by a variable resistor as in Figure 11-57.

Note that the base-emitter circuit is controlled by a reference and feedback signal. These terms are explained and illustrated later in this chapter. Figure 11-58 is a controlled full-wave a-c to d-c circuit suitable for a d-c load. Current through transistor Q_1 charges capacitor C_1 to a voltage where the emitter of Q_2 becomes slightly more positive than the voltage present at the point on the UJT where the emitter is attached. This turns on Q_2; C_1 then discharges through base *1* and R_2, producing a positive pulse across R_2. The top of R_2 is connected to the gate of SCR_1, causing it to fire. Triggering the SCR causes it to conduct and complete the circuit through the load.

In Figure 11-59, a Zener diode, is used to supply the unijunction transistor with a voltage suitable for its operation. Transistor Q_1 will control the current charging C_1. If the resultant reference and feedback signal in the base-emitter circuit of Q_1 is such that a relatively large current flows through the emitter-collector circuit, then a large current will charge C_1, charging it rapidly to the voltage required for a positive pulse. As described previously, the timing of the pulse, and consequently the speed control of a motor, will depend on the charging rate of the capacitor.

SCR Motor-control Applications

Electric controllers, as explained in the chapters on a-c and d-c motor control, have many functions. Some of the more important functions are to start and stop a motor, to reverse rotation, to provide overload protection, to provide braking, to limit starting current, and to obtain speed control.

SCR drives provide all these functions and more. However, we will concentrate mainly on speed control for single-phase, universal, and d-c motors. SCR drives have high efficiency, provide stepless speed control, and require a minimum of maintenance.

Reference and Feedback Signals

We know that a small gate current will trigger an SCR if the anode is positive with respect to the cathode. We also know that the gate voltage must be positive with respect to the cathode. The timing of the gate pulse will depend on the type of triggering circuit used: a phase-displaced a-c signal or a positive pulse using the capacitor and unijunction transistor. There are numerous other methods of firing an SCR.

Since it is necessary to have a positive voltage of a definite value to fire the SCR and since this voltage is related to a setting on a speed control potentiometer, we can call this voltage the *reference voltage*. The reference signal current is obtained from this reference voltage. If it is desired to regulate the speed of a motor, it will be necessary to compare this reference voltage to the voltage developed by the motor itself— the counter e.m.f. The voltage used for this comparison is called the *feedback voltage*, and its current direction is always such as to oppose the reference current. The feedback voltage may be the counter e.m.f. developed by the motor or it may be the voltage developed by a tachometer generator mechanically attached to the motor. There are a number of methods used to provide for feedback voltage.

Figure 11-60(a) illustrates a circuit in which the reference and feedback voltage are compared to produce the signal current for the gate circuit. If the reference and feedback voltages are connected in series and if their polarities oppose one another, the total voltage will be the difference between their voltages. For example, if the reference voltage is 20 volts positive and the counter e.m.f. is 15 volts opposing, the resultant voltage will be 5 volts positive. Similarly, using voltage sources as in Figure 11-60(b), the resultant voltage is equal to the reference voltage minus the back e.m.f. Thus, this voltage is 30 — 25, or 5 volts positive. Also, the reference and feedback signals can be compared by connecting them in parallel with opposite polarities. In this case the *currents* are compared. The difference between the currents (error current) is fed to the firing circuit.

Universal Motor Control

As described above, one of the methods of obtaining a feedback signal is by means of the counter e.m.f. of the motor. This is easily obtainable since the universal motor is a brush type of motor. The back or counter e.m.f. generated by the motor during the time when the SCR is off depends mostly on the speed of the motor and the residual magnetism in the field poles.

Half-wave Control with Feedback *

The following circuit makes use of the motor residual field to induce a back e.m.f. in the armature proportional to speed. This voltage is employed as the speed feedback signal.

Figure 11-61(a) is a circuit advanced by Momberg and Taylor.† In this circuit, the position of the SCR relative to the motor armature and its field is changed so that it is now connected between the field windings and the armature. Voltage V_g is tapped off a potentiometer connected directly across the line and is thus an attenuated sine wave in phase with the voltage across SCR, in the blocking state. When the motor armature is standing still, no voltage is induced in the armature by the residual field and the SCR fires early in the cycle, providing ample armature voltage to accelerate the motor. As the motor speeds up, its residual induced voltage

*Adapted from General Electric Co., Semiconductor Products Department.
†U.S. Patent No. 2,939,064, J. W. Momberg et al, "Motor Control Systems", May 31, 1960, assigned to The Singer Manufacturing Company.

increases proportional to speed. This voltage on the armature prior to firing the SCR bucks the flow of gate current, and requires that voltage V_g reach a higher value before firing the SCR. This automatically retards the firing angle, allowing the motor to reach a stable equilibrium speed.

If a load is applied to the motor, there will be a tendency for the speed to decrease. This will reduce the residual induced voltage in the armature and automatically advance the firing angle. This will cause the SCR to fire earlier in the cycle, thereby increasing the motor torque to handle the increased load and maintain essentially constant speed.

Figure 11-61(b) illustrates waveforms in the circuit with the potentiometer arm in a high-speed position at which V_g reaches a relatively large amplitude. This fires the SCR early in the half cycle. In the low-speed setting of part (c) the amplitude of V_g is low and the SCR fires at approximately midpoint in the half cycle.

Although this circuit is a very simple one, there is a considerable amount of power dissipated in R_1P_1 network. Also, the SCR cannot be consistently fired at a firing angle greater than 90 electrical degrees. This prevents stable operation at low speeds. The circuit also has a tendency to hunt with line variations when operating around a firing angle of 90 electrical degrees. However, in many applications these limitations are not serious.

Half-wave Control—Improved Performance *

If stable operation at low speeds is required, the circuit of Figure 11-62(a) may be used. This circuit also makes use of the motor residual field for a speed feedback signal but permits a very short conduction time for the SCR and hence a slow speed.

During the negative half cycle of the supply voltage, capacitor C_1, which may be of the polarized type, is discharged to zero. During the positive half cycle, C_1 charges from a constant potential (Zener voltage of CR_3) at a rate dependent on the time constant P_1C_1. If the motor armature is standing still, no voltage is induced in it by the residual field, and gate current to the SCR flows as soon as V_c, the voltage across C_1, exceeds the forward voltage drop of CR_1 and the gate drop of SCR_1. This will fire SCR_1 early in the cycle, providing ample energy to accelerate the motor. As the motor

*Adapted from General Electric Co., Semiconductor Products Department.

approaches its preset speed, the residual induced voltage in the armature builds up. This voltage is positive on the top terminal of the armature and opposes the flow of gate current from C_1 until V_c exceeds the armature voltage. This higher voltage requirement on C_1 retards the firing angle and allows the motor to cease accelerating.

Once the motor has reached operating speed, the residual induced voltage provides automatic speed-regulating action. For instance, if a heavy load starts to pull down the motor speed, the induced voltage decreases, and the SCR fires earlier in the cycle. The additional energy thus furnished to the motor supplies the necessary torque to handle the increased load. Conversely, a light load with its tendency to increase speed raises the motor residual induced voltage, retarding the firing angle and reducing the voltage on the motor.

P_1 adjusts the desired speed by controlling the charging rate of C_1. When a relatively high speed is desired, P_1 is adjusted to a low value. V_c builds up fast and fires SCR_1 early in the cycle. The wave form of V_c on capacitor C_1 is shown in Figure 11-62(b). Note that the counter e.m.f. at this setting will be relatively high also because of the high motor speed. When P_1 is set to include a large portion of the resistance, V_c builds up slowly so that firing occurs late in the cycle, as in Figure 11-62(c), and the motor speed is therefore low. Notice the graph of Figure 11-62(d). Each positive half cycle has been clipped by the Zener diode so that the voltage across the Zener diode is practically constant for each positive half cycle. C_2 and resistor *1K* are connected from gate to cathode to stabilize the circuit by by-passing commutator hash and extraneous signals which could fire the SCR prematurely.

Although the two circuits of Figures 11-61(a) and 11-62(a) use a feedback signal, there is the disadvantage of requiring separate connections for the field and armature. In the following circuits this objection has been removed. The circuit of Figure 11-63(a), just as the two previous circuits, uses the residual counter e.m.f. of the armature as a feedback signal to maintain a nearly constant speed with varying torques. When the load is increased the motor speed tends to fall. At this time more current is fed into the armature, preventing the speed from dropping appreciably. When the motor tends to speed up with a drop in load, the reverse occurs.

If the motor slows down, the SCR is fired earlier in the positive half cycle. This causes the current delivered to the motor to increase, speeding up the motor. The reverse is also true, so that in either case the motor maintains nearly constant speed.

A half-wave rectified current flows through the series network of R_1P_1 and CR_2 when the a-c source makes the cathode of CR_2 negative to the anode. This provides the adjustable reference voltage from the arm of P_1. Capacitor C_1 smoothes out this sine wave, producing a cosine ramp voltage which permits a prolonged phase control beyond 90 electrical degrees in the positive half cycle. The ideal waveshape would be to obtain a signal that has a minimum magnitude of 0 and a maximum at 180 electrical degrees, as shown in Figure 11-63(b). However, since the ramp voltage on C_1 is not quite a cosine wave, there is a limitation on how early and how late in the half cycle the SCR can be fired.

It can be seen in Figure 11-63(c) that the SCR cannot be fired later than point Z in the half cycle, since the cosine wave gets distorted beyond this point. It is important to note that a low capacitance value of C_1 may not give enough phase shift to fire the SCR late in the cycle to obtain slow-speed operation, and increased capacitance value may cause unstable operation (hunting) at low speeds.

In operation, the counter e.m.f. of the motor is compared through the gate of the SCR with the reference voltage out of diode CR_1. The SCR will fire early or late in the positive half cycle, depending on the result of the comparison through the gate. When the motor starts running, there is no back e.m.f. on the armature, and gate current starts to flow as soon as the voltage on the arm of P_1 exceeds the forward drop of CR_1 and the gate-to-cathode drop of the SCR. This fires the SCR early in the half cycle, delivering sufficient energy to the motor. The counter e.m.f. increases as the motor builds up speed. The voltage on the capacitor now has to be greater than the forward drop of CR_1 and the counter e.m.f. produced. This higher voltage requirement on C_1 retards the firing angle and causes the motor to cease accelerating.

To avoid hunting of the motor every time potentiometer P_1 is returned to its minimum setting, a resistor or a trimpot can be added in series between P_1 and CR_2 to preset the minimum speed of the motor to a nonhunting level. Capacitor C_1 would remain tied from the arm of P_1 to CR_2. The parallel network of R_2-C_2 from gate to cathode by-passes the commutator hash and prevents it from reaching the gate.

It should be noted that for different load conditions, the values of the components should be changed. This is given in the table of Figure 11-63(d).

Wider Speed Range

The previous circuit provides a good performance for speed ranges from several hundred r.p.m. to full speed. At lower speeds this circuit tends to hunt. A circuit that gives a good performance at low speeds as well as at high speeds is shown in Figure 11-64. This circuit requires an intermediate amplifier stage between the reference voltage of P_1 and the gate of SCR_1. This can be accomplished in several ways, one of which uses a silicon unilateral switch, abbreviated SUS.

Note that this circuit is very similar to the previous circuit, with the exception that an SUS is used. The SUS is essentially a miniature SCR having an anode gate instead of the usual cathode gate and a built-in low-voltage avalanche diode between the gate and cathode. It is used similarly to a UJT to provide a pulse, but is different in that the SUS switches at a fixed voltage rather than a fraction of another voltage, as in a UJT. In Figure 11-64, the triggering of the SCR is accomplished by a pulse from SUS_1 rather than by a continuous current to the gate through CR_1. The SUS_1 essentially acts as an amplifier stage between the reference voltage and the gate of the SCR. Note the symbol for the SUS.

Full-wave d-c Control with Feedback*

Figure 11-65 shows the circuit of a full-wave series motor speed control with feedback which requires that a separate connection be available for the motor armature and field. The full-wave bridge supplies power to the series networks of motor field, SCR_1 and armature, and R_1 and P_1. Basically, this circuit works on the same principle as the circuit in Figure 11-61(a), using the counter e.m.f. of the armature as a feedback signal. When the motor starts running, the SCR fires as soon as the reference voltage across the arm of P_1 exceeds the forward drop of CR_1 and the gate-to-cathode drop of SCR_1. The motor then builds up speed, and as the back e.m.f. increases, the speed of the motor adjusts to the setting of P_1 in the

*Adapted from General Electric Co., Semiconductor Products Department.

same manner as the circuit of Figure 11-61(a). CR_6 is a freewheeling diode that is used to maintain current flow in the field.

One of the drawbacks of this circuit is that at low-speed settings, because of the decreased back e.m.f., the anode-to-cathode voltage of the SCR may not be negative for a sufficient time for the SCR to turn off. When this happens, the motor receives full power for the succeeding half cycle and the motor starts hunting. Furthermore, just like the circuit in Figure 11-61(a), this circuit is limited by the fact that SCR_1 cannot be fired consistently later than 90 electrical degrees. A capacitor on the arm of P_1 is not a cure because there will be no phase shift on the reference due to full wave rectified charging.

Full-wave without Feedback *

In the circuit of Figure 11-66, a Diac is used as the trigger element and a Triac is used instead of an SCR. Note the symbols for these devices. The Diac is a two-terminal silicon bidirectional trigger diode which may be used to trigger a Triac or an SCR. The Triac is a three-terminal semiconductor switch which triggers into conduction by a gate signal in a manner similar to that of an SCR. It differs from an SCR in that it can conduct current in either direction in response to a positive or negative gate signal, thereby promoting more efficient use of the device on alternating current, where current reverses every half cycle.

In this circuit, C_1 starts charging by current flow through the series network consisting of R_1, P_1, and C_1. When the voltage on capacitor C_1 reaches the breakover voltage of the Diac, it fires the Diac, producing a pulse which fires the Triac. This process takes place during both positive and negative halves of the a-c line. This circuit has no feedback control and therefore has low starting torque on low-speed settings and a very poor speed regulation. The series network of R_2-C_2 in parallel with the Triac is used for the purpose of keeping the rate of voltage rise in the Triac as low as possible immediately following turn off at current zero (commutation dv/dt). This permits the Triac time to commutate, or turn off, so that it may be fired at the proper angle during the following half cycle. We pointed out previously that too fast a voltage rise may result in a failure of the Triac to turn off.

*Adapted from General Electric Co., Semiconductor Products Department.

Full-wave Control with Synchronization

In order to ensure that the timing pulse which triggers the SCR occurs at the same point during each half cycle, it is necessary to synchronize the charging of C_1 with the line alternations. Synchronization is vital to the correct operation of the circuit because the firing pulse must have the same relationship to the input frequency during each half cycle. Although there may be a number of firing pulses during each half cycle, it is the first timing pulse that must have a fixed relationship to the start of each alternation.

In Figure 11-67, the UJT triggers at the end of each half cycle when the voltage at B_2 drops to zero. Any residual charge in C_1 is discharged rapidly at this time, permitting C_1 to start charging again with the beginning of each half cycle. Note that a full-wave rectified voltage from a bridge rectifier supplies power to the load and to the trigger circuit. Zener CR_1 is used to clip and regulate the peaks of the pulsating direct current. Note the wave forms at different parts of the circuit.

Shunt Motor Control without Feedback

Most of the circuits and controls described thus far are designed to control the speed of universal motors. The following circuits can be used for the control of shunt or compound motors. These are mainly elementary diagrams and are shown primarily for explanatory purposes.

The shunt motor is primarily a constant-speed machine. To change the speed of this motor, the voltage applied to the armature is controlled while the field excitation is held constant. A simple diagram showing half-wave control of a shunt motor is illustrated in Figure 11-68.

During the positive half cycle, capacitor C_1 in the RC network of R_1, P_1, and C_1 charges and supplies a phase shift signal to the trigger device which in turn fires the SCR into conduction. The timing of the phase shift signal is accomplished by varying the potentiometer, P_1, setting. This determines the conduction point in each half cycle and thus controls the speed of the motor. The trigger device may be a Diac, SUS, neon bulb, and so on.

The shunt field is supplied with half-wave current through diode D_2 during the time L_1 is negative with respect to L_2 (see solid arrows Figure 11-68). In the next half cycle, when L_2 is negative with respect to L_l and diode D_2 is reverse biased and therefore non-conducting, the current in the shunt field will tend to decrease. However, the shunt field is an inductance, and, since an inductance has the property of resisting a change in current, the energy, in the form of current due to self-inductance, will circulate through D_1 (see dotted arrows), thereby supplying continuous unidirectional current to the field. In this circuit, D_1 is known as a *back rectifier* or *free-wheeling rectifier.*

Shunt Motor Control (Square D)

Precautions must be taken in the use of SCR's since they have a definite breakdown voltage in the reverse direction. While the current flow is negligible up to this breakdown voltage, once the voltage occurs, the SCR will be destroyed. As shown in Figure 11-69, to protect the SCR, Square D Company has mounted conventional silicon diodes in parallel and also in series with the SCR. The parallel rectifier marked *3 REC* is connected in the reverse direction to the SCR. It is biased ON, or conducting, while the SCR has reverse potential connected across it. It, in effect, shorts out the SCR on the negative half of the applied single-phase a-c wave. The series rectifier, *2 REC*, blocks the negative half of the supply voltage. During the negative half cycle, the SCR does not experience any reverse voltage because of this network. The diode network plus fuse *1 FU* and surge protector *1 SP* protect *1 SCR* from high currents or extremely high peak inverse voltages which may destroy this component. *1 REC* is a commutating diode for the armature. This diode provides a discharge path for the inductive energy in the armature.

Figure 11-70 is a typical elementary diagram of a Square D Company Class 8835 Type SFG 14 a-c powered drive designed to control the speed of a d-c shunt motor by motor armature control (constant torque range) from base speed to $\frac{1}{20}$ base speed. This diagram contains some of the elements shown in Figure 11-69.

A single silicon controlled rectifier, *1 SCR*, provides half-wave rectified d-c power, adjustable over a 20:1 range, to the motor armature: *1 REC* is a commutating, or discharge, rectifier connected across the armature; *2 REC* is a silicon rectifier which acts to block the reverse voltage on alternating negative half cycles, thereby protecting the SCR. This drive contains an encapsulated module (*1 PM*) consisting of a resistor, capacitor, and unijunction transistor firing network which phase-shifts the gate to cathode voltage to *1 SCR*, providing the adjustable voltage output to the armature of the d-c shunt motor.

For the shunt field, two silicon rectifiers are encapsulated in the 1 PM phase-shift module. These are connected exactly as shown in Figure 11-68 and provide constant voltage to the shunt field. Note the free-wheeling diode connected across the shunt field. Some drives incorporate a full bridge circuit for shunt-field supply.

Speed control in the constant-torque range is obtained by adjusting the motor armature voltage while the shunt-field supply is kept at full strength.

Adjustable armature voltage is obtained by controlling the degree of conduction of the SCR. Control of the SCR is accomplished by phasing back the gate-to-cathode voltage (E_gK) of the SCR with respect to the input line voltage. The phase shift circuit consists of the "speed potentiometer" and module.

A speed reference voltage is selected by a setting of the speed potentiometer. High-speed setting, corresponding to base speed of the motor, permits almost full conduction of the SCR during the positive half wave of the a-c input voltage. This is shown in Figure 11-71(a), where the gate-to-cathode voltage E_gK is almost in phase with the 120-volt a-c supply. Point *X* is the firing point where the gate becomes positive with respect to the cathode and where the SCR begins to conduct. The motor counter e.m.f. is shown as the solid line in Figure 11-71(a). Here the counter e.m.f. is approximately 90 volts, corresponding to the motor base speed. Note that the armature current is discontinuous at this speed setting.

In Figure 11-71(b), the speed pot is set at 0° which corresponds to $\frac{1}{20}$ the speed of the motor. Note that the firing point *X* is phased back almost 135° with respect to the input 120-volt a-c supply. Here the counter e.m.f. is approximately 5 volts, corresponding to $\frac{1}{20}$ of motor base speed.

In Figures 11-71(a) and (b), the counter e.m.f. dips down at point *Y*. This is caused by motor armature inductance setting up a voltage which is opposite to the counter e.m.f. of the motor. The commutating diode *1 REC* connected across the armature, as shown in Figure 11-70, provides a discharge path for the inductive energy of the motor similar to the field supply. At low speeds, this inductive voltage sets up a continuous armature current, resulting in a better motor form factor, thus permitting a smaller motor to be selected. Note the START-STOP station for *1M1* contacts and also the dynamic braking resistance and normally closed *DB* contacts *1M3*.

Full-wave Speed Control for a Shunt Motor *

Another circuit for the speed control of a fractional hp. shunt-wound d-c motor is shown in Figure 11-72. This circuit uses a bridge rectifier to provide full-wave rectification of the a-c supply. The field winding is permanently connected across the d-c output of the bridge rectifier. Armature voltage is supplied through the SCR and is controlled by turning the SCR on at various points in each half cycle; the SCR turning off only at the end of each half cycle. Rectifier D_3 provides a circulating current path for energy stored in the inductance in the armature at the time the SCR turns off. Without D_3 the current will circulate through the SCR and the bridge rectifier, prohibiting the SCR from turning off.

At the beginning of each half cycle, the SCR is in the OFF state and C_1 starts charging by current flow through the armature, rectifier D_2, and the adjustable resistor R_2. When the voltage across C_1 reaches the breakover voltage of the diac trigger diode, a pulse is applied to the SCR gate, turning the SCR on and applying power to the armature for the remainder of that half cycle. At the end of each half cycle, C_1 is discharged by current through rectifier D_1, resistor R_1, and the field winding. The time required for C_1 to reach breakover voltage of the diac governs the phase angle at which the SCR is turned on and is controlled by the magnitude of resistor R_2 and the voltage across the SCR. Since the voltage across the SCR is the output of the bridge rectifier minus the counter e.m.f. across the armature, the charging of C_1 is partially dependent upon the counter e.m.f., and hence upon the speed of the motor. If the motor runs at a slower speed, the counter e.m.f. will be lower and the voltage applied to the charging circuit will be higher. This decreases the time required to trigger the SCR, thus increasing the power supplied to the armature and thereby compensating for the loading of the motor.

Energy stored in the armature inductance will result in current flow through rectifier D_3 for a short time at the beginning of each

*Adapted from General Electric Co., Semiconductor Products Department.

half cycle. During this time, the counter e.m.f. of the armature cannot appear; hence, the voltage across the SCR is equal to the output voltage of the bridge rectifier. The length of time required for this current to die out and for the counter e.m.f. to appear across the armature is determined by both speed and armature current. At lower speeds and at higher armature currents, the rectifier D_3 will remain conducting for a longer period of time at the beginning of each half cycle. This action also causes faster charging of capacitor C_1, and hence provides compensation that is sensitive to both armature current and to motor speed.

Resistor R_1 is chosen so as to limit the discharge current of C_1 to a value less than the field winding. If this discharge current is higher than the field current, the excess may be diverted through the SCR and can result in failure of the SCR to turn off at the end of each half cycle. On the other hand, if R_1 is made too large, the voltage on capacitor C_1 may not be properly reset at the end of each half cycle and irregular operation will be noticed at low-speed settings.

This circuit provides a very large range of speed control adjustment. The feedback signal derived from speed and armature current improves the speed regulation over the inherent characteristics of the motor.

Half-wave Control for a Shunt Motor *

Many shunt motors have been designed for operation on half-wave rectified 120-volt supply rather than on full-wave rectification as shown in previous circuits. Figure 11-73 shows a circuit designed for half-wave control of such shunt-wound motors. Field current is supplied by rectifier D_1, and free-wheeling rectifier D_3 provides a circulating current path for smoothing of field current waveform. The armature is supplied by current through the SCR and also has a free-wheeling rectifier D_5. Voltage for the control circuit is derived from the voltage across the SCR, as in the previous circuit. At the end of each positive half cycle, the voltage across the field drops to zero and control capacitor C_1 is discharged through diode D_2 at this time. This action ensures that the voltage on capacitor C_1 is always zero at the beginning of each positive half cycle

*Adapted from General Electric Co., Semiconductor Products Department.

(synchronization), regardless of the setting of the speed control resistor R_1.

The operation of this half-wave control circuit is essentially the same as the full-wave circuits previously described. In this circuit, free-wheeling diode D_5 across the armature may be eliminated, but only at the expense of greatly reduced available torque, particularly at low speeds. It should be noted that the voltage rating required of the SCR is twice what would normally be used with a resistive load, because the counter e.m.f. of the armature at high speeds adds to the voltage of the power supply during the negative half cycle, thus nearly doubling the reverse voltage appearing across the SCR. This voltage also appears across diode D_4, requiring that it also be rated for 400 volts.

Miscellaneous Power-control Circuits

Half-wave and full-wave speed controls for shunt and compound motors are used extensively in many applications for industrial and commercial work. Most of these solid state motor controls are similar in that they may be controlled by varying the armature voltage while the field voltage is kept constant. Most of the following circuits are elementary and are given because they serve to explain the function of the various components used in the controls.

Figure 11-74(a) shows the power circuit of a shunt motor solid state control. In this circuit, the armature is connected through an SCR while a pair of diodes D_2 and D_3 forms a half-wave and back-rectifier system for supplying excitation to the shunt field. Figure 11-74(b) shows how field excitation is obtained. When L_1 is negative, current flows through D_2, the field, and back to L_2. When L_2 is negative, D_2 is reverse biased and the inductive energy in the field will flow through D_3, keeping constant excitation in the field.

Pressing the START button of Figure 11-74(a) closes normally open contacts M and opens normally closed dynamic braking contact M. During the positive half cycle when L_2 is negative with respect to L_1, and assuming the SCR is triggered into conduction, a circuit will be completed from L_2 through the armature, the SCR, diode D_1, and fuse F. During the negative half cycle, the SCR will not conduct. However, during this half cycle, a circuit will be completed from L_1 through D_2 and the field. The current through the field will continue during the next half cycle because of free-wheeling diode D_3 and the field self-inductance, thus providing a relatively constant unidirectional current flow through the field.

SP is a surge protector, usually a selenium rectifier to protect the SCR from high currents or extremely high peak inverse voltages which may destroy this component. R_3 is a shunting resistor which protects the SCR by by-passing high peak reverse voltages to diode D_1. On many drives, an additional resistor is shunted across D_1 to protect it as well. D_1 is also used to prevent reverse transient voltages from damaging the SCR. R_1 is a holding-current resistor for the SCR. This is placed in parallel with the inductive load (armature in this case) and permits an in-phase holding current in the SCR (as opposed to a lagging current) due to the inductance of the load. In other words, with a lagging load current, the SCR may trigger before holding current is reached and consequently revert to its blocking state. The resistor allows the SCR to remain in a conducting state from the time it is triggered. D_4 is a commutating or free-wheeling diode. This rectifier allows the armature to discharge its inductive energy, which at low speeds sets up a continuous armature current, resulting in smooth operation.

Full-wave Control

In Figure 11-75(a), a shunt motor is speed controlled by varying the armature voltage while the field voltage is kept constant. The firing circuit is not shown. A full-wave circuit is used to supply power. Single-phase alternating current is converted to direct current by the full-wave bridge rectifier consisting of diodes D_1 and D_2 and SCR's *1* and *2*. To prevent reverse transient voltages from damaging the SCR's, diodes D_3 and D_4 and resistors R_1 and R_2 are used. The network of resistor R_3 and capacitor C_1 and the network of R_4 and C_2 protect the SCR's against false triggering from too rapid rate of rise in applied voltage due to line voltage fluctuations.

During the half cycle when L_1 is positive with respect to L_2, the current flows from L_2 through F_2, SCR$_2$, D_4, R_5, armature A_1, A_2,D_1, F_1, and to L_1. The direction of current flow in the armature is from A_1 to A_2. During the next half cycle, electron current flows from L_1 through F_1, D_2, R_5, armature A, A_2, SCR$_1$, D_3, F_2, and to L_2. Note that the armature current flow is unidirectional.

In this circuit D_1 and D_2 are used for the free-wheeling path for the armature-induced current. If one SCR is used, as in Figure

11-75(b), instead of two, a back rectifier diode across the armature would be necessary. If the back, or commutating, rectifier is not used, the inductive energy of the armature would keep the SCR conducting continuously. Consequently, the SCR could not turn off and regain its blocking ability during each half cycle. The commutating rectifier provides a path for the inductive energy, thereby permitting the SCR to turn off after each half cycle. R_5 is a resistor connected in series with the armature. The voltage across this resistor is used for load regulation. R_6 is a holding-current resistor.

The shunt field is supplied with a full-wave rectified direct current from the bridge circuit consisting of diodes D_5.

The output of the motor of Figure 11-75(a) is controlled by SCR_1 and SCR_2. A small output is obtained when the SCR's are fired late in the half cycle, and a larger output is obtained when the SCR's are fired earlier in the half cycle. Only one SCR is fired in each half cycle. The SCR that fires is the one with the anode positive with respect to its cathode.

Another shunt motor circuit somewhat similar to the previous one is shown in Figure 11-76(a). As in the other circuits shown thus far, electron current flow is used for tracing out the circuit. A full-wave bridge circuit is used to supply power to the armature. The full-wave bridge circuit is formed by SCR_1, SCR_2, D_1, and D_2. Assuming the SCR_2 is triggered into conduction, current flows from L_2 through F_2, D_1, *Arm,* SCR_2, F_1, and to L_1. If SCR_1 is triggered, current flows from L_1 to F_1, D_2, *Arm,* SCR_1, F_2, and to L_2. Current flows through the armature in the same direction during each alternation of the a-c line.

R_2, R_3, R_4, and R_5 are connected across the rectifiers to prevent damage from reverse transient voltages. R_1 is used to maintain a holding current in the SCR's, as described in the circuit of Figure 11-74(a). D_3 is a commutating diode, used to discharge inductive energy of the armature and consequently permit the SCR to shut off at the end of each half cycle. It also keeps a continuous current flow in the armature at low speeds, resulting in more efficient operation.

Resistance-capacitor networks can be connected across the bridge rectifiers to prevent a too rapid rate of rise in voltage resulting in premature triggering. Capacitors may be connected from cathode to gate in both SCR's to filter extraneous gate signals which may turn on the SCR's.

Although the motor field is connected in a half-wave circuit through diode D_1, the field is supplied with constant excitation because of the inductive discharge through free-wheeling diode D_2 during the half cycle when L_2 is positive. This is shown in Figure 11-76(b).

Firing Circuits

The last few diagrams show the armature and field circuits for small-motor static drives. In order to control and regulate the speed of these motors, we must be able to control the time during each conducting half cycle the SCR is fired. The method of firing differs in many circuits. In the following circuits, firing will be accomplished by means of a positive pulse, and a unijunction transistor will be used for this purpose. In many of the firing circuits a transformer T_1 is used to supply power for the reference signal.

Figure 11-77 shows an elementary circuit in which a positive pulse is supplied by a discharging capacitor C_2 through a unijunction transistor Q_1 and resistor R_3. A pulse transformer can be substituted for resistor R_3 to isolate the d-c voltage in the firing circuit from the SCR circuit. D_1 is used to provide half-wave rectification, and C_1 filters the pulsating direct current to a nearby constant direct current through R_4. Capacitor C_2 charges through potentiometer R_1. When the capacitor voltage rises above the existing voltage at the emitted junction, the unijunction transistor is forward biased and the capacitor discharges through B_1 and R_3, producing a positive pulse voltage across R_3.

After the capacitor discharges, the UJT returns to the OFF condition and a new cycle begins. The timing of the pulse depends on the RC constant, and the rate at which the capacitor charges depends on the setting of R_1 and therefore on the current flow through C_2.

It is important to synchronize the charging of C_2 with the line voltage alternations. This can be accomplished in a number of ways, one of which is shown in Figure 11-78. In this circuit, diode D_2 conducts the negative half cycle and, since it is connected across C_2, clamps a voltage of about 0.5 volt on the capacitor. At the next half cycle C_2 is ready to charge, its rate of charge depending on the potentiometer setting.

Instead of using a potentiometer to vary the current charging C_2, a transistor is very often used. Its function is to amplify the error signal (reference-feedback) applied at the base of the transistor and thus control the flow of a much larger current from the emitter to the collector. This will, in turn, determine the rate at which C_2 is charged.

In Figure 11-79, transistor Q_2 is the PNP type. To turn on this transistor, it must be biased positive on the emitter to negative on the base. A potentiometer across the rectified line is used to set the reference voltage. The arm on the potentiometer is connected to the base of the transistor and should be negative with respect to the emitter if there is no feedback from the armature. The feedback current through transistor Q_2 should be in such a direction that it will decrease the charging rate of capacitor C_2. This will, in turn, decrease the speed of the motor.

With a feedback voltage from the armature, a fairly good speed regulation can be obtained. This feedback voltage is compared with the reference voltage from the potentiometer, and since the direction of the feedback current is in direct opposition to the speed reference signal current, a resultant current is formed and appears at the base of amplifier Q_2. It should be understood that the feedback current is in a direction to decrease the charging rate of capacitor C_2. If Q_2 permits a large current flow to the capacitor, C_2 will charge rapidly to a voltage required for a pulse. If a small amount of current is passed, C_2 will charge slowly. From previous information we know that the speed of the motor will depend on the charging rate of the capacitor.

The operation is as follows. If the motor is running at the speed called for by the setting of the potentiometer, the feedback voltage will be slightly less than the reference voltage. If, however, the speed should drop because of excessive load, the feedback voltage will be substantially less than the reference voltage, and consequently there will be a greater base-emitter current. Since this controls the emitter-collector current, the capacitor C_2 will charge at a faster rate, causing the speed of the motor to increase.

Figure 11-80 shows how a center-tapped transformer can be used to supply full-wave rectified current filtered by means of capacitor C_1. This power supply can be used instead of the half-wave supply of Figure 11-79.

The above material does not take into account the *IR* drop in the armature due to load fluctuations. In actual practice, *IR* drop compensation is often provided for in the circuit so that the drive may be well regulated. However, *IR* drop compensation, as well as linear acceleration, has been purposely omitted, since the purpose of this chapter is to make understandable just the fundamentals of drives.

Synchronizing by Use of Transistors

Several methods of synchronizing the charging of C_2 with the line voltage alternations have been shown thus far. In Figure 11-81, a transistor is used to synchronize the timing of the pulse to the alternations. Notice that Q_3 collector-emitter circuit is connected directly across C_2. If Q_3 can be made to conduct at the beginning of each half cycle, C_2 would discharge through it. For the remainder of each half cycle after C_2 has been discharged, Q_3 must be switched into a nonconductive state.

To switch NPN transistor Q_3 on, the base must be positive with respect to the emitter. This is accomplished by sending full-wave direct current through R_4 in a direction that turns Q_3 on. At the same time, direct current is sent through R_6 in a direction that turns Q_3 off. This current flows through D_3. The resultant current from these two circuits turns Q_3 on at the very beginning of the half cycle and turns it off for the remainder of the circuit, thereby permitting C_2 to charge through R_1. This circuit has been added to show the many uses of transistors in solid state circuits.

Single-phase Motors

Split-phase and capacitor-start motors use a centrifugal switch to disconnect the starting winding after the motor has attained approximately 75 percent of base speed. Where the arcing of the centrifugal switch is undesirable or where there may be explosive fumes, the mechanical switch can be replaced by a current or potential switch as described earlier in this book or by a solid state switch. In this type of circuit, shown in Figure 11-82, a current transformer is used to trigger a bidirectional solid state switch as soon as power is supplied from the line. As the motor approaches base speed, the current through the windings decreases and the switch ceases to fire, disconnecting the starting winding from the circuit. The primary of the transformer is connected in series with the line, and, at start, when the current is high, the induced secondary triggers the switch, placing the starting winding in the circuit. As the motor speeds up, the current drops and no longer fires the switch, keeping only the running winding in the circuit.

Three-phase Drives

Three-phase drives are used mainly for integral horsepower motors. There are several types; the most popular ones are the magnetic drive, motor-generator sets, and static drive.

The magnetic drive consists essentially of a constant-speed induction motor and a magnetic clutch. The magnetic clutch consists basically of three members: (1) a stationary field assembly mounted on a support bolted to the housing of the machine; (2) a drum assembly mounted on the motor shaft and concentric with the field assembly so that the inner surface of the drum surrounds the field assembly and rotates at the speed of the motor; and (3) an output pole assembly which rotates at a speed determined by the control and which is the output adjustable speed member. This assembly is mounted on the output shaft. As described above, there are two rotating members and a stationary member. Assuming no current flow, the drum mounted on the motor shaft is free to turn, the output assembly mounted on the output shaft is free to turn, and the field assembly remains stationary. See Figure 11-83.

When direct current is applied to the stationary field coil while the three-phase induction motor is rotating, magnetic lines of force are built up around the field and flow through the drum and output poles. Actually, an electromagnetic torque is produced by the interaction of the magnetic field and a field established by eddy currents in the drum as it rotates.

The amount of excitation current in the field coil will determine the strength of the magnetic field and, in turn, will govern the output torque and speed. This cannot exceed the base speed of the motor or the maximum torque output of the motor.

The strength of the field is determined by the firing point of the SCR which is connected in series with the field coil. The firing point is obtained from a controller which responds to a reference signal and a feedback signal usually from a tachometer generator. Firing circuits for these drives are somewhat similar to those previously shown. Figure 11-84 shows a very elementary circuit of a magnetic drive. Notice that a three-phase motor is operated with a standard START-STOP pushbutton station. The field coil circuit consists of an a-c supply voltage converted to an unfiltered d-c voltage by means of a bridge rectifier. The SCR is fired once during each half cycle. As in previous diagrams, a reference circuit and a feedback circuit (not shown) are used to obtain the pulse to fire the SCR.

Motor-generator Drives

This type of drive consists essentially of a motor-generator set, a d-c drive motor, and controller. The motor-generator set consists of a three-phase alternating current motor mechanically coupled to a d-c generator. Alternating current is therefore converted to direct current when power is applied to the a-c motor. The direct current from the generator is then used as the power source for the d-c drive motor. The voltage generated by the d-c generator depends on the field strength of the generator, provided the speed remains constant. By changing the strength of the generator field, the voltage applied to the d-c drive motor armature can be controlled, and consequently its speed can be controlled if the motor field excitation is held constant.

In this type of drive, it is usually the armature voltage of the drive motor which is varied to give a constant torque motor. This is accomplished by weakening or strengthening the generator field. Figure 11-85 shows an elementary diagram of this type of drive.

The operation is as follows: The three-phase motor starts to rotate when the START button is depressed. At the same time, the d-c generator will revolve. Since the generator field is excited through the full-wave bridge rectifier and the SCR, a d-c voltage is generated at A_1A_2. The value of the generated voltage will depend on the timing of the pulse to the gate of the SCR. A_1A_2 is connected directly to the armature of the drive motor, and the motor field receives direct current from a full-wave bridge circuit. The speed of the motor then will depend on the voltage to the motor armature. The firing circuit for the generator field is similar in some respects to the firing circuits shown thus far. It should be understood that these can be involved and are not explored in detail in this book.

Three-phase Static Drive

The power circuit for a three-phase static drive is shown in Figure 11-86. The operation of this circuit is as follows: Three phase is converted to direct current by means of a full-wave rectifying network. Assuming SCR_1 is fired, current flows from L_1 through SCR_1, D_1, armature A, D_5, and to L_2. L_1 must be negative with respect to L_2 and L_3 for SCR_1 to be fired. Similarly, L_2 must be negative with respect to L_1 and L_3 for SCR_2 to be fired, and so on. Note that the current flow through the armature is in the same direction regardless of which line takes its turn to be negative.

Rectifier D_7 is a free-wheeling rectifier for the armature. The motor field is connected directly across D_6, which also acts as a free-wheeling diode for the field. D_1, D_2, D_3, R_1, R_2, R_3 are in the circuit to protect the SCR's from reverse transient voltages. Contact *M* closes when the START button is pressed for an across-the-line starter to operate this contact. Firing circuits are involved, but nevertheless use the same principles previously discussed. Usually each SCR has its own firing circuit.

The circuits shown in this chapter are just a few of the numerous circuits used for solid state drives. Most drives are more involved and require detailed analysis and study. However, most manufacturers of drives have detailed plans and troubleshooting charts which enable the repairman to service these drives. Most of the circuits shown in this chapter are elementary and should form a basis for further understanding of solid state control.

Appendix

TABLE I—Table for Bare Copper Wire

AWG	Diameter, Inches	Circular Mils	Pounds per 1000 ft	Ohms at 68°F. per 1000 ft
0000	0.4600	211,600.0	640.5	0.0490
000	0.4096	167,800.0	507.9	0.0618
00	0.3648	133,100.0	402.8	0.0779
0	0.3249	105,500.0	319.5	0.0982
1	0.2893	83,694.0	253.3	0.124
2	0.2576	66,370.0	200.9	0.156
3	0.2294	52,630.0	159.3	0.197
4	0.2043	41,740.0	126.4	0.248
5	0.1819	33,100.0	100.2	0.313
6	0.1620	26,250.0	79.46	0.395
7	0.1443	20,820.0	63.02	0.498
8	0.1285	16,510.0	49.98	0.628
9	0.1144	13,090.0	39.63	0.792
10	0.1019	10,380.0	31.43	0.998
11	0.09074	8,230.0	24.92	1.260
12	0.08081	6,530.0	19.77	1.588
13	0.07196	5,170.0	15.68	2.003
14	0.06408	4,107.0	12.43	2.525
15	0.05707	3,257.0	9.858	3.184
16	0.05082	2,583.0	7.818	4.016
17	0.04526	2,048.0	6.200	5.064
18	0.04030	1,624.0	4.917	6.385
19	0.03589	1,288.0	3.899	8.051
20	0.03196	1,022.0	3.092	10.15
21	0.02846	810.1	2.452	12.80
22	0.02535	642.4	1.945	16.14
23	0.02257	509.5	1.542	20.36
24	0.02010	404.0	1.223	25.67
25	0.01790	320.4	0.9699	32.37
26	0.01594	245.1	0.7692	40.81
27	0.01420	201.5	0.6100	51.47
28	0.01264	159.8	0.4837	64.90
29	0.01126	126.7	0.3836	81.83
30	0.01003	100.5	0.3042	103.2
31	0.00892	79.70	0.2413	130.1
32	0.00795	63.21	0.1913	164.1
33	0.00708	50.13	0.1517	206.9
34	0.00630	39.75	0.1203	260.9
35	0.00561	31.52	0.09542	329.0
36	0.00500	25.00	0.07568	414.8
37	0.00445	19.83	0.0601	523.1
38	0.00396	15.72	0.04759	659.6
39	0.00353	12.47	0.03774	831.8
40	0.00314	9.888	0.02990	1,049.0

Additional Information on Copper Wire

This wire table can be remembered very easily if a few simple points are kept in mind:

1. A wire three sizes smaller than another wire has half the area of the larger wire. For instance, No. 20 AWG copper wire has half the area of No. 17 AWG. Therefore, two No. 20 wires in parallel have the equivalent area of one No. 17.
2. A wire three sizes smaller than another wire has twice the resistance of the larger wire.
3. A wire three sizes smaller than another wire has half the weight of the larger wire.
4. A No. 10 AWG copper wire is approximately 0.10 inch in diameter, has an area of approximately 10,000 circular mils and has a resistance of 1 ohm per 1000 feet.

Although it is much better to use the same size wire in rewinding a motor as was used in the original winding, sometimes circumstances make it necessary to substitute another size. Table II shows equivalent wire sizes:

TABLE II—Wire-size Equivalents

Wires Not Available	Use	Wires Not Available	Use
No. 10	Two No. 13	Two No. 28	One No 25
No. 11	Two No. 14	Two No. 27	One No. 24
No. 12	Two No. 15	Two No. 26	One No. 23
No. 13	Two No. 16	Two No. 25	One No. 22
No. 14	Two No. 17	Two No. 24	One No. 21
No. 15	Two No. 18	Two No. 23	One No. 20
No. 16	Two No. 19	Two No. 22	One No. 19
No. 17	Two No. 20	Two No. 21	One No. 18
No. 18	Two No. 21	Two No. 20	One No. 17
No. 19	Two No. 22	Two No. 19	One No. 16
No. 20	Two No. 23	Two No. 18	One No. 15

TABLE III—Full-load Currents in Amperes Direct-current Motors*

The following values of full-load currents are for motors running at base speed.

HP	120V	240V
¼	2.9	1.5
⅓	3.6	1.8
½	5.2	2.6
¾	7.4	3.7
1	9.4	4.7
1½	13.2	6.6
2	17	8.5
3	25	12.2
5	40	20
7½	58	29
10	76	38
15		55
20		72
25		89
30		106
40		140
50		173
60		206
75		255
100		341
125		425
150		506
200		675

*Tables III, IV, V, VI have been reproduced from the *National Electrical Code,* NFPA No. 70-1968, USAS C1-1968, with the permission of the National Fire Protection Association. Copies of the complete *National Electrical Code* are available from the NFPA and the United States of America Standards Institute at $2.00 per copy.

TABLE IV—Full-load Currents in Amperes Single-phase Alternating-current Motors

The following values of full-load currents are for motors running at usual speeds and motors with normal torque characteristics. Motors built for especially low speeds or high torques may have higher full-load currents, and multispeed motors will have full load current varying with speed, in which case the nameplate current ratings shall be used.

To obtain full-load currents of 208- and 200-volt motors, increase corresponding 230-volt motor full-load currents by 10 and 15 percent, respectively.

The voltages listed are rated motor voltages. Corresponding nominal system voltages are 110 to 120 and 200 to 240.

HP	115V	230V
1/6	4.4	2.2
1/4	5.8	2.9
1/3	7.2	3.6
1/2	9.8	4.9
3/4	13.8	6.9
1	16	8
1 1/2	20	10
2	24	12
3	34	17
5	56	28
7 1/2	80	40
10	100	50

TABLE V—Full-load Current Two-phase Alternating-current Motors (4-wire)

The following values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Motors built for especially low speeds or high torques may require more running current, and multispeed motors will have full load current varying with speed, in which case the nameplate current rating shall be used. Current in common conductor of 2-phase, 3-wire system will be 1.41 times value given.

The voltages listed are rated motor voltages. Corresponding nominal system voltages are 110 to 120, 220 to 240, 440 to 480 and 550 to 600 volts.

	Induction Type Squirrel-cage and Wound Rotor Amperes					Synchronous Type †Unity Power Factor Amperes			
HP	115V	230V	460V	575V	2300V	220V	440V	550V	2300V
½	4	2	1	.8					
¾	4.8	2.4	1.2	1.0					
1	6.4	3.2	1.6	1.3					
1½	9	4.5	2.3	1.8					
2	11.8	5.9	3	2.4					
3		8.3	4.2	3.3					
5		13.2	6.6	5.3					
7½		19	9	8					
10		24	12	10					
15		36	18	14					
20		47	23	19					
25		59	29	24		47	24	19	
30		69	35	28		56	29	23	
40		90	45	36		75	37	31	
50		113	56	45		94	47	38	
60		133	67	53	14	111	56	44	11
75		166	83	66	18	140	70	57	13
100		218	87	87	23	182	93	74	17
125		270	135	108	28	228	114	93	22
150		312	156	125	32		137	110	26
200		416	208	167	43		182	145	35

†For 90 and 80 percent P.F. the above figures should be multiplied by 1.1 and 1.25 respectively.

TABLE VI—Full-load Current* Three-phase Alternating-current Motors

	Induction Type Squirrel-cage and Wound Rotor Amperes					Synchronous Type †Unity Power Factor Amperes			
HP	115V	230V	460V	575V	2300V	220V	440V	550V	2300V
½	4	2	1	.8					
¾	5.6	2.8	1.4	1.1					
1	7.2	3.6	1.8	1.4					
1½	10.4	5.2	2.6	2.1					
2	13.6	6.8	3.4	2.7					
3		9.6	4.8	3.9					
5		15.2	7.6	6.1					
7½		22	11	9					
10		28	14	11					
15		42	21	17					
20		54	27	22					
25		68	34	27		54	27	22	
30		80	40	32		65	33	26	
40		104	52	41		86	43	35	
50		130	65	52		108	54	44	
60		154	77	62	16	128	64	51	12
75		192	96	77	20	161	81	65	15
100		248	124	99	26	211	106	85	20
125		312	156	125	31	264	132	106	25
150		360	180	144	37		158	127	30
200		480	240	192	49		210	168	40

For full-load currents of 208- and 200-volt motors, increase the corresponding 230-volt motor full-load current by 10 and 15 percent, respectively.

*These values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Motors built for especially low speeds or high torques may require more running current, and multispeed motors will have full load current varying with speed, in which case the nameplate current rating shall be used.

†For 90 and 80 percent P. F. the above figures shall be multiplied by 1.1 and 1.25 respectively.

The voltages listed are rated motor voltages. Corresponding nominal system voltages are 110 to 120, 220 to 240, 440 and 480 to 600 volts.

TABLE VII—Possible Synchronous Speeds

Poles	60 Cycles	50 Cycles	40 Cycles	25 Cycles
2	3600	3000	2400	1500
4	1800	1500	1200	750
6	1200	1000	800	500
8	900	750	600	375
10	720	600	480	300
12	600	500	400	250
14	514.2	428.6	343	214.3
16	450	375	300	187.5
18	400	333.3	266.6	166.6
20	360	300	240	150
22	327.2	272.7	218.1	136.3
24	300	250	200	125
26	277	230.8	184.5	115.4
28	257.1	214.2	171.5	107.1
30	240	200	160	100
32	225	187.5	150	93.7
34	212	176.5	141.1	88.2
36	200	166.6	133.3	83.3
38	189.5	157.9	126.3	78.9
40	180	150	120	75
42	171.5	142.8	114.2	71.4
44	163.5	136.3	109	
46	156.6	130.5	104.3	
48	150	125	100	
50	144	120	96	
52	138.5	115.4	92.3	
54	133.3	111.1	88.9	

TABLE VIII—Chord Factor for Slots per Pole

Span	Slots/Pole 6	7	8	9	10	11	12	13	14
1-3	.50	.43	.38	.34					
1-4	.71	.62	.57	.50					
1-5	.87	.78	.71	.64	.59				
1-6	.98	.90	.83	.77	.71	.66	.61		
1-7	1.00	.98	.92	.87	.81	.76	.71	.66	.62
1-8		1.00	.98	.94	.89	.84	.79	.75	.71
1-9			1.00	.98	.95	.91	.87	.83	.78
1-10				1.00	.98	.96	.92	.88	.85
1-11					1.00	.98	.97	.94	.90
1-12						1.00	.99	.97	.94
1-13							1.00	.99	.97
1-14								1.00	.99
1-15									1.00

STUDY QUESTIONS

Foreword

This section contains study questions for each chapter in *Electric Motor Repair*. They are arranged to follow the sequence of information found in the book. Complete explanations or illustrations or both are necessary for the correct answers.

For those who are studying the book without benefit of an instructor these questions should prove of value. First, they serve to test the student's knowledge gained in studying the book because he will have to check his answers by referring to the book. Second, these questions test the student's ability to apply the knowledge gained from the book to practical jobs. Third, by successfully answering these questions, the student will be preparing himself for examinations in which similar questions may be asked. And fourth, by answering these questions correctly, the student will gain confidence in his ability to tackle more difficult problems in motor repair work.

From the instructor's point of view, the questions can be used as a basis for discussion during school periods. Weekly quizzes, which are given to test the student's knowledge and comprehension of the subject, may be based on these questions, and daily or weekly assignments may be made from them.

Motor repair men, helpers, apprentices and all others interested in electric motor repair will find these questions valuable as a guide to show them how much knowledge they have of the subject.

CHAPTER 1

Split-phase Motors

1. (a) What is a split-phase motor? (b) What are its characteristics? (c) Give several applications.

2. List the main parts of a split-phase motor and give a brief description and function of each.

3. (a) What is a squirrel-cage winding? (b) Describe two types of squirrel-cage windings. (c) Draw all the parts of a rotor.

4. (a) What is a centrifugal switch? (b) Where is the switch located? (c) Draw a diagram to show how this switch operates.

5. Name and describe the different types of bearings that are found in split-phase motors.

6. (a) What are the names usually given to the windings in a split-phase motor? (b) Diagram and describe each winding briefly.

7. Explain the operation of a split-phase motor.

8. (a) What is the procedure in analyzing motor troubles? (b) Must this procedure be adhered to rigidly? Why?

9. Name at least seven steps usually taken in repairing a split-phase motor.

10. (a) How should the end plates and frame be marked before disassembling for repair? (b) Why is this necessary?

11. (a) List all of the information necessary in taking data for the rewinding of a split-phase motor. (b) What would be the consequence if incorrect data were taken? (c) List the minimum amount of information usually found on the name plate of a split-phase motor. Explain each item.

12. (a) What is meant by the pitch of a coil? (b) How is it recorded? Illustrate.

13. (a) Draw a simple circuit of the connections of a split-phase motor. (b) Explain the diagram.

14. Draw a chart showing how the windings and other information of a 36-slot split-phase motor can be recorded.

15. (a) Show separate diagrams of a split-phase motor winding when the motor is at a standstill and when it is running. (b) What is the difference between the two illustrations?

16. (a) What is meant by a "pole of the winding"? (b) Show a drawing of one pole of a running winding have four coils with pitches 1-3, 1-5, 1-7, and 1-9.

17. Explain several methods of stripping a split-phase motor stator.

18. Explain what is meant by electrical and mechanical degrees. Give several examples to show the difference between them.

19. (a) How many electrical degrees separate the running and starting windings of a split-phase motor? (b) How many mechanical degrees separate the running and starting windings of a split-phase motor?

20. (a) How is wire size recorded? (b) Name several types of insulation with which wire is covered. (c) What may happen to a motor if the winding is replaced with the wrong size of wire? (d) Why?

21. (a) Why is insulation used in slots? (b) Describe several types of slot insulation. (c) What precautions should be used in cutting and inserting the insulation?

22. Name, describe, and diagram the different methods of winding a split-phase motor. Explain in detail how one pole is wound.

23. How are measurements taken to obtain the size of a skein coil?

24. Describe and give an example of how to change a hand winding to a skein winding.

25. (a) What precautions must be taken when coils are placed into the slots of a stator? (b) What consequences may result from poor and careless workmanship?

26. Draw a sketch of a form used in form winding. How is the size of each form obtained?

27. In regard to polarity, how should the poles of a split-phase motor be connected?

28. Draw a straight-line diagram of a four-pole series split-phase motor showing the running and starting windings and the centrifugal switch. Trace and explain the circuit.

29. Draw a circular-form diagram of the motor referred to in Question 28. Place arrows under each pole to indicate direction of flow of current.

30. What is meant by a two-parallel or a two-circuit connection? Why is it used?

31. (a) Draw a circular-form diagram of a two-circuit winding for a six-pole split-phase motor. (b) Repeat (a) for a three-circuit winding. (c) What method may be used to determine whether the poles of the motor are connected correctly?

32. (a) How is the rotation of a split-phase motor reversed? (b) Illustrate how this is accomplished by using two diagrams showing clockwise and counter-clockwise rotation.

33. Explain in detail how to check the stator connection before and during the stripping process.

34. Describe different methods of varnishing new windings.

35. What is meant by a dual-voltage split-phase motor?

36. Draw a straight line diagram of a six-pole dual-voltage split-phase motor.

37. Explain and diagram the "overload device" that is used to some extent on split-phase motors.

38. (a) Show how the overload device is connected in the circuit of a split-phase motor. (b) What troubles may occur in this device and how would you remedy them?

39. Show by means of illustrations, the terminal markings of a split-phase motor.

40. (a) What factors govern the speed of a split-phase motor? (b) Which of these factors is usually used to control the speed?

41. Explain three methods that may be used in changing the speed of a split-phase motor.

42. (a) Show a schematic and straight-line diagram of a two-speed split-phase motor which has one starting and two running windings. (b) Explain in detail the operation of this motor. (c) Describe the centrifugal switch used with this motor.

43. (a) Explain what is meant by a consequent-pole winding and connection. (b) Why and where is it used?

44. (a) What troubles may result if the starting winding in a single- or two-speed motor is permitted to remain in the circuit while the motor is in operation? (b) Explain how you arrive at your conclusions.

45. Explain, by means of an example, how a split-phase motor may be rewound for a change in voltage.

46. Explain how a split-phase motor is reconnected for a change in voltage.

47. What is meant by (a) chord factor? (b) effective turns?

48. Describe how a split-phase motor may be rewound for a change in speed.

49. (a) What tests should a split-phase motor be given in order to detect faults? (b) When and why should these tests be made?

50. Draw two or more diagrams that will illustrate what is meant by a "ground."

51. (a) What test is recommended to determine whether a motor winding is grounded? (b) Explain where and how grounds usually occur and the precautions which should be taken to prevent them.

52. Assuming that an open circuit exists in the starting-winding circuit of a split-phase motor, explain the procedure to find the "open" and the measures taken to correct the fault.

53. (a) What is meant by a short circuit in a motor? (b) How do short circuits occur? (c) Where do they take place?

54. (a) What are some of the indications that there is a short circuit in a motor? (b) What means are employed to test for short circuits?

55. What is an internal growler? Explain its construction and use.

56. Name and explain the various methods which are used for testing poles for correct polarity. Draw diagrams to illustrate.

57. List some of the reasons why a split-phase motor may fail to start. Explain each reason.

58. Explain three practical tests for determining whether the starting winding has an open circuit.

59. (a) What is meant by "end play"? (b) What is its cause and how can it be remedied? (c) How much end play can be allowed in a split-phase motor?

60. (a) Explain how a motor is tested for bearing troubles. (b) How are sleeve and ball bearings removed and new ones put in?

61. (a) What troubles could worn bearings cause in a motor? (b) How would you detect that these troubles are due to worn bearings?

62. What is meant by a "reamer"? Name several kinds and explain the purposes of each.

63. Give several reasons why a motor may run slower than its normal speed. Explain each reason.

64. (a) Explain several methods of testing for loose rotor bars in a motor. (b) How would a motor with this defect operate?

65. List and explain the conditions that may cause a motor to run too noisily.

66. How can you tell which two leads belong to the starting winding and which two leads to the running winding, assuming that the leads cannot be traced to their respective windings?

67. When a defect in the winding of a split-phase motor causes it to run at lower-than-normal speed, or not at all, describe in detail the procedure used in diagnosing the trouble and the steps recommended to correct the fault.

68. Explain the use of a snap around volt ammeter-ohmmeter.

CHAPTER 2

Capacitor Motors

1. (a) Give a general description of a capacitor motor. (b) What are its characteristics and uses? (c) How does it differ from a split-phase motor?

2. (a) Explain the construction of an oil-filled capacitor, and an electrolytic capacitor. (b) In what ways do they differ from each other and for what purpose is each used?

3. (a) How are capacitors rated? (b) What precautions must be taken in the use of each? (c) How would you go about ordering a new one?

4. (a) Name the main parts of a capacitor-start motor and give the function of each. (b) Draw a diagram showing the construction of each part.

5. Explain the operation of a capacitor start motor.

6. List the steps in the procedure for analyzing motor troubles.

7. List the operations in the repair and rewinding of a capacitor motor with a damaged winding.

8. (a) What type of capacitor is generally used on a capacitor-start motor? (b) What difficulties might be encountered if another type of capacitor were used? Explain.

9. Draw straight-line and circular diagrams of a four-pole capacitor-start motor. Show arrows under each group to indicate the direction of the flow of current.

10. (a) Draw a circular diagram of a six-pole, two-circuit capacitor-start motor. (b) What will be the approximate speed of this motor if the frequency is 60 cycles? 50 cycles?

11. (a) Draw a diagram of a capacitor-start motor with an overload device in the circuit. (b) Explain the operation of this circuit.

12. (a) What troubles may be encountered in a capacitor-start motor in which the overload device is defective? (b) What procedures are recommended to determine the exact nature of the defect?

13. (a) Explain and diagram the operation of a current relay used to open the starting-winding circuit of a capacitor-start motor. (b) Why is it used instead of a centrifugal switch?

14. Explain and diagram the operation of a voltage relay used to

disconnect the starting winding of a capacitor-start motor.

15. (a) What are some of the reasons for manufacturing capacitor motors that will operate on either of two voltages? (b) What is the advantage over single-voltage motors?

16. (a) Describe the construction of a two-voltage motor, with the emphasis on the description of the windings. (b) Explain how the main windings are used as an autotransformer.

17. Explain several methods of winding a two-voltage capacitor-start motor.

18. (a) How are the main windings connected for high-voltage operation in a two-voltage capacitor motor? (b) How is the starting winding connected for low-voltage operation?

19. (a) Draw simple diagrams of a two-voltage capacitor-start motor connected for low-voltage and high-voltage operation. (b) What will be the consequences if a low-voltage connection is used on the high-voltage line and vice versa?

20. Draw a circular diagram of a four-pole two-voltage motor connected for low-voltage operation.

21. (a) Explain how the direction of rotation of a two-voltage motor is reversed. (b) How many leads are brought out of a two-voltage reversible capacitor motor? A nonreversible two-voltage capacitor motor? Explain.

22. (a) Sometimes it is necessary to reverse a capacitor-start motor by simply throwing a switch; show how this can be done with a three-pole double throw knife switch. (b) What will happen if the switch is thrown quickly from one position to the other?

23. (a) What is the principle of operation of an instant-reversal motor? (b) Prepare a connection diagram for this motor and a three-pole double-throw switch. (c) What will happen if the switch is thrown quickly from one position to another?

24. (a) Prepare a connection diagram for a two-voltage capacitor-start motor having a main winding consisting of two sections. (b) What is the difference between this type and the previous type of two-voltage motors?

25. Explain in detail how the starting-winding leads can be determined if there are no markings on any of the leads.

26. Ordinarily four leads are necessary outside the motor in order to reverse a capacitor-start motor. Explain how this can be accomplished with only three leads.

27. Draw a simple diagram of a three-lead reversible motor and explain the circuit.

28. (a) Prepare a diagram for a two-speed capacitor-start motor having two main windings and one starting winding. (b) Explain the operation.

29. (a) Upon what factor does the speed of a capacitor-start motor depend if the frequency is assumed to be constant? (b) How is this factor controlled in a two-speed capacitor motor?

30. What is meant by a permanent-split capacitor motor? By a two-value capacitor-run motor?

31. (a) Draw a simple diagram of a permanent-split capacitor motor. (b) Give several characteristics and applications of this motor. (c) What type capacitor is used with this motor?

32. (a) What is meant by slip in a motor? (b) What does slip depend upon and how can it be controlled?

33. (a) How can slip be used to vary the speed of a capacitor motor? (b) Draw a simple diagram of a two-speed single-value capacitor motor and explain the principle of operation.

34. Draw a diagram of a two-speed, six-pole permanent-split capacitor motor connected for high-speed operation. Explain the circuit.

35. (a) Draw a schematic diagram of a three-speed permanent-split capacitor motor which utilizes the principle of slip for speed control. (b) In what ways is this motor similar to the motor in Question 34?

36. (a) What is meant by a two-value capacitor-run motor? (b) What are some of its characteristics and applications? (c) How does it differ from a single-value motor?

37. Explain the different methods used for obtaining the two values of capacity for a two-value capacitor-run motor.

38. (a) Describe the capacitors which are used on the two-capacitor type of two-value motor. (b) Which type of two-value capacitor motor would you use if you had your choice? Why?

39. (a) Draw a diagram of a two-capacitor type two-value capacitor-run motor and fully describe the circuit and operation. (b) What will happen if the electrolytic capacitor is defective? If the paper capacitor is defective?

40. (a) Draw simple diagrams of a two-voltage two-value capacitor-run motor using a capacitor-transformer unit and a two-capacitor unit. (b) How many leads are brought out of the motor if it is to be externally reversible?

41. Draw a diagram of a single voltage two-value capacitor motor using a voltage relay and overload protector.

42. Explain in detail the steps and calculations necessary in rewinding a capacitor motor for a change in voltage.

43. (a) Explain how capacitors are tested for short circuits. (b) What would happen if you tried to start a capacitor motor with a shorted capacitor? (c) Give the reasons for capacitor failures.

44. (a) Describe how to test a capacitor for capacity in micro-

farads. (b) What effect would a capacitor which has lost some of its capacity have on the starting and running of a capacitor motor?

45. (a) Prepare a diagram showing how to change a two-value capacitor-run motor into a capacitor-start motor. (b) Why would a changeover of this kind be undertaken?

46. Describe the operation of a capacitor motor which has (a) a shorted pole in its running winding; (b) dirty centrifugal switch contacts; (c) an open in one circuit of a two-circuit capacitor motor.

47. What are some of the causes of smoke issuing from a capacitor motor? Explain each cause.

CHAPTER 3

Repulsion-type Motors

1. Name the different types of repulsion motors and give the characteristics and applications of each.

2. (a) What construction features are common to each type of repulsion motor? (b) Describe the different types of commutators used on repulsion motors.

3. (a) Name and describe the main parts of the repulsion-start induction motor. (b) Why is this motor so named?

4. Explain in detail the principle of operation of a repulsion-start induction motor.

5. (a) Describe the construction and operation of two types of centrifugal short-circuiting mechanisms used on repulsion-start induction motors. (b) Why are different types of mechanisms used on different motors?

6. (a) What is the function of the short-circuiting device on repulsion-start motors? (b) How will the operation of the motor be affected if the device does not function?

7. (a) Name the different parts of the brush-lifting type of centrifugal mechanism and prepare a diagram showing the order in which they are placed on the armature. (b) What function does the governor spring have? (c) How is the pressure of the spring varied?

8. What troubles are likely to occur (a) when the short-circuiting necklace becomes dirty and does not make good contact with the commutator? (b) when the brushes do not lift off the commutator?

9. (a) How many brushes are necessary for the operation of a repulsion-start induction motor? (b) What would happen if one brush was broken and did not contact the commutator?

10. (a) Describe the construction of the stator core and the stator winding of a repulsion-start induction motor. (b) How does it differ from that of a split-phase motor?

11. (a) Draw a diagram of the stator connection for a six-pole repulsion-start motor. (b) In making the internal connections how would you make sure that the polarity is correct? (c) Why are four leads brought out of most repulsion motors?

12. (a) Prepare a sketch of the stator winding of a four-pole motor having 24 coils. (b) In winding the stator, why is it important that each pole be in exactly the same coils as in the original winding?

13. (a) Explain how to take and record data for the stator winding of a repulsion-start motor. (b) Show a sample data chart. (c) Explain in detail how to wind one pole of the motor of Question 12.

14. (a) What precautions should be taken when replacing commutators on repulsion motors? (b) What information is needed when ordering a new commutator?

15. (a) Explain the difference between a lap and wave winding, and show a simple diagram of each. (b) What advantage has one winding over the other? Explain.

16. After rewinding a stator explain the tests you would give it in order to detect any defects.

17. (a) What data should be taken while stripping an armature of a repulsion-start motor? (b) Show a data chart with sample data. (c) Why is it necessary to record the name-plate data?

18. (a) Describe a step-by-step procedure for winding an armature for a repulsion-start motor. (b) What advantage is there in putting bottom leads into the commutator as each coil is wound, rather than waiting until the entire armature is wound?

19. (a) Diagram and explain the difference between a one-, two- and three-coil-per-slot armature winding. (b) How does the number of commutator bars compare with the number of slots in these different windings?

20. (a) Show a diagram of six coils of a two coil-per-slot lap-wound armature connected to a commutator. (b) Repeat for a wave-wound armature.

21. (a) What are equalizer connections? (b) What purpose do they serve? (c) What would be the effect on the operation of a motor if the equalizer or cross connections were left out?

22. (a) Show a diagram of six coils of a two-coil-per-slot lap-wound armature connected to a commutator. (b) Repeat for a wave-wound armature.

23. (a) How are armatures with cross-connections tested for short circuits? (b) Explain why a growler short-circuit test cannot be used. (c) Where are short circuits likely to occur in this armature and what steps would you take to eliminate them in each case?

24. (a) Explain the formula for determining the commutator pitch for a wave-wound armature. (b) Give several examples of how to find the pitch. (c) Why don't wave-wound armatures have cross connections?

25. (a) Show by diagram why the rotation of a repulsion-start motor can be reversed by shifting the brushes. (b) How do you determine the amount of shift necessary?

26. Describe the construction of carbon brushes used on repulsion motors.

27. (a) What is meant by the neutral point in a repulsion-start motor? (b) How is this point located? (c) Why is it necessary sometimes to locate the neutral point? (d) What is the soft neutral point and how is it recognized?

28. (a) What would happen if there were an open between brush connections? (b) Will the operation of the motor be affected if the brush holders are grounded in a repulsion-start motor? Why?

29. (a) How does the repulsion motor differ from the repulsion-start induction motor? (b) How can you recognize the difference by inspection?

30. (a) What is a compensating winding and how is it connected in the circuit? Illustrate in a diagram. (b) Why do some repulsion motors have a compensating winding?

31. (a) Show a diagram of a four-pole compensated-repulsion motor; a two-pole motor; a six-pole motor. (b) What factors regulate the speed of these motors?

32. (a) How can the repulsion-induction motor be distinguished from the other types of repulsion motors? (b) Is this possible just by inspection? Why?

33. Explain the operation of an electrically reversible repulsion motor.

34. By means of an example describe how you would rewind a repulsion motor stator for a change in voltage.

35. (a) What are some of the reasons why a repulsion motor will refuse to start when the switch is closed? (b) Explain how current will flow in the motor if the brushes are not connected to the line.

36. How many line wires are used for a repulsion motor? (b) for a single-phase motor?

37. (a) Explain why the wrong brush-holder position may prevent a repulsion-type motor from starting. (b) How do you determine the correct position of the brushes? (c) What will happen if the brushes are not moved sufficiently?

38. (a) What effect will worn bearings have on the operation of a repulsion-type motor? (b) How are worn bearings detected? (c) Explain how they are removed and replaced.

39. (a) How will a dirty commutator affect the operation of a repulsion-start induction-run motor? (b) How will it affect the other types of repulsion motors?

40. (a) Describe the operation of a repulsion-start induction motor that has a defective governor spring. (b) How do you determine the correct spring tension?

41. Of all the single-phase motors that you have studied, which in your opinion has the highest starting torque? the lowest starting torque? Explain your answer.

42. (a) What are some possible troubles if a repulsion-type motor does not start when the switch is put on? (b) if it blows a fuse when the switch is put on?

43. (a) List several causes of sparking at the commutator in a repulsion-start induction motor. (b) What procedure would you follow to determine the exact cause of sparking?

44. (a) Draw a diagram of a dual-voltage eight-pole stator of a repulsion-induction motor. Show connections for both voltages. (b) How do you identify the four leads coming out of the motor in order to make the right connection?

45. If you were called upon to repair a repulsion-start induction motor which has stopped running, list the steps you would take in order to put the motor into running condition.

CHAPTER 4

Polyphase Motors

1. (a) What is meant by a polyphase motor? (b) Describe the general construction of a polyphase motor, listing and illustrating the main parts.

2. (a) Give some of the characteristics and applications of a three-phase motor. (b) What advantages does this motor have over a split-phase motor?

3. (a) Describe briefly the operation of a three-phase motor. (b) How many windings does this motor have? (c) Show by a single diagram how these windings are connected.

4. (a) Name at least eight steps involved in rewinding a three-phase motor. (b) How would you know that the motor needs rewinding?

5. (a) What information is needed when recording data for rewinding? (b) Show a data sheet for a polyphase motor.

6. (a) Show a diagram of the slot assembly and coils of a portion of a three-phase stator. (b) How many coil sides are in each slot?

7. (a) Diagram the different types of slots which are found in stators. (b) What advantage has one over the other? (c) Which do you prefer? Why?

8. (a) Describe how the slots of a three-phase stator are insulated. (b) What is the purpose of "cuffing" the ends of the insulation? (c) Why are different grades and thicknesses of insulation used in different motors?

9. (a) What is a gang-winding? (b) Why is this winding used? (c) Prepare a diagram of a four-coil gang winding.

10. (a) What is meant by a diamond coil? (b) Draw this coil and explain why this type of coil is used on most medium-size polyphase motors.

11. (a) Describe how a coil is taped. (b) Why are the coil in some motors taped? (c) What is meant by half lap? full lap?

12. (a) What are the two main types of three-phase windings? (b) Explain how these windings are connected, and show a simple diagram of each.

13. (a) How is the number of coils in each pole found? (b) Find the number of coils in each pole of a two-pole, 24-slot motor; a four-pole, 36-slot motor; and a six-pole, 48-slot motor.

14. (a) How is the number of coils in each pole found (b) Find the number of coils in each pole of a two-pole, 24-slot motor; a four-pole, 36-slot motor; and a six-pole, 48-slot motor.

15. (a) Explain what is meant by a pole-phase group. (b) Illustrate a four-coil group. (c) Why is phase-group insulation needed?

16. (a) How do you determine the number of groups in a three-phase motor? (b) How many groups are there in a three-phase, six-

pole motor? in a three-phase, eight-pole motor? in a two-phase, two-pole motor?

17. (a) Explain how to compute the number of coils in a group of three-phase motors. (b) Compute the number of coils per group in a three-phase, four-pole, 48-coil motor; in a three-phase, six-pole, 36-coil motor; in a two-phase, four-pole, 48-coil motor.

18. (a) Outline the procedure in making the internal connections of a three-phase star-connected motor. (b) Determine the number of groups, the coils per group, coils per phase and coils per pole, assuming a 24-slot single-circuit, four-pole motor.

19. Draw a straight-line diagram of a two-pole, single-circuit, star motor showing groups only. Show the direction of current flow in each phase.

20. (a) Draw a circular diagram of a single-circuit, six-pole, star- (wye) connected motor. (b) How can you tell by inspecting the diagram that it is connected properly?

21. (a) Describe the procedure in connecting the phases of a delta-connected three-phase motor. (b) How does this differ from a star-connected motor?

22. Draw a diagram showing the connections of a six-pole, single-circuit delta motor. Show all coils and current direction in all groups.

23. (a) Make a circular diagram of a four-pole, series delta motor. (b) Explain how the current in each phase is traced.

24. Draw schematic diagrams of the following: two-, four-, six-pole series star; two-, four-, and six-pole series delta.

25. Explain what is meant by a two-parallel or two-circuit connection and show the difference between this and a series connection by means of schematic diagrams.

26. Make circular diagrams for the following motors: (a) four-pole, two-circuit star; (b) six-pole, three-circuit delta; (c) eight-pole, two-circuit star; (d) four-pole, four-circuit delta; (e) Why are some motors connected single circuit while others are two or more circuits?

27. (a) What procedure is used to determine the type of connection already in a three-phase motor for which data are to be taken? (b) What is wrong with just tracing the circuit through each phase in order to determine the connection?

28. Give several specific examples of how you would identify a parallel-star and parallel-delta winding prior to stripping a three-phase motor.

29. (a) How would you go about determining the number of poles in a three-phase motor? (b) Describe several methods for doing this. (c) Why is this information and that of Question 28 necessary when data are being taken?

30. (a) Why are many motors made so that they can be connected

for either of two voltages? (b) What is meant by a dual-voltage motor? (c) How can you recognize a motor as being a single- or two-voltage motor?

31. Draw a straight-line diagram of a four-pole, two-voltage star-connected motor. Number the leads and show the connections for low and high voltage.

32. Assuming there are nine leads coming from a two-voltage, three-phase motor, how can you tell which is which in order to connect for either voltage? Explain.

33. (a) Explain the difference between short and long jumpers. (b) Give diagrams of both. (c) Why should one be used in preference over the other and what other names are given to these connections?

34. List at least seven identifying terms on three-phase motor name plates and define each term.

35. (a) What is meant by a part winding-start motor? (b) Show schematic diagrams of a star and delta part winding-start motor.

36. Describe in detail how to identify the nine leads of an untagged three-phase dual-voltage motor.

37. (a) What factors govern the speed of a three-phase motor? (b) Give the formula to determine the speed of an induction motor. (c) Diagram several examples using this formula.

38. (a) What is meant by a consequent-pole connection? (b) Explain the principle involved in this connection. (c) Draw a diagram showing how consequent poles are formed.

39. (a) Show a straight-line diagram of a four-and eight-pole constant-torque motor. Show how many leads are brought from this motor. (b) Make the external connection for high speed and trace out the circuit. Place current-direction arrows under each group.

40. Repeat Question 39 for a constant h.p. motor.

41. (a) What is meant by odd grouping? (b) Why do some motors have odd grouping? (c) Show by diagram how the number of coils for each group in an odd-grouped motor is determined and show the grouping for a three-phase, eight-pole, 36-coil motor.

42. (a) How does a two-phase motor differ from a three-phase motor? (b) What advantage has one over the other? (c) Describe the construction of a two-phase motor. (d) Show a schematic diagram of a four-pole, single-circuit, two-phase motor.

43. Explain how to determine the number of groups in a two-phase motor. How are the number of coils-per-group found? Compute these for a two-phase, six-pole, 36-coil motor.

44. (a) Show a circular diagram of a six-pole, two-phase, single-circuit motor. (b) Show the direction of the flow of current in each group of a two-phase motor. (c) What is the rule for the direction of arrows in each group?

45. (a) Name and describe several methods for converting a two-phase motor to a three-phase motor. (b) Why are many two-phase motors changed to three-phase?

46. (a) Describe in detail and show by diagram how to reconnect a two-phase motor to a three-phase star motor. (b) What would happen if some coils were not removed from the circuit in this reconnecting operation?

47. (a) Describe the procedure in rewinding a two-phase motor to operate satisfactorily on three-phase current. (b) Explain how you arrive at different wire size and number of turns.

48. (a) On what voltage should a three-phase motor operate if it is changed from a star to a delta motor? Assume a 230-volt star motor. (b) Explain how you arrived at the result.

49. What changes are necessary when a three-phase motor is rewound for a different voltage? Assume a three-phase, single-circuit star, 230-volt motor having 36 coils, 30 turns of No. 18 magnet wire to be rewound to operate on 460 volts. Make all computations.

50. (a) Explain in detail how to change the speed of a three-phase motor by reconnecting the winding. List a step-by-step procedure for doing this. (b) Explain why a speed change by this method is not always possible.

51. (a) Explain how to change the speed of a three-phase motor by rewinding it. (b) How is the new size wire and number of turns computed?

52. (a) Show by means of diagrams how a two-phase and three-phase motor are reversed. (b) How is a two-phase, three-lead motor reversed?

53. (a) Explain and make a diagram to show how a three-phase motor is tested for grounds. (b) Where are grounds most likely to occur? Explain some of the reasons why the winding becomes grounded.

54. (a) List the different places where an open circuit is likely to occur in a three-phase motor. (b) What are some of the causes for these opens?

55. (a) Explain how to locate an open in a three-phase motor. (b) Explain what you would do if an open coil could not be closed.

56. (a) Why won't a three-phase motor start if one phase is open? What will happen if one phase opens while the motor is running?

57. (a) Explain how short circuits in a three-phase winding are found. (b) How do you know when a three-phase motor is shorted? (c) How would you repair a three-phase motor if just one coil is found to be shorted? If one group is shorted? If an entire phase is shorted?

58. (a) What may be some of the sources of trouble in a poly-

phase motor if it fails to start when the switch is thrown? (b) Explain each defect.

59. (a) What effect will worn bearings have on the operation of a polyphase motor? (b) Explain how to test for worn bearings.

60. (a) What is meant by "single phasing"? (b) How can you tell that a three-phase motor is "single phasing"? (c) What harm will there be in a three-phase motor if it runs this way?

61. (a) List and explain the troubles that may cause a polyphase motor to run excessively hot. (b) What effect will this heat have on the winding?

CHAPTER 5

Alternating-current Motor Control

1. (a) What is the function of a starter or controller? (b) Why is it necessary to have starters in most installations? (c) Name the main types of starters used for a-c motors.

2. (a) Explain what is meant by an "across-the-line" starter. (b) Name several applications for this type of starter. (c) What characteristics of the motors make it possible to use "across-the-line" starters?

3. (a) Why is it necessary to have reduced-voltage starters for some motors? (b) Give several specific applications where this type of starter would be necessary.

4. (a) Show a simple diagram of a pushbutton switch starter and explain its operation. (b) For approximately what size motors are these starters used and why?

5. Explain the operation of (a) the solder pot overload relay, (b) the bimetallic overload relay. (c) What is meant by "trip free"?

6. How many overload relays are used on a three-phase full voltage starter? Explain your answer.

7. (a) Explain the construction of the holding coil on a magnetic across-the-line starter. (b) Why is the shading coil needed?

8. (a) What are the advantages of a magnetic across-the-line

starter over a manual across-the-line starter? (b) Explain why these advantages are important.

9. (a) Describe the construction of a simple start-stop push-button station. (b) Explain the operation of a station having four contacts.

10. (a) Explain how a START-STOP pushbutton station should be connected to a magnetic switch. (b) Show a diagram of this connection. (c) How many wires should there be between station and starter?

11. (a) Show by a diagram the connection for a START-STOP station to a magnetic switch to control a three-phase motor. (b) Explain the operation and trace out the circuit.

12. Show a diagram of a three-phase full-voltage starter with a step down transformer in the control circuit.

13. Explain the reaction of the starter if the maintaining contacts do not close when the START button is pressed.

14. (a) Connect two START-STOP stations to control a three-phase magnetic switch. (b) How are the maintaining contacts always connected? (c) How should the STOP buttons be connected? (d) How should the start buttons be connected?

15. (a) What is meant by jogging or inching a motor? (b) Give several applications where jogging is used.

16. (a) Draw a diagram of a three-phase magnetic starter connected to a station having a JOG button. (b) Explain the operation of the starter when the JOG button is pressed.

17. Explain and diagram a jogging relay.

18. (a) What is the purpose of a pilot or indicating lamp on a start-stop station? (b) Show how it is connected in the circuit.

19. (a) What is a reversing magnetic starter? (b) Give some applications for which a starter of this type is used.

20. (a) Explain the construction and operation of a reversing magnetic starter. (b) Show a diagram of this starter. Label all parts and explain their function.

21. (a) Connect a magnetic-reversing, three-phase starter to a FORWARD-REVERSE-STOP station, and explain the circuits when each button is pressed. (b) What is likely to happen if the REVERSE button is pressed while the FORWARD contacts are in?

22. (a) What is meant by a mechanical interlock as used in a reversing starter? (b) Give a specific example of how a mechanical interlock is used to prevent the forward and reverse contacts from operating at the same instant.

23. (a) Draw a diagram of a reversing magnetic starter connected to FORWARD-REVERSE-STEP station having an electrical interlock. (b) Trace each circuit and explain how the interlock operates.

24. (a) Why must some a-c motors be started with reduced

voltage? (b) Give the names of several starters that start motors at a reduced voltage.

25. (a) What is a primary-resistance starter? (b) Describe the construction and operation of a primary-resistance starter of the manual type. (c) Show this type connected to a three-phase motor.

26. (a) Describe the construction and operation of a magnetic primary-resistance starter. (b) Connect this starter to a three-phase motor and explain the circuit when the START button is pressed.

27. (a) What is the purpose of the definite-time mechanism used on the magnetic primary-resistance starter? (b) How does it operate? (c) How is the time interval changed on these devices?

28. (a) Draw a diagram of a secondary-resistance starter and label all parts. (b) Explain its principle of operation.

29. (a) Show a three-phase slip-ring motor connected to a secondary-resistance starter. (b) Explain the circuit and operation. (c) Describe the construction of a three-phase slip-ring motor and its principle of operation.

30. (a) Show by diagram how a magnetic secondary-resistance starter is connected to a three-phase slip-ring motor. (b) Explain how the timing mechanism operates.

31. (a) What is a three-phase autotransformer starter? (b) What advantage does this starter have over a resistance starter?

32. (a) Diagram the construction and principle of operation of a three-phase compensator. (b) Why are three transformers used?

33. (a) Show a diagram of a three-phase compensator connected to a three-phase motor. (b) Explain the sequence of operation. (c) What would happen if one transformer should open while the motor is running?

34. (a) Describe briefly a magnetic compensator, and explain its advantage over the manual type (b) What is meant by closed transition?

35. (a) Explain the star-delta method of reduced-voltage starting. (b) How many wires must be brought out of a motor started in this way? (c) What are these wires connected to inside the motor?

36. (a) Connect a three-phase motor so that it can be started star and run delta. Use a three-pole double-throw switch. (b) Trace out and explain the circuit.

37. (a) Show a schematic diagram of an automatic star-delta starter. (b) Explain its operation. (c) Where is this type of starter used?

38. (a) What is a part winding starter? (b) Show a diagram of a part-winding starter connected to a nine-lead wye connected motor. (c) Describe the sequence of operation.

39. (a) Show diagrams of a small drum switch operating a three-phase motor; capacitor motor; split-phase motor. (b) Where are these drum switches used?

40. (a) What types of two-speed starters are in common use? (b) What applications require the use of two-speed starters for three-phase motors? (c) What construction features of the motor permit it to operate at different speeds?

41. (a) Connect a two-speed starter to a three-phase motor having two sets of windings. (b) Explain in detail the sequence of operation.

42. (a) Connect a two-speed starter to a three-phase motor having a consequent-pole winding. (b) Is this operation more efficient than that of Question 41 (a)? Why?

43. (a) What is meant by "plugging" a three-phase motor? (b) How is this accomplished? (c) Why is plugging necessary in some applications?

44. (a) Show a diagram of a starter that uses a plugging relay. (b) Explain the operation of the relay and the entire circuit.

45. What procedure would you follow in locating the source of trouble if a motor does not start when the main contacts of an across-the-line starter close?

46. (a) What may be the trouble if the main contacts of a magnetic starter do not close when the START button is pressed? (b) Explain how you would remedy each trouble.

47. What trouble usually causes a fuse to blow or the overload relays to operate when the START button is pressed?

48. (a) List some other troubles, besides those listed above. which may be encountered in automatic starters. (b) How would you remedy these faults?

CHAPTER 6

Direct-current Armature Winding

1. (a) Show by diagram the construction of a typical armature. Label all the parts. (b) How are the commutator and the laminations placed on the shaft?

2. (a) Name the operations involved in the process of armature

winding. (b) Which operations in your opinion are more important than others?

3. (a) By means of simple schematic diagrams show how the coils in an armature are connected to the commutator. (b) How many commutator bars are necessary for an armature with nine coils? Why?

4. (a) Why is it necessary to insulate an armature before winding? (b) Where is the insulation placed? (c) Explain how the insulation should be cut so that the armature will be properly insulated.

5. (a) What is meant by pitch of a coil? loop winding? coil throw? (b) Diagram each.

6. Assume a small seven-slot armature and describe in detail the steps to be taken in winding this armature after it has been stripped. Show several coils in the slots of this armature.

7. (a) What is meant by lead swing? (b) Show the methods used in determining the position of the leads in the commutator. (c) Why is it necessary to put leads into the correct commutator bars? (d) What effect would an incorrect lead swing have on the operation of a motor?

8. (a) Explain why wedges are placed in each slot after the armature is wound. (b) Show by diagram how this is done. (c) What would happen if wedges were not placed in the slots?

9. (a) What is meant by a two-coil-per-slot winding? Show in a diagram. (b) In an armature of this type how many slots will there be if the commutator has 18 bars? 30 bars? (c) How many bars should the commutator have if there are eleven slots in the armature?

10. (a) Diagram and explain how you would wind a nine-slot, two-coil-per-slot armature. (b) How many loops will this winding have?

11. (a) Give the names of the two main types of armature windings. (b) In what way do they differ?

12. (a) Define a simplex lap winding and draw a simple diagram of it. (b) Explain the drawing.

13. (a) Explain how duplex and triplex lap windings differ from the simplex winding. (b) Show diagrams of these windings. (c) Which of these windings are most frequently used on small armatures? Why?

14. (a) What methods are used to identify adjacent loops in a two-coil-per-slot winding? (b) What is the reason for marking the leads?

15. Show by diagrams several coils of a simplex lap winding that does not have loops and explain how the leads are placed into the commutator bars.

16. (a) Show by diagram several coils of a two-in-hand simplex lap winding and explain how the leads are tested to determine their correct location in the commutator bars. (b) Do the same for a three-in-hand lap winding.

17. (a) What is the difference between a lap and a wave winding?

Show diagrams of each. Why are some armatures lap wound and others wave wound? (b) How would the operation of a motor be affected if a wave-wound armature was reconnected to a lap winding.

18. Show a circular diagram of a one-coil-per-slot wave winding having 23 slots and a pitch of 1 and 7. Trace the winding through half the coils.

19. (a) What is the difference between a coil winding and a hand winding? (b) Why are these two types of winding used? (c) Can all armatures be hand wound? Explain.

20. (a) What is meant by commutator pitch? (b) Give the formula for determining commutator pitch for a wave-wound armature. (c) Determine the pitch for a 59-bar, four-pole armature.

21. (a) Explain the difference between a progressive and retrogressive winding. (b) What effect has each one on the operation of a motor?

22. (a) Explain what equalizer connections are and why all motors do not have them. (b) How do you determine the span of an equalizer connection?

23. (a) What instruments can be used to measure wire size? (b) How is it recorded? (c) What different types of insulation are used on magnet wire?

24. (a) What information should be recorded before an armature is rewound? (b) Show a typical data sheet.

25. (a) Describe how the position of the leads on the commutator may be recorded by marking the commutator and the slots of the armature. (b) Diagram this for a loop, lap, and wave winding.

26. (a) What precautions should be observed in stripping an armature? (b) Why should at least one coil of a coil-wound armature be saved during the stripping process?

27. (a) Explain how the leads are soldered in the commutator bars. (b) What precautions should be taken to prevent solder from flowing behind the commutator?

28. (a) What is the purpose of cord, tape, and wire bands on armatures? (b) Describe how cord, tape, and steel bands are placed on armatures.

29. (a) What is meant by a shorted commutator? (b) Diagram and explain how a commutator is tested for short circuits. (c) At what point during the winding process should the commutator be tested for shorts?

30. (a) Give some of the causes of grounds in a winding. (b) Where do the grounds usually occur? (c) Show by means of a diagram how the winding is tested for grounds.

31. (a) What is a growler? (b) How is a grounded coil located by

means of the growler? (c) Explain the construction and operation of a growler.

32. (a) What is meant by a bar-to-bar meter test? (b) Show by diagram how the winding is connected to the line wires for such a test. (c) How is the amount of current flow to the winding controlled?

33. Explain and show separate diagrams of how a grounded coil is removed from the circuit of a loop-, lap-, and wave-wound armature. (b) Why is it necessary to remove a grounded coil from the circuit? (c) Is it always possible to do this? (d) If not, what must be done?

34. (a) Explain why armatures should be balanced. (b) How is this done?

35. (a) Explain the purpose of baking and varnishing an armature. (b) When and how is this done?

36. (a) Show by diagram the growler hack-saw blade test for a shorted armature. (b) Why can't this test be used on an armature having equalizer connections?

37. (a) Show by diagram the bar-to-bar meter test for locating a shorted coil. (b) Describe how an armature can be tested for shorts by means of the growler-meter method. (c) What precautions must be observed in these tests?

38. (a) Under what conditions is it advisable to eliminate shorted coils from the armature circuit? (b) When is it not advisable? (c) Why is it not always possible to cut out a shorted coil?

39. (a) How does a shorted coil show itself in the operation of a motor? (b) Why is it not advisable to run a motor with a shorted coil for any length of time?

40. (a) In testing an armature for shorts how can you tell whether the short is in a coil or in the commutator? (b) How can you tell whether there is more than one short?

41. (a) Describe and show by a diagram the bar-to-bar meter test for locating an open in an armature. (b) What precautions must be taken with the meter in this test?

42. (a) How is an open coil located by means of a growler test? (b) In what way is this test different from that in Question 41?

43. (a) Show by diagram the method of jumping out an open coil in a lap and wave winding. (b) Explain how you would jump out an open coil on six-pole wave winding.

44. (a) Describe the bar-to-bar test for a reversed coil in a loop winding. (b) How would you make this test using a growler?

45. (a) Describe how to test for reversed coils in a two-in-hand lap winding and wave winding. (b) How would you remedy this condition when it has been found? (c) What effect does a reversed coil have on the operation of a motor?

46. (a) Name the various parts of a commutator. (b) Diagram and label each part.

47. (a) Describe the construction and function of the commutator. (b) What material is the commutator bar made of? (c) Why must the bars be insulated from the rings?

48. (a) Explain how a commutator is disassembled preparatory to insulating it. (b) What information must be taken while it is being disassembled? Why?

49. (a) What is a mica V ring? (b) Explain the three methods that can be used to make these rings. (c) Why must heat be used to shape the rings? (d) Can this be done without heating the mica?

50. (a) How can you eliminate a short between commutator bars that is due to carbonized mica? (b) What must be done if much scraping is necessary?

51. (a) Explain how two shorted bars can be reinsulated without disassembling the entire commutator. (b) How could you quickly make a repair if the bars could not be reinsulated?

52. Assuming that the entire commutator has to be reinsulated, how would you go about it when the commutator is connected to a good winding?

53. (a) What is meant by high bars? low bars? (b) What is their cause and how is it remedied?

54. (a) What is a commutator stone? (b) When is it used? (c) What precautions must be observed in using it? (d) Why can't sandpaper be used as a substitute?

55. (a) What is meant by high mica? (b) How is it caused and what is the remedy? (c) What effect will it have on the operation of a motor?

56. (a) What is meant by undercutting? (b) How is this done? (c) Why must this be done on certain commutators?

CHAPTER 7

Direct-current Motors

1. (a) Name the main parts of a d-c motor. (b) Describe the construction of each part and give the function of each. (c) Diagram an armature and label each part.

2. (a) Show a simple drawing of a sleeve bearing and an oil ring. (b) What is the purpose of the oil ring? (c) How is oil conducted along the shaft resting in the bearing?

3. (a) Describe and diagram a ball bearing. (b) Why are ball bearings used in some motors and sleeve bearings in others? (c) What advantage has one over the other?

4. (a) What is meant by brush rigging? (b) Why is this movable on some motors and not on others? (c) Why are the brushes insulated from the end brackets?

5. (a) Describe the construction of a series motor and give some of its characteristics and applications. (b) Make a simple diagram of this motor.

6. (a) Describe the construction of a shunt motor and give its characteristics and applications. (b) Show a simple diagram of this motor and explain the circuit. (c) In what ways is this motor different from the series motor?

7. (a) How does the compound motor differ from the series and shunt motors in construction, characteristics, and application? (b) Make a simple diagram of this motor.

8. (a) Describe the method used for winding series-field coils. (b) What is the general construction of the series-field-coil? (c) Make a diagram of the form used for winding these coils.

9. (a) Describe in detail how a compound-field coil is wound. (b) Make a diagram of this coil. (c) What precautions must be taken when winding it?

10. (a) What is an interpole field? (b) How is it wound? (c) Why is heavy wire used in its construction?

11. (a) What is the rule for connecting field poles for proper polarity? (b) What effect would improper polarity have on the operation of a motor? Diagram the field-coil connection of a two-pole motor having correct polarity.

12. (a) Describe and diagram three methods for testing coils to determine if they have correct polarity. (b) Which of these methods do you prefer? Why?

13. How would you test for correct field-coil polarity while the motor is completely assembled?

14. Show three diagrams of the connections of a series motor. (b) Trace out and explain the circuit. (c) What characteristics of the series motor make it dangerous to run this motor without a load?

15. (a) Make several diagrams of a shunt motor. (b) Explain the circuit and trace out the connections.

16. (a) Draw a diagram of a two-pole compound motor. (b) Show arrows on all connecting wires to indicate the direction of current flow in the field poles.

17. (a) Name four different types of compound motors in general use. (b) Which one is mostly used in industry? Why?

18. Define the following: (a) cumulative; (b) differential; (c) long shunt; (d) short shunt.

19. Draw the following diagrams: (a) two-pole, long-shunt cumulative motor; (b) two-pole, long-shunt differential motor; (c) two-pole, short-shunt cumulative motor; (d) two-pole, short-shunt differential motor.

20. What is an interpole? What purpose does it serve in a motor? How many interpoles are there in a four-pole motor?

21. (a) What is the rule for interpole polarity? (b) What two factors govern interpole polarity?

22. Draw the poles of a two-pole interpole motor showing the polarity of all the poles, assuming main pole polarity and counter-clockwise rotation.

23. Draw a simple diagram showing how interpoles are connected in a motor.

24. Draw the same diagram as in Question 22 for a four-pole interpole motor.

25. (a) Describe the procedure for connecting a two-pole, cumulatively connected, compound-interpole motor for a proper polarity, assuming main pole polarity and counter-clockwise rotation. (b) Diagram to show the direction of current in each field coil.

26. (a) How is the direction of rotation of any d-c motor reversed? (b) How is a series motor reversed? (c) Diagram to show how a series motor is reversed.

27. (a) Show by diagram how an interpole motor is reversed. (b) What precautions must be taken in reversing an interpole motor?

28. Draw a diagram of a six-pole compound-interpole machine showing the polarity of all the poles and show how this motor is reversed.

29. (a) List some of the tests that should be given to a motor before it is installed. (b) Which of these tests do you consider the most important? Why?

30. (a) Explain and diagram the procedure for making a ground test on a motor. (b) What is meant by a ground?

31. Explain and draw a diagram showing how a shunt motor is reversed.

32. (a) Show by means of a diagram where grounds in a field coil are most likely to occur. (b) When a ground is indicated in the field of an eight-pole motor, show how to find the coil in which the ground is located. (c) What would happen if the series and shunt field of a compound motor were grounded?

33. (a) What is meant by an open circuit in a motor? (b) Explain

by diagram how series motors are tested for open circuits. (c) What may be the causes for open circuits in this motor?

34. (a) How are shunt motors tested for open circuits? Where are these opens usually located? (b) What would happen if the field should open while the motor is running? when the motor is started?

35. (a) What markings are usually put on the leads of a compound motor? (b) Why are these markings necessary?

36. (a) How are the six leads of a compound motor identified when the markings are missing? (b) Give the procedure in making this test.

37. (a) How are the leads of a compound motor identified when only five wires are brought out of the motor? (b) Will it be necessary to open the motor for this test? Why?

38. (a) Give the steps in testing a compound motor to determine whether it is connected cumulatively or differentially. (b) What difference will it make in the operation of a motor?

39. (a) Describe a practical test to determine correct interpole polarity. (b) How would wrong interpole polarity show up in the operation of a motor?

40. (a) Describe one method of locating properly the brush holders in the neutral position for an interpole motor and a noninterpole motor. (b) Why will the wrong location cause the armature to spark?

41. (a) Describe three other methods for setting the brushes on neutral. (b) Which of these methods would you use? Why?

42. (a) With what pressure should carbon brushes press against the commutator? (b) How is this pressure measured? (c) What effect will improper pressure have on the operation of the motor?

43. (a) How are brushes made to fit the curvature of the commutator? (b) Why are different grades of brushes used on different motors?

44. (a) What are some of the causes of open circuits in the armature circuit of a d-c motor? (b) Explain how to locate the open.

45. (a) What is meant by a motor "running away"? (b) What is the usual cause of this and how can it be prevented?

46. (a) What are some of the symptoms of a shorted armature in the operation of a motor? (b) What will the consequences be if a motor is allowed to run this way?

47. (a) Assuming that a motor with one or two shorted coils had to be put into operation very quickly, what would you do? (b) What would you do if two or more commutator bars were shorted?

48. (a) How does an open armature coil manifest itself while the motor is running? (b) How can you locate the open by inspecting the commutator?

49. (a) Name some of the conditions that may cause armature

opens and explain how you would effect a repair. (b) How would you know that the open is repaired?

50. What importance has the name-plate data on a motor?

51. Explain what is meant by counter electromotive force.

52. Explain in detail why a shunt motor will tend to race when the shunt field is opened.

53. Explain why a series motor must always run with a load.

54. (a) What are some of the reasons for sparking at the commutator? (b) Explain why each of these causes produces sparking and give the remedy for each.

55. (a) Why will incorrect lead swing cause sparking at the brush? (b) What other effect will this have on the motor?

56. (a) What are the symptoms of a motor running with wrong interpole polarity? (b) How can you tell that these symptoms are due to wrong interpole polarity?

57. (a) What is meant by high bars? low bars? (b) To what are these conditions due and how are they remedied?

58. Describe some of the defects that may cause a motor to run noisily.

59. (a) How is a motor tested for defective bearings? (b) Describe how sleeve and ball bearings are removed and then replaced.

CHAPTER 8

Direct-current Motor Control

1. (a) Name some of the functions of a starting box and controller. (b) What is the difference between the two? (c) Why is it necessary to use these devices?

2. Explain why a small motor can be started by placing full voltage across it while large motors must be started with reduced voltage.

3. (a) Describe the construction and operation of a three-point starting box. (b) Draw a diagram of all its internal connections and label all parts. (c) Why is it called a three-point box?

4. (a) Why is the holding coil of a three-point box called a no-field release? (b) What is the function of the holding coil? (c) How are the terminals of the box marked?

5. (a) Show a diagram of a three-point starting box connected to a compound motor. (b) Explain this circuit.

6. (a) Describe the construction and operation of a four-point starting box? (b) Draw a diagram of the internal connections of this box. Label all parts.

7. (a) Why is the starting box in Question 6 called a four-point starting box? (b) What are some of the essential differences between a three-point and a four-point starting box? (c) What are the reasons for using a three-point box on some applications and a four-point box on others?

8. (a) What is the function of the holding coil on a four-point box? (b) Why is this coil called a no-voltage release coil?

9. (a) Draw a diagram of a four-point starting box connected to a shunt motor; to a compound motor. (b) Trace out and explain the circuit.

10. (a) What is a speed-regulating rheostat? (b) Make a connection diagram of a four-point, speed-regulating rheostat. (c) Describe its operation. (d) Where would you use a rheostat of this kind.

11. (a) What is meant by a combination four-point starting box and speed-regulating rheostat? (b) Show by means of a diagram the internal wiring of this device and explain fully how it operates. Label and describe its various parts.

12. Connect the box in Question 11 to a compound motor and describe in detail all of the circuits involved.

13. (a) How is the direction of rotation of a d-c motor changed? (b) Name several applications where the motor reverses periodically.

14. Connect a double-pole, double-throw switch in the armature circuit of a shunt motor; in the field circuit of a shunt motor; in both instances. Explain the circuits.

15. (a) Diagram to show a two-pole, compound-interpole motor with a double-pole, double-throw switch connected in the armature circuit for reversing. (b) What precaution must be taken in reversing this motor? Why?

16. By means of a double-pole, double-throw switch, reverse a shunt motor connected to a three-point starting box. Explain exactly how you would start and stop this motor.

17. Draw a diagram of a four-point starting box connected (a) to a shunt motor and use a double-pole, double-throw switch for reversing; (b) to a compound motor and use a double-pole, double-throw switch for reversing.

18. (a) Show a sketch of the external appearance and internal construction of a small drum-type switch. (b) Show all contacts, label all parts, and explain the operation. (c) What is this switch used for?

19. (a) Show by diagram the connection of a series motor to a drum switch and the contacts for forward rotation. (b) Explain the circuit. (c) Show another diagram for reverse rotation.

20. (a) What is an overload relay? (b) Show by diagram several devices that can be used to protect a motor from overloads. (c) How can you tell that a motor is overloaded?

21. (a) Show a simple sketch of a magnetic circuit breaker and explain its construction and operation. (b) Why is this device used?

22. (a) Explain with a diagram the construction and operation of a thermal relay. (b) What is the difference between a thermal relay and an overload relay? (c) What troubles can develop on a thermal relay?

23. (a) Explain what is meant by a pushbutton station and show a sketch of a station having a START-STOP button. (b) Why is a pushbutton station used?

24. (a) Draw a diagram of a magnetic switch and small d-c motor connected to a START-STOP pushbutton station. (b) Trace out and explain the connection fully. (c) Show an elementary diagram of this connection.

25. (a) Show the same diagram as in Question 24, but with two START-STOP stations. (b) Show the connection with three stations. (c) How should the STOP button always be connected?

26. (a) What may be the source of the trouble when the magnetic switch does not operate after pressing the START button? (b) Explain.

27. Explain what may be the trouble when the magnetic switch does not stay closed when the finger is removed from the START button.

28. What is the purpose of using several START-STOP stations to operate one magnetic switch?

29. (a) Explain the use of a JOG or INCH button in a pushbutton station. (b) Show all the contacts in a station having a START, a JOG, and a STOP button.

30. (a) Draw a diagram of a START-JOG-STOP station connected to a magnetic switch to operate a small motor. (b) Explain the circuits when each button is pressed. (c) Show one elementary diagram of this connection.

31. (a) What may be the trouble if the magnetic switch does not operate when the JOG button is pressed? (b) Explain.

32. (a) Why is resistance needed in the motor circuit in order to start a medium-sized or large-sized motor? (b) What will happen if the motor is started without resistance? Why?

33. List five different types of automatic controllers generally used for the control of medium-sized and large-sized d-c motors.

34. (a) Explain the principle of the counter electromotive force controller. (b) Give an application of this controller.

35. (a) Show a diagram of a counter electromotive force controller with one step of resistance connected to a compound motor. (b) Explain the operation of this circuit.

36. (a) What is a lockout controller? (b) Why is it called by this name? (c) Why is it also known as current-limit starter? (d) Where would this type of controller be used?

37. (a) Connect a two-coil lockout controller with one step of resistance to a compound motor. (b) Explain the operation of the circuit.

38. Show in a diagram a two-coil lockout controller with two steps of resistance connected to a compound motor. Show the complete circuit with magnetic switch and START-STOP station.

39. (a) Diagram a single-coil lockout contactor. (b) Explain the principle of operation of this contactor. (c) What is the difference between this and the two-coil lockout contactor?

40. (a) Draw a wiring diagram of a single-coil lockout controller with one step of resistance connected to a compound motor. (b) Explain the operation.

41. (a) What is meant by a definite magnetic time controller? (b) Explain the principle of operation of this type of controller. (c) Diagram one of these controllers and label the parts.

42. (a) Draw a diagram and explain the circuit of a definite magnetic time starter connected to a compound motor. (b) Show also an elementary diagram of this starter.

43. (a) What advantages does this starter have over the lockout type of starter? (b) Why do you consider these advantages?

44. (a) Show a simplified diagram of a definite magnetic time starter having two steps of resistance. (b) For what applications would this starter be used?

45. (a) Show in a diagram what is meant by dynamic braking. (b) Why is dynamic braking needed in many instances? (c) Give several instances where it is necessary.

46. Draw a diagram of a definite magnetic time controller equipped with dynamic braking.

47. (a) List and explain as many troubles as you can which may cause a definite magnetic time starter to function improperly. (b) How do you regulate the time element in this starter?

48. Explain the difference between a definite magnetic time starter and a definite mechanical time starter.

49. (a) Describe by means of a diagram a definite mechanical time

controller using dashpot acceleration and explain the operation. (b) Explain the operation of a dashpot.

50. (a) What are some of the things that may go wrong with the controller of Question 49? (b) Explain each trouble and the remedy for it.

51. Show a typical diagram of a simple type of drum controller and describe the circuit when the handle is at the first point of acceleration. Assume this controller is used with a compound motor.

52. Draw a straight line diagram of a reduced voltage starter with time limit acceleration. Explain its operation.

53. Draw a straight line diagram of an adjustable speed starter using a field accelerating relay. Explain the operation of the field accelerating relay.

CHAPTER 9

Universal, Shaded-pole, and Fan Motors

1. What is a universal motor? Name some of its characteristics and applications.

2. (a) Name and describe the main parts of a universal motor. (b) Show simple sketches of each part. (c) How would you proceed in taking apart a universal motor for repairs?

3. (a) Explain the operation of a universal motor. (b) What characteristics of construction make it possible to operate on either alternating or direct current?

4. (a) What procedure should be followed when it is necessary to rewind the field coils of a universal motor? (b) How do you determine the size of wire to use? (c) Do you count the number of turns in each field or do you weigh the coil for rewinding? Why?

5. (a) Explain by means of a diagram how to make a form for winding field coils. (b) How are the right measurements for making

the form obtained? (c) What would happen if the form were made too small? too large?

6. (a) Prepare a diagram to show how the field coils are connected and tested for correct polarity. (b) Why wouldn't a universal motor run if both fields of a two-pole motor were connected for like polarity?

7. (a) Show in a diagram how the field coils and armature are connected in a two-pole universal motor. (b) Is this the only way they can be connected? Explain.

8. (a) Show by diagram how to reverse the direction of rotation of a universal motor. (b) Is it always necessary to take the motor apart to reverse it? Explain.

9. (a) Why does severe sparking generally occur when the rotation is reversed on some types of universal motors? (b) How can the sparking be eliminated?

10. Name and explain some important features that are common to all universal motors.

11. (a) What information must be recorded before an armature can be rewound? (b) Draw a chart with a sample recording. (c) What might be the result if the wrong information is recorded?

12. (a) Describe in detail how to determine the correct lead throw on a small armature. (b) What would happen if the armature was rewound with wrong lead throw? Why?

13. (a) Describe how to determine correct lead throw by using a growler. (b) What are some other functions of a growler?

14. (a) How must an armature be prepared before it is ready for winding? (b) Describe briefly the method of rewinding the armature of a universal motor.

15. (a) What differences will sometimes be found in the windings on the armature of a universal motor. (b) Show some of these differences by means of sketches. (c) How do these differences affect the operation of the motor?

16. (a) What precautions should be taken with respect to the position of the leads in the commutator? (b) What would happen if the leads are placed one or more bars out of the way?

17. (a) What is meant by a compensated universal motor? (b) Describe the single-field compensated universal motor.

18. (a) Describe the two-field compensated universal motor. (b) What function does the compensating field serve in this motor?

19. (a) What precautions should be taken when stripping the stator of a compensated universal motor? (b) List all the information that should be recorded.

20. (a) Describe briefly how the stator of a compensated universal

motor is rewound. (b) Why is the compensating winding located 90 electrical degrees from the main winding?

21. (a) List and explain as many methods as you can to show how the speed of a universal motor can be varied and regulated. (b) What applications do you know of for universal motors that can be varied in speed.

22. Diagram and explain the layout of the coils of a two-field compensated universal stator having four poles and 24 slots.

23. Show by diagram how the speed of a universal motor may be regulated by using a variable resistance in the motor circuit.

24. (a) How may different speeds be obtained by tapping one field of a universal motor? (b) Explain the principle of operation of this type of speed control.

25. (a) Explain how speed may be controlled by means of a centrifugal device. (b) Diagram and explain the circuit.

26. (a) What are some of the troubles that may cause a universal motor to spark excessively? (b) Explain and give a remedy for each trouble.

27. List as many troubles as you can that may cause the universal motor to (a) run hot; (b) to smoke; (c) to have poor torque.

28. When a universal motor runs slower than it should, it is an almost certain sign that it is defective. Explain how you would diagnose the trouble of such a motor and repair it.

29. (a) Give a simple definition of a shaded-pole motor. (b) List some of its characteristics and applications.

30. Name and illustrate the main parts of a shaded-pole motor and explain the function of each.

31. (a) Explain the principle of operation of a shaded-pole motor. (b) What is the purpose of the shaded coil? What will happen to the operation if the shading coil opens?

32. (a) Show a connection diagram of a six-pole shaded-pole motor. (b) How do you test for correct polarity? (c) Why isn't it necessary for the shaded coils to be insulated from ground?

33. (a) What precautions should be taken in rewinding the field coils of shaded-pole motors? (b) Some shaded-pole motors have an iron bridge between pole pieces. What is this for?

34. (a) Show by diagram how a shaded-pole motor is reversed. (b) How can you tell just by looking at the stator in which direction the motor will rotate?

35. (a) Describe and make a diagram of a shaded-pole motor that can be reversed by means of external leads. (b) Explain the operation of this motor.

36. (a) Describe and make a diagram of a reversible shaded-pole

motor that has two main windings and one shaded-coil winding. (b) How many leads are brought out of this motor?

37. (a) What may be some of the reasons for a shaded-pole motor failing to start? (b) Why is it particularly important that the bearings of a shaded-pole motor be in perfect condition?

38. (a) Explain how a shaded-pole motor is tested for grounds, short circuits, opens. (b) Describe how you locate and eliminate all of these defects.

39. List the possible troubles of a shaded-pole motor when it runs too hot; when it has very poor starting torque.

40. (a) Make a connection diagram of a two-speed, split-phase fan motor having two running windings and one starting winding. (b) How many leads are brought out of this motor? (c) How can you tell which is the correct lead for connecting?

41. (a) Explain and show a diagram of a three-speed split-phase fan motor having one running, one starting, and one auxiliary winding. (b) Explain the principle involved in the speed control of this motor.

42. (a) Show by diagram the connections of a two-speed split-phase motor having one running and one starting winding. (b) Explain how two different speeds are obtained from this motor. (c) Explain the principle of consequent connections.

43. (a) How is a universal motor controlled for changes in speed? (b) What would happen if a field coil on this motor should open while the motor is running?

44. Many split-phase fan motors have a transformer in the base of the stand to control the speed. Show by means of a diagram how this transformer is connected to the motor.

45. Many fans are driven by capacitor motors and are controlled for speed by means of a transformer, as in the case of the motor in Question 44. Show how three different speeds can be obtained from this connection.

46. (a) With a diagram show how a fan motor used on unit heaters is connected for different speeds. (b) Explain the principle involved in its operation.

47. Explain with a diagram how the speed of a shaded-pole motor is varied.

48. (a) What is meant by a basket winding? (b) Diagram this type of winding.

CHAPTER 10

Direct-current Generators; Synchronous Motors and Generators; Synchros; Electronic Control of Motors Using Electron Tubes

1. (a) What is the difference between a motor and a generator? (b) Since both look alike, how can you identify them?

2. (a) How are d-c generators rated? (b) List all the information generally found on a generator name plate.

3. (a) Describe the construction of a d-c generator. (b) How does it differ from that of a d-c motor?

4. (a) Show by a simple sketch how a potential is induced in a conductor when it cuts lines of force. (b) Explain the principle.

5. What factors will cause a change in the amounts of voltage generated in a d-c generator? Why?

6. (a) How can the direction of the generated voltage be changed? (b) Explain your answer.

7. (a) What are the three essentials necessary to cause a voltage to be generated? (b) Explain why each of these is necessary.

8. (a) Name several ways of producing the flux necessary in the generation of electricity. (b) How is the direction of this flux changed?

9. (a) What is meant by a separately excited generator? a self-excited generator? (b) Diagram each one.

10. (a) Explain in detail the operation of a self-excited generator. (b) Explain what is meant by the "building-up process."

11. (a) Explain with a diagram the connection and operation of a self-excited series generator. (b) What happens to the generated voltage when load is added or taken away?

12. (a) Show a diagram of a self-excited, shunt generator and explain its operation. (b) What are the characteristics of this generator?

13. (a) Describe the most common type of compound generator, (b) Show a diagram of this generator and describe its operation.

14. (a) What is meant by an over-compounded generator? flat-

compounded generator? under-compounded generator? (b) Describe the characteristics and uses of each.

15. (a) How does the polarity rule of interpoles in a d-c generator differ from that of a d-c motor? (b) Show simple illustrations of each.

16. Diagram to show the connection of a four-pole compound-interpole generator and explain all the connections.

17. How would reversed interpole polarity affect the operation of an interpole generator? Explain.

18. How does direction of rotation affect the operation of a d-c generator?

19. It is necessary sometimes to change a compound motor to a compound generator. Show with a diagram how this is accomplished.

20. (a) What kind of device is used to regulate the voltage generated? (b) How is it connected in the circuits? Explain how it is used in the circuit.

21. (a) What is an ammeter? voltmeter? (b) Show by diagram how both of these are connected in a generator circuit. (c) What is an ammeter shunt?

22. What is meant by paralleling generators and why is it done?

23. In order to connect two generators in parallel, what three conditions are necessary? Why?

24. (a) What is an equalizer connection? (b) What is the reason for having this when two generators are paralleled? (c) Explain with diagram.

25. (a) Draw a diagram of two compound generators in parallel. (b) Explain all the connections.

26. (a) If a generator refused to generate, what troubles would you suspect? (b) How would you remedy them?

27. Why would wrong field-pole connections prevent a generator from building up?

28. (a) What would cause the generated voltage to drop if a load is added to a generator? (b) Explain your answer.

29. (a) What may be some of the troubles if the voltage does not build up completely? (b) How do you proceed to locate the fault?

30. (a) How is the neutral point of the brushes located in a compound-interpole generator? (b) How would you know that you have the correct position?

31. (a) What would cause the armature to spark while the generator is operating? (b) Give remedies for each of the troubles.

32. How would you define a synchronous motor?

33. What are some of the characteristics and uses of a synchronous motor?

34. (a) Describe and diagram the construction of a synchronous motor. (b) What methods are used to excite it?

35. (a) What is an amortisseur winding? (b) What purpose does it serve? (c) In what type of motor is it used?

36. (a) Explain how you would start a synchronous motor. (b) Explain how the magnetic poles on the motor lock in with the rotating magnetic field.

37. Explain how the stator of a synchronous motor is wound and how the rotor is wound.

38. Show a complete connection diagram of a synchronous motor having external excitation.

39. (a) Describe the construction of a synchronous motor with a rotor that is not externally excited. (b) Explain its operation. (c) What happens if you overexcite or underexcite the rotor field?

40. (a) Draw a diagram showing the internal connections of a brushless synchronous motor. (b) Explain its operation.

41. (a) What types of motors do electric clocks use? (b) Describe two of these types and explain their operation.

42. What troubles are usually encountered on clock motors and how are these troubles remedied?

43. (a) How does a synchronous generator differ from a synchronous motor? (b) What methods are used to run synchronous generators?

44. Show a complete wiring diagram of a synchronous generator and explain its operation.

45. What effect will varying the exciting currents have on a synchronous generator?

46. Name and explain the conditions that must be satisfied when alternators are paralleled.

47. Explain with diagram the "all dark" and "one dark and two bright" methods of synchronizing two alternators.

48. What would happen if the synchronizing switch is closed when the lamps of the "all dark" method are not entirely dark?

49. (a) Explain what is meant by a "synchro." (b) Explain its use and characteristics.

50. (a) In what way does a synchro resemble a synchronous generator? (b) How do they differ? (c) Describe the construction of the synchro and show a simple diagram of the windings.

51. Draw an elementary diagram of a brushless synchronous generator and explain its operation.

52. (a) How does a synchro operate? (b) Draw a diagram of two synchros, one of which is the transmitter and one the receiver. (c) Trace out and describe in detail the function of each.

53. What effects would two reversed-phase wires have on the operation of the synchros?

54. Electronic controls have tubes which contain anodes and

cathodes. What are these terms and what are their functions in the tubes?

55. (a) Describe a two-electrode tube and explain how this tube operates. (b) Make a simple diagram of this tube.

56. (a) What is meant by an indirectly heated cathode? (b) Show a diagram of this type of tube.

57. (a) Draw a diagram of a diode connected to show the flow of electrons. (b) Explain the diagram. Show by diagram what would happen if the negative of the battery were connected to the anode.

58. (a) What is one of the chief functions of the two-element tube? (b) Explain by diagram how rectification is obtained when the anode is alternately positive and negative. (c) What is this rectification called?

59. (a) Explain the difference between half-wave and full-wave rectification. (b) Which is more desirable?

60. (a) Show a diagram of a full-wave rectifier using two diodes and explain fully the circuits. (b) Draw the curves of the output of a full-wave rectifier and explain how it differs from that of a half-wave rectifier.

61. (a) Show how it is possible to run a small d-c motor from an a-c line by using a full-wave rectifier. (b) Explain the circuit.

62. (a) What is meant by a grid in a tube? (b) Explain its function in a triode. (c) Show by diagram its symbol.

63. Explain by diagrams how the grid in a triode controls the flow of electrons to the anode.

64. Explain the following terms: ionization; space; charge: starting anode; bias; trigger-type tube; phase-shift control.

65. (a) Show by diagram how to operate a small d-c motor on alternating current by using thyratron tubes. (b) Explain the circuit.

66. Explain the construction and operation of a phototube.

67. (a) Show by diagram a circuit containing a phototube operating a relay. (b) Explain in detail the entire operation of this circuit.

CHAPTER 11

Solid State Motor Control

1. How are all substances classified in terms of electrical conductivity?

2. (a) What elements are mainly used in the manufacture of semiconductors? (b) What advantage has one over the other?

3. (a) Describe an atom. (b) What charges do the particles in an atom carry?

4. By means of an illustration, show what is meant by a shell or orbit in describing the path of an electron around the nucleus.

5. What is meant by a valence electron?

6. (a) Illustrate a silicon atom. (b) How many valence electrons are there in an atom of silicon?

7. (a) Why are impurities added to pure silicon or germanium? (b) Define "doping."

8. (a) What is meant by covalent bonding? (b) Define N-type semiconductors and P-type semiconductors.

9. Define "hole" as applied to the crystal structure of a semiconductor.

10. (a) Describe a P-N diode using an illustration. (b) Label all parts and define the term "barrier."

11. (a) What is meant by reverse and forward bias?

12. Show a symbol of a diode and label its parts.

13. (a) Define a diode rectifier. (b) Show current flow when a diode rectifier is connected to a d-c source.

14. By means of a characteristic curve explain the operation of a diode.

15. (a) Explain by means of diagrams how a-c is converted to pulsating d.c., using a diode semiconductor for rectification. (b) Define half-wave rectification.

16. (a) What is meant by filtered d-c? (b) Show a diagram using a capacitor for filtering purposes.

17. (a) In what way does full-wave rectification differ from half-wave rectification? (b) Show a full-wave rectifier using a center tap

transformer. (c) using a bridge rectifier. (d) How would you filter these circuits?

18. (a) What is a Zener diode? (b) Show the symbols for this diode and its characteristic curve.

19. Show a circuit in which a Zener diode is used for voltage regulation.

20. Describe in detail the construction and operation of a semiconductor triode or transistor.

21. Illustrate the NPN and PNP transistors and label the terminals.

22. (a) What is the function of each element in the transistor? (b) Why is the emitter-base circuit forward biased? (b) Why is the collector circuit reverse biased?

23. In what ways are the transistor and three element vacuum tube similar?

24. Illustrate and describe the common emitter-type of circuit configuration.

25. (a) Describe the construction and operation of the unijunction transistor. (b) Show the symbol for the UJT and label all parts.

26. Show a diagram of a UJT used in a relaxation oscillator circuit arrangement and trace its circuit.

27. (a) What is an SCR? (b) Show a symbol for the SCR and label the terminals. (c) Describe its construction and function.

28. (a) By means of a curve, describe the characteristics of an SCR. (b) Define holding current, blocking state, forward breakover voltage, reverse breakdown voltage.

29. Explain the operation of an SCR, assuming the SCR as two transistors, a PNP and NPN. Illustrate.

30. List at least six important factors in the operation of SCR's.

31. What is meant by a control or trigger signal?

32. (a) Explain the meaning of phase control. (b) Illustrate half-wave phase control.

33. By means of illustrations, discuss full-wave phase control.

34. (a) Explain the term "resistance triggering." (b) Show how this type of triggering is used with a constant resistance and a variable resistance.

35. Draw a diagram in which a capacitor is used in conjunction with a variable resistor for the purpose of triggering the SCR.

36. (a) What is meant by *RC* Time Constant? (b) How is the Time Constant computed? Give an example.

37. Show diagrams and explain the operation of half-wave and full-wave circuits employing the unijunction transistor for triggering purposes.

38. Draw a diagram and explain how a transistor can be used in place of a variable resistor for purposes of charging a capacitor.

39. (a) Define reference signals, feedback signals. (b) Show a circuit explaining reference and feedback voltages.

40. (a) What is meant by the counter-electromotive force? (b) How is the counter e.m.f. used as a feedback signal?

41. (a) Draw an elementary diagram of a universal motor connected for half-wave control with feedback. Explain its operation. (b) What are some of the disadvantages of this circuit?

42. How may the circuit of Question 41 be improved in terms of a shorter conduction time for the SCR? Show this diagram.

43. Show a half-wave control circuit with feedback in which a Zener diode is used for supplying a constant potential.

44. Draw a diagram of a Half-wave Universal Motor Control in which the field and armature do not have separate connections. Explain its operation and explain in what ways this circuit is an improvement over that of Question 41.

45. (a) What is a silicon unilateral switch? (b) Show its use in a half-wave circuit.

46. (a) Diagram a full-wave d-c control circuit in which there are separate connections for the series field and armature. (b) In what way is the circuit an improvement over the half-wave circuit?

47. (a) What is a Diac, a Triac? (b) Show a circuit using these devices and explain the operation.

48. (a) Define synchronization as it applies to solid state circuits. (b) Explain how synchronization is accomplished with a UJT.

49. (a) Draw an elementary diagram of a half-wave control for a shunt motor. (b) Explain how the shunt field is supplied with a continuous unidirectional current.

50. How are SCR's protected against reverse voltages.

51. (a) Explain what is meant by a commutating diode. (b) What is the function of this diode?

52. Show a diagram of a full wave speed controlled shunt wound d-c motor. Label each component and explain the function of each device.

53. Connect the diagram of Question 52 for half-wave control. Explain the function of each component.

54. (a) Describe the operation of Figure 56(a) and explain the function of all the diodes. (b) What is a surge suppressor?

55. Explain the operation of the power circuit of Figures 75(a), and 76(a).

56. (a) What is a pulse transformer? (b) Show a circuit in which this device is used.

57. (a) Define "error signal." (b) Explain the operation of the circuit of Figure 60(a).

58. Show a diagram of a circuit in which synchronization is ac-

complished by means of an NPN transistor. Explain how this is done.

59. (a) How may the centrifugal switch of a split-phase or capacitor motor be replaced by a solid-state switch? (b) Explain how such a circuit operates.

60. (a) Name several types of drives used for three-phase supply. (b) Explain each briefly.

61. Show an elementary power circuit of a magnetic drive and describe its operation.

62. Answer Question 61 for a motor-generator drive and a three-phase static drive.

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APPENDIX

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CHAPTER 1

Split-phase Motors

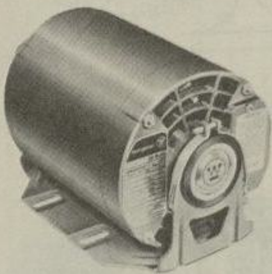


Fig. 1-1. A split-phase motor. (*Westinghouse Electric Co.*)

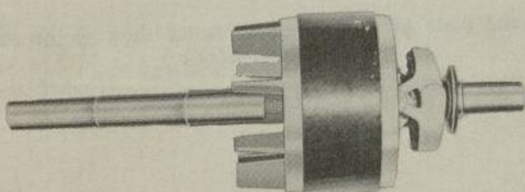


Fig. 1-2. A rotor of a split-phase motor. (*Wagner Electric Co.*)

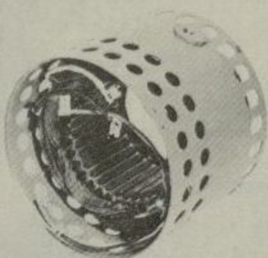


Fig. 1-3. A stator of a split-phase motor. (*Delco Products*)

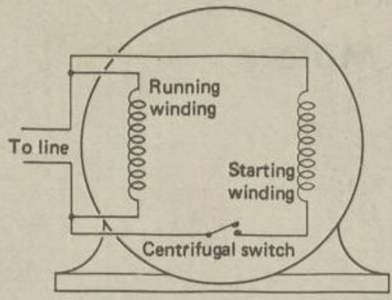


Fig. 1-4. A circuit of the two windings and the centrifugal switch when the motor is operating at full speed. The running winding is also called the main winding. The starting winding is the auxiliary winding.

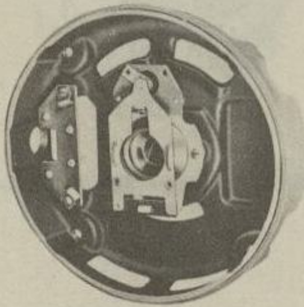


Fig. 1-5. One end plate of a single-phase motor showing the stationary switch. (*Wagner Electric Co.*)

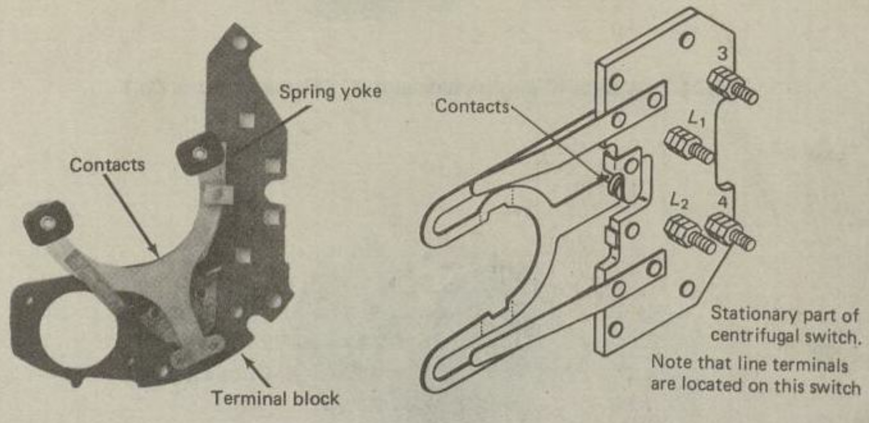


Fig. 1-6. Two variations of the stationary section of one type of centrifugal switch which consists of a U-shaped yoke mounted on a terminal block.

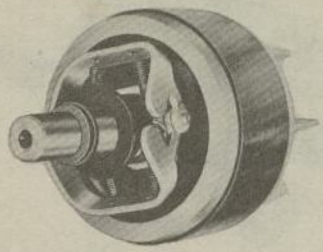
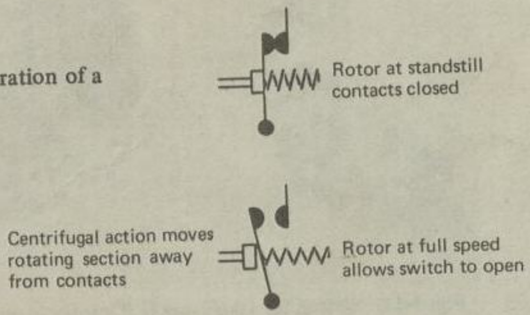


Fig. 1-7. The rotating mechanism of a centrifugal switch. (*Wagner Electric Co.*)

Fig. 1-8. Steps in the operation of a centrifugal switch.



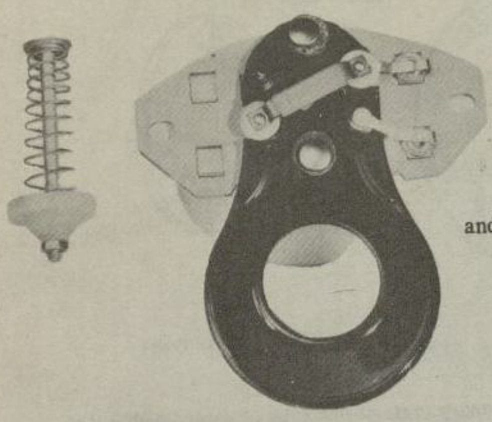


Fig. 1-9. Governor weight mechanism and stationary switch. (*Delco Products*)

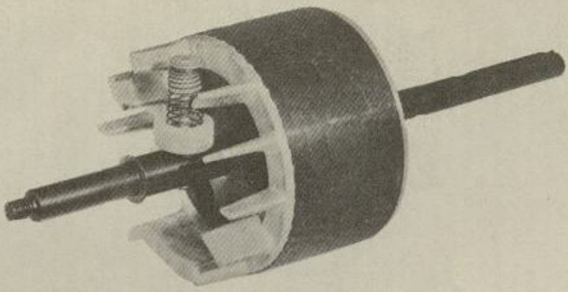


Fig. 1-10. Rotating mechanism of a centrifugal switch attached to rotor. *(Delco Products)*

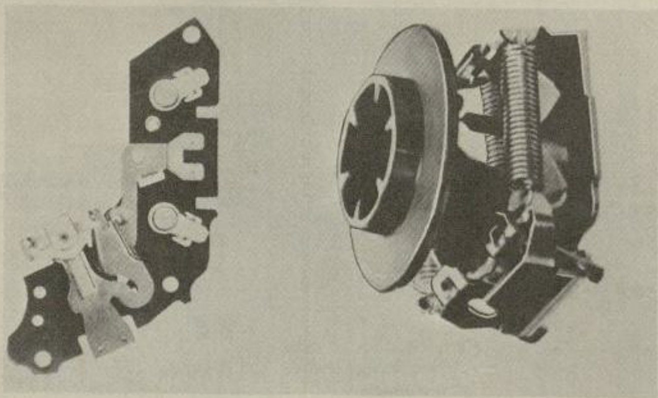


Fig. 1-11. Switch for fractional H.P. motor – centrifugal mechanism. (*General Electric Co.*)

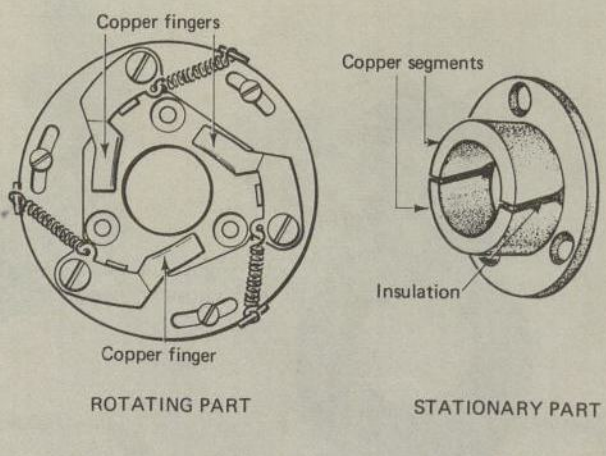


Fig. 1-12. The rotating and stationary parts of one type of centrifugal switch.

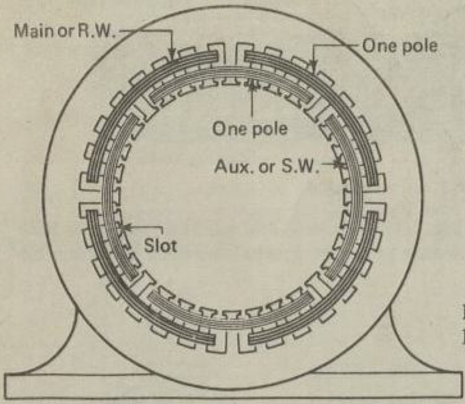


Fig. 1-13. The two windings of a split-phase motor. Note the four sections or poles in each winding.

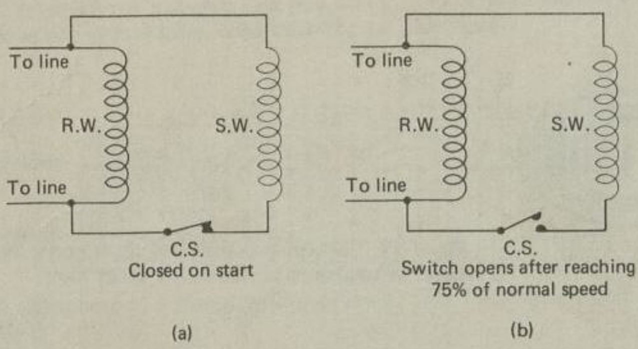


Fig. 1-14. The change in motor circuit caused by a centrifugal switch.

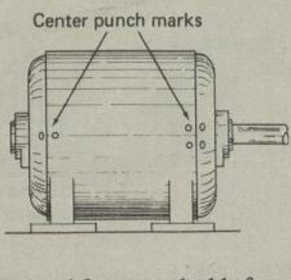


Fig. 1-15. End plates and frame marked before disassembling.

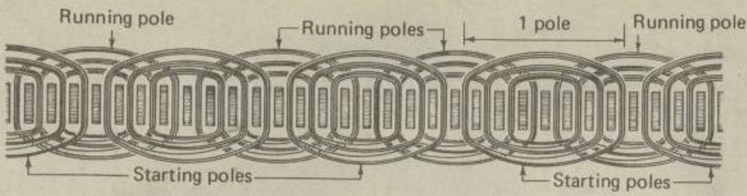


Fig. 1-16. A diagram of the stator in **Fig. 1-13** with slots and windings shown as they would look if rolled flat. The starting-winding poles are located between two running-winding poles.

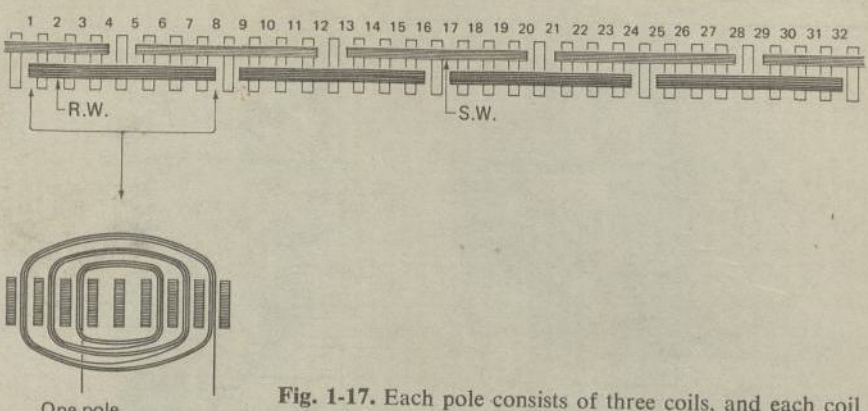


Fig. 1-17. Each pole consists of three coils, and each coil is wound in two slots separated by other slots.

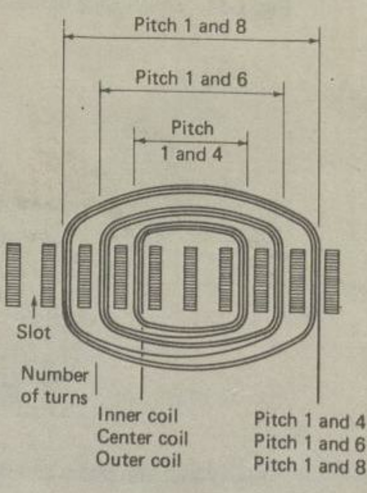


Fig. 1-18. The pitch, or span, of the three coils forming one pole.

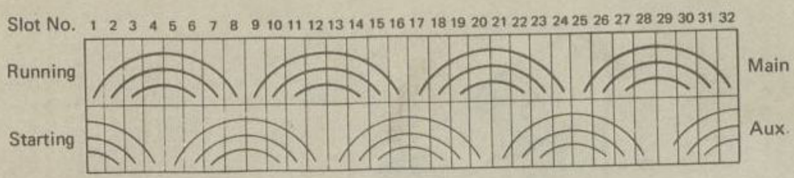


Fig. 1-19. The method of recording the pitch of the coils in a 32-slot, four-pole motor. The number of turns in each coil can be recorded alongside each coil in the diagram if so desired.

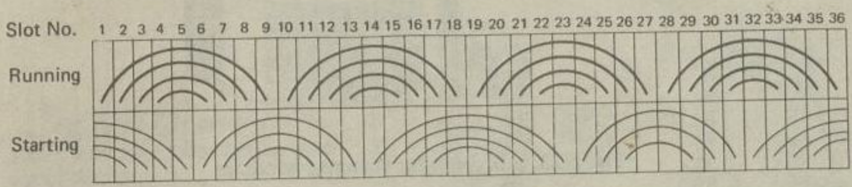


Fig. 1-20. Pitch data of a 36-slot, four-pole motor. The poles of the starting winding are not the same; one pole has four coils while the next has three.

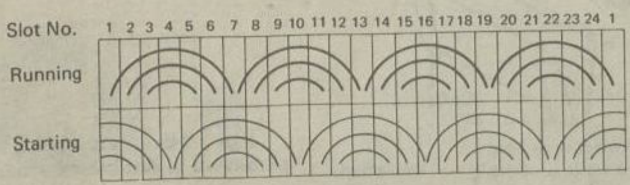


Fig. 1-21. Pitch data of a 24-slot, four-pole motor. The outer coils of adjacent poles are in the same slot.

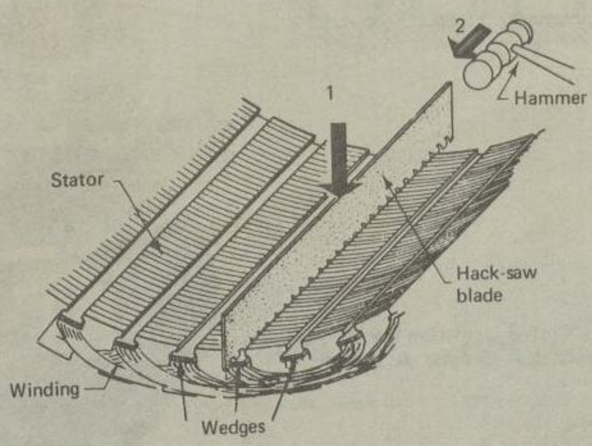


Fig. 1-22. The method of forcing a hack-saw blade into a wedge.

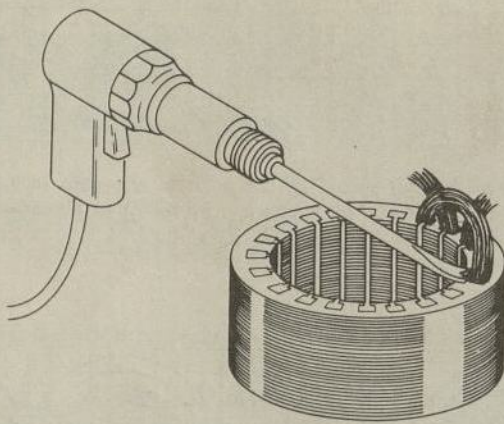


Fig. 1-23. Air chisel for stripping windings.

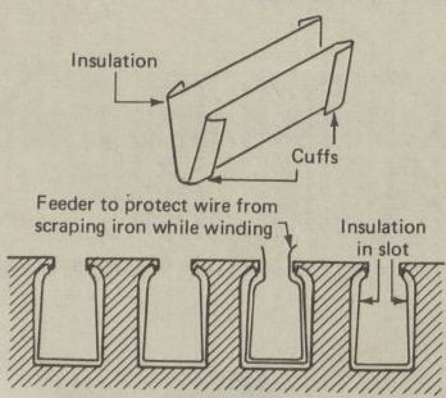


Fig. 1-24a. An insulating strip and its placement in slot before winding.

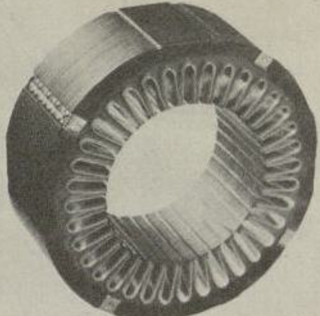


Fig. 1-24b. Cuffed insulation installed in slots. (*Courtesy E.I. duPont de Nemours Co. Inc.*)

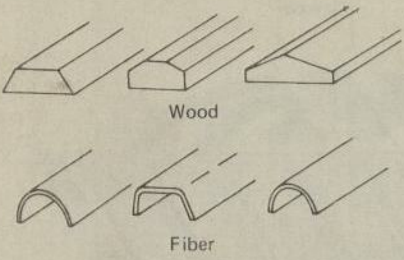


Fig. 1-25. Preformed wedges – fiber, wood.

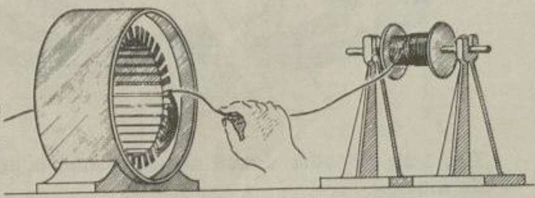


Fig. 1-26. The position of the motor and wire spool during wind ing operation.

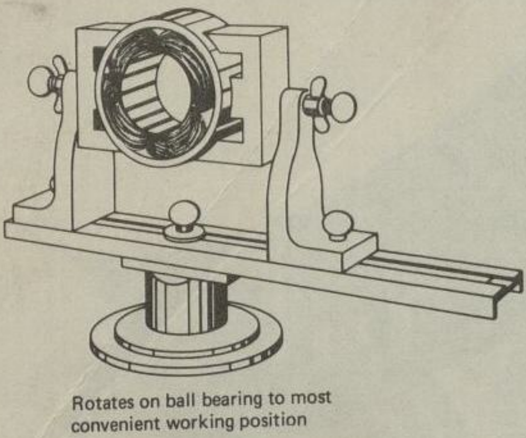


Fig. 1-27. Stator holder. (*Crown Industrial Products*)

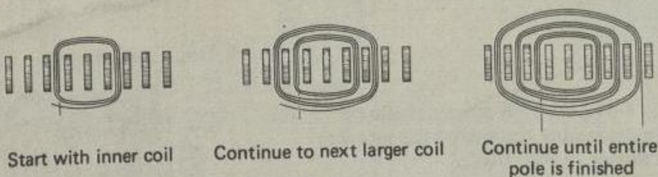


Fig. 1-28. The procedure for winding one stator pole by hand.

Figures 1-25; 1-26; 1-27 1-28

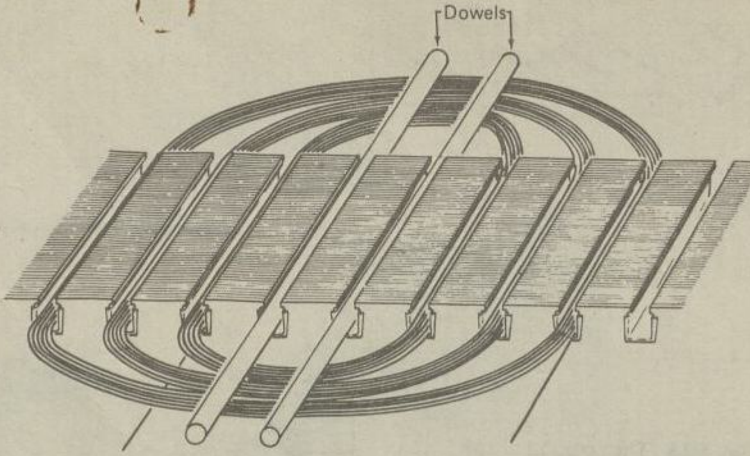


Fig. 1-29. Wooden dowels may be placed in empty slots to hold coils in position while winding.

foot = 0,3048 m

ch = 2,54 cm

3/16'' = 0,47 cm

1/4'' = 0,63 cm

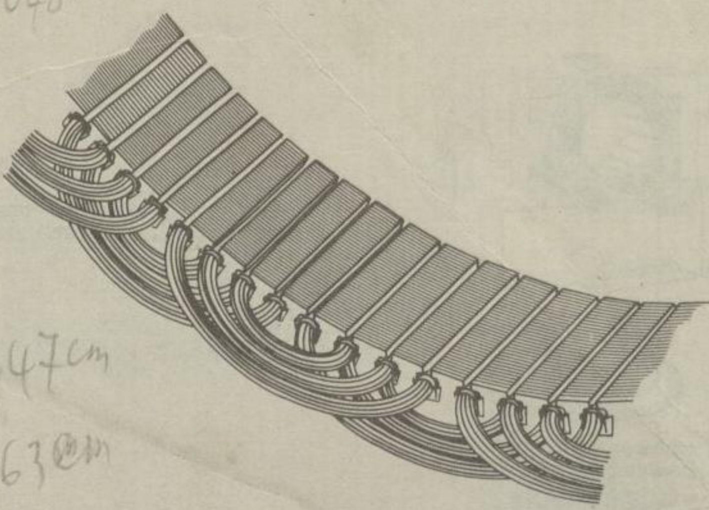
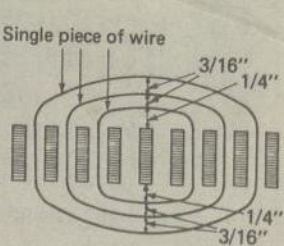


Fig. 1-30. Several poles of completed winding.

Fig. 1-31. Properly spaced single turns of wire determine the size of the wooden forms shown in Fig. 1-32a.



Figures 1-29; 1-30; 1-31

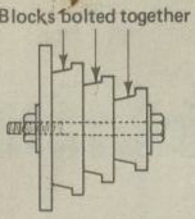


Fig. 1-32a. Wooden blocks provide forms on which to wind coils.

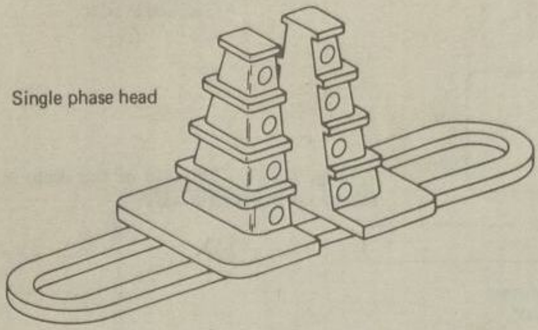


Fig. 1-32b. Single phase adjustable concentric winding head.

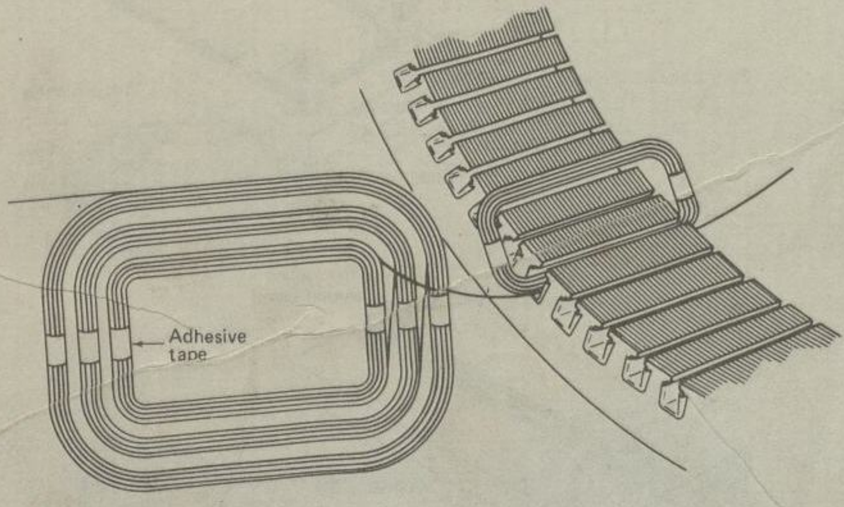


Fig. 1-33. Method of inserting form wound coils in stator.

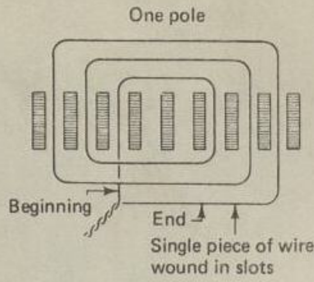


Fig. 1-34a. The method of determining the size of the skein.

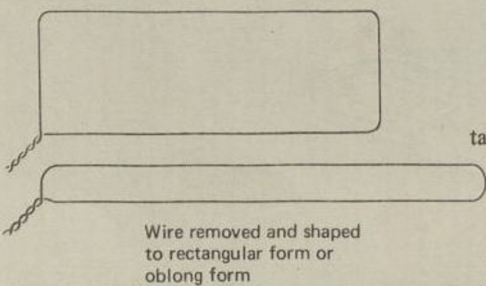


Fig. 1-34b. The size of the skein obtained from a single wire.

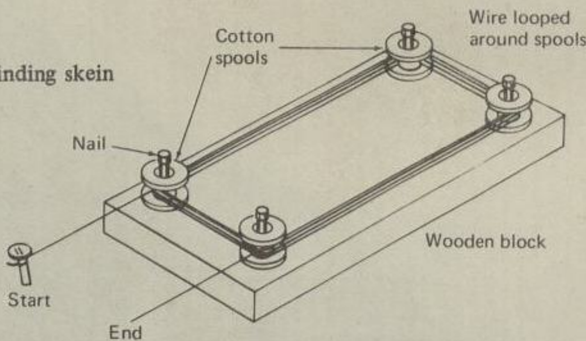


Fig. 1-35a. Form for winding skein coils.

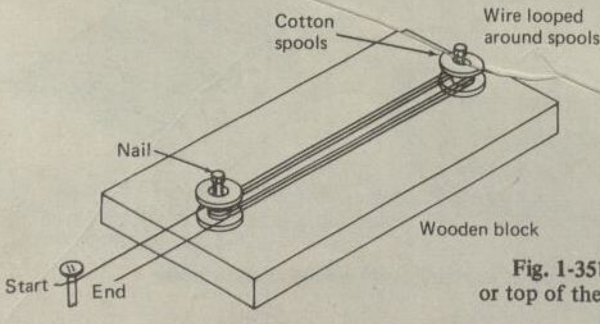


Fig. 1-35b. Spools nailed to the side or top of the work bench.

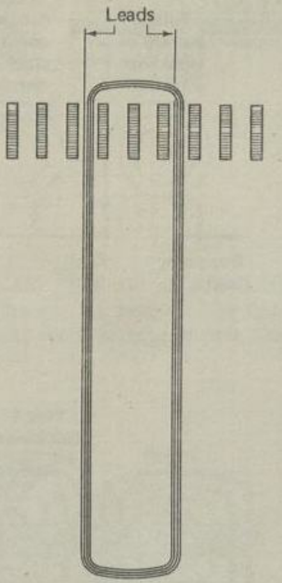
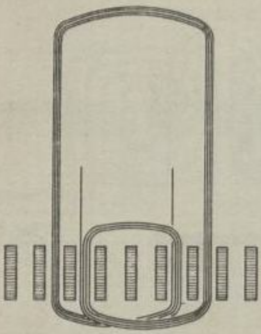


Fig. 1-36a. After it is removed from the form, the skein is placed in slots of the lowest pitch.



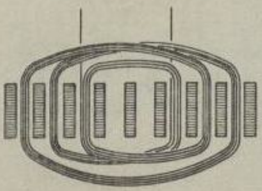
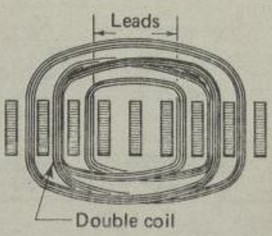


Fig. 1-36b. The skein is twisted and placed in the slots of next pitch and twisted again to form final pole.

Fig. 1-37. A skein winding with a double coil in the center.



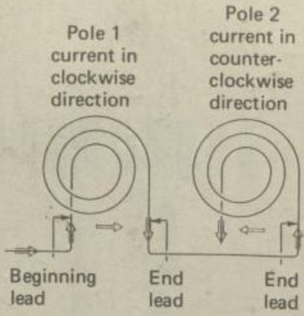


Fig. 1-38. The connection of adjacent poles to obtain opposite polarity.

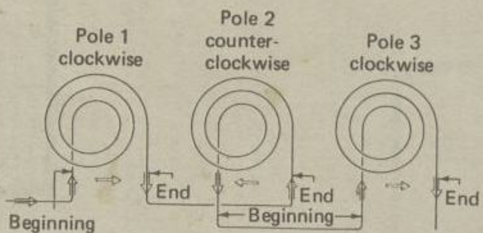


Fig. 1-39. The connections of three poles.

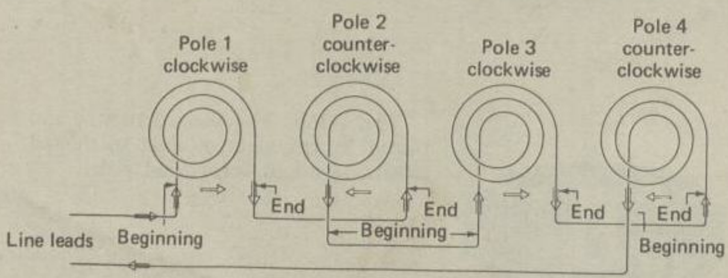


Fig. 1-40. Four poles connected together and to the line.

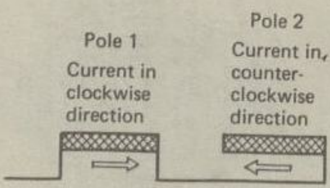
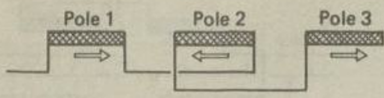


Fig. 1-41. A block diagram of circuit of Fig. 1-38.

Fig. 1-42. Continued from Fig. 1-41. The beginning of pole 2 connects to the beginning of pole 3.



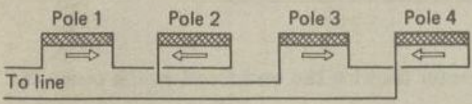


Fig. 1-43. The end of pole 3 connects to the end of pole 4. The line is connected to the beginning of pole 1 and pole 4.

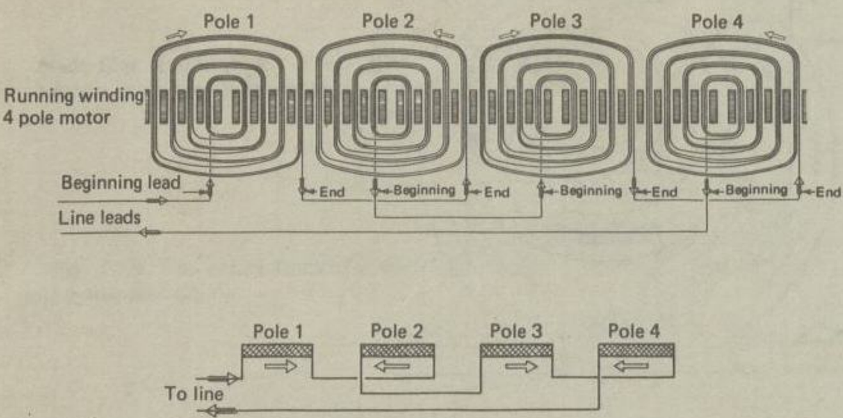


Fig. 1-44. Four poles of the running winding. The poles are connected so that the current through pole 1 is in a clockwise direction; through pole 2, in a counterclockwise direction; pole 3, clockwise; pole 4, counterclockwise.

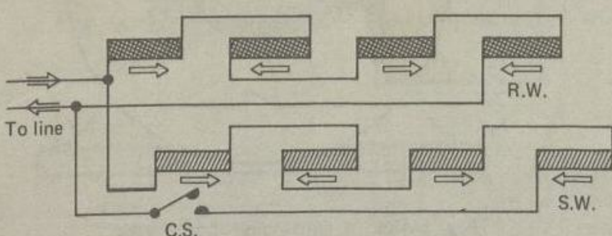


Fig. 1-45. A four-pole split-phase motor connection.

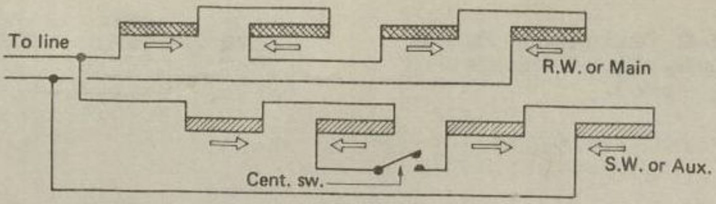


Fig. 1-46. A four-pole, split-phase motor showing the centrifugal switch connected in the center of the starting winding.

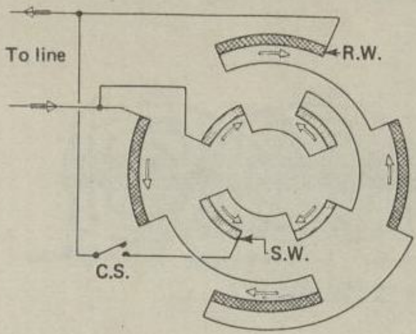


Fig. 1-47. A four-pole split-phase motor connection shown in a circular diagram.

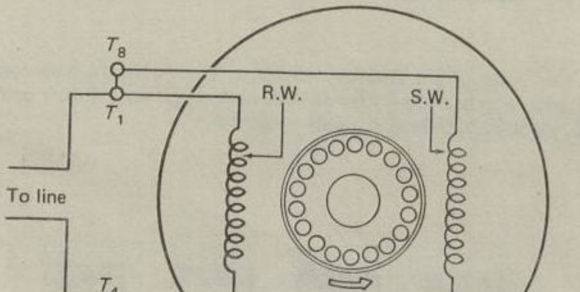


Fig. 1-48a. A split-phase motor with four leads brought outside the frame for reversing.

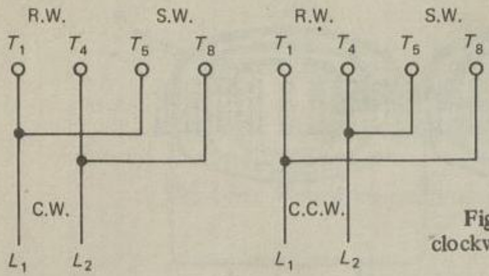


Fig. 1-48b. Terminal connection for clockwise and counterclockwise rotation.

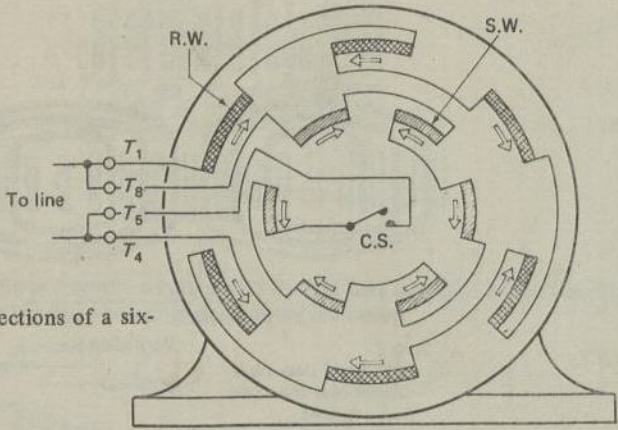


Fig. 1-49. The connections of a six-pole split-phase motor.

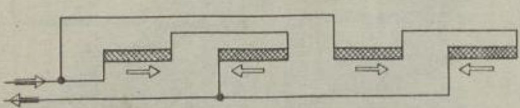


Fig. 1-50. A two-circuit connection of a four-pole running winding.

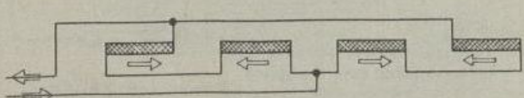


Fig. 1-51. Another method for connecting a two-circuit, four-pole running winding.

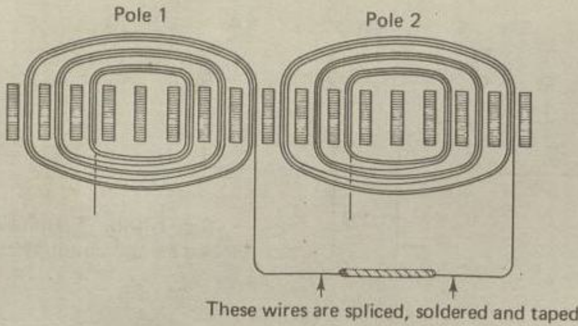


Fig. 1-52. One method of connecting wires between poles.

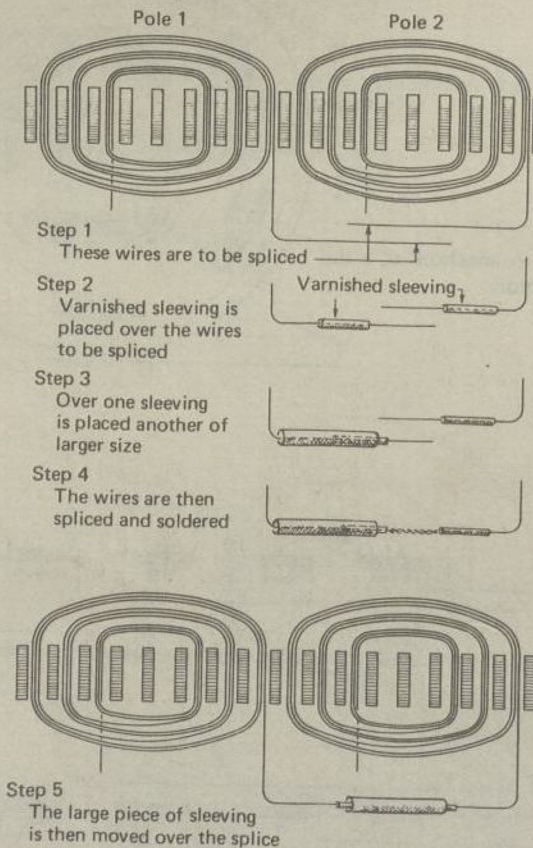


Fig. 1-53. A method of connecting leads together.

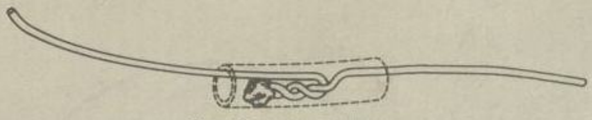


Fig. 1-54. Welded joint with sleeving of insulation.

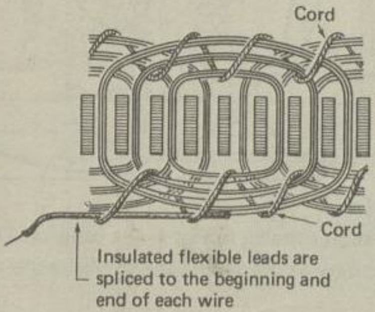
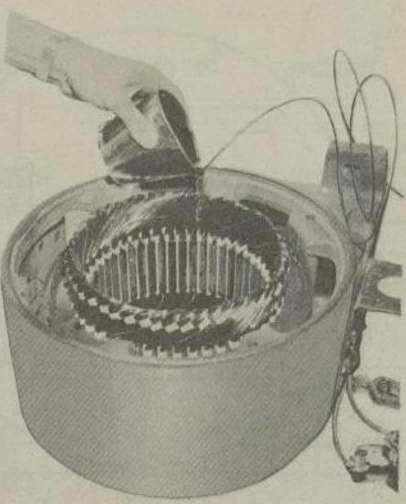


Fig. 1-55. The lead is tied to the winding with cord so that it cannot be broken off. The windings are also tied to one another to prevent unraveling.



Stator in position for pouring, leads down. Windings at 270°F. Mixed resin poured until resin gels at lead end.

Fig. 1-56. Manual application of solventless resin. (*3M Company*)

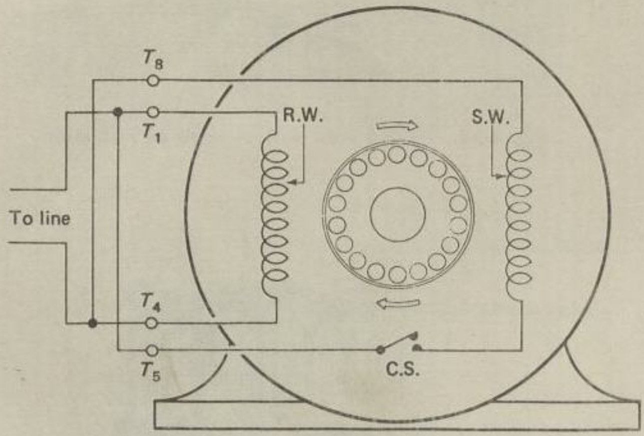


Fig. 1-57. The motor shown in Fig. 1-48a connected for reversed rotation.

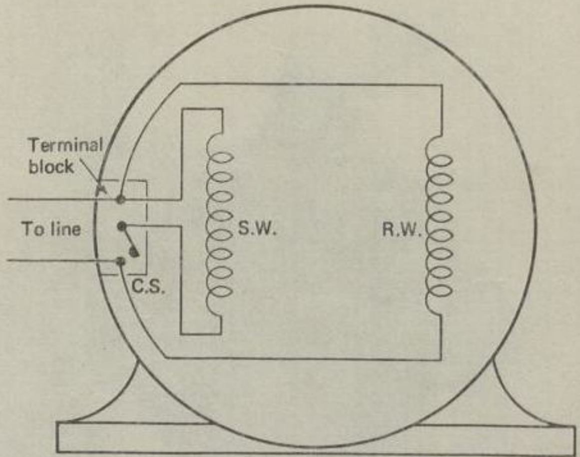


Fig. 1-58. The connections of the terminal block on the end plate. The centrifugal switch is mounted on the terminal block.

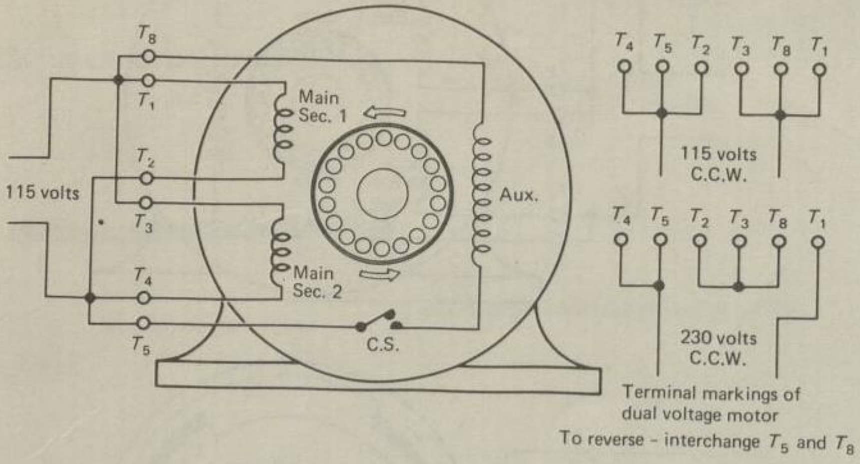


Fig. 1-59. Dual-voltage split-phase motor lower voltage-counterclockwise rotation.

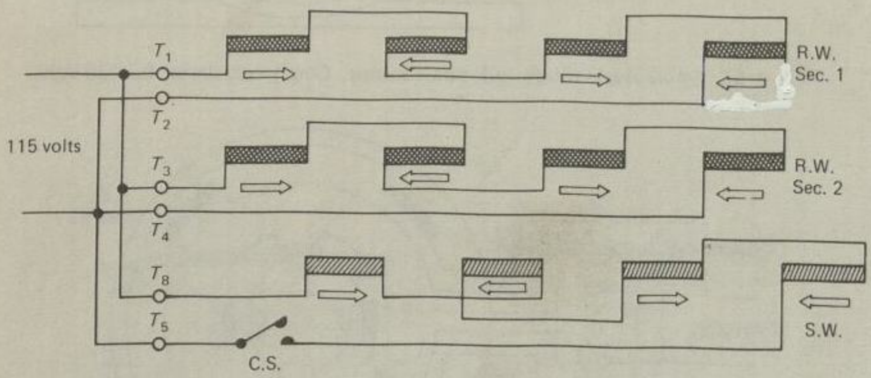
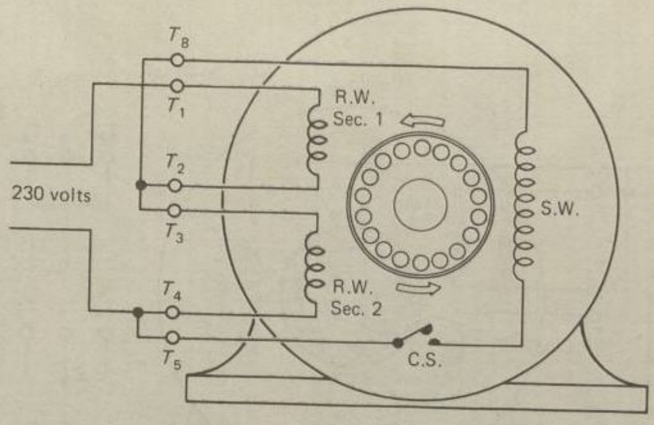


Fig. 1-60. Layout and connection of a 4-pole dual-voltage split-phase motor. Counter-clockwise for low voltage.



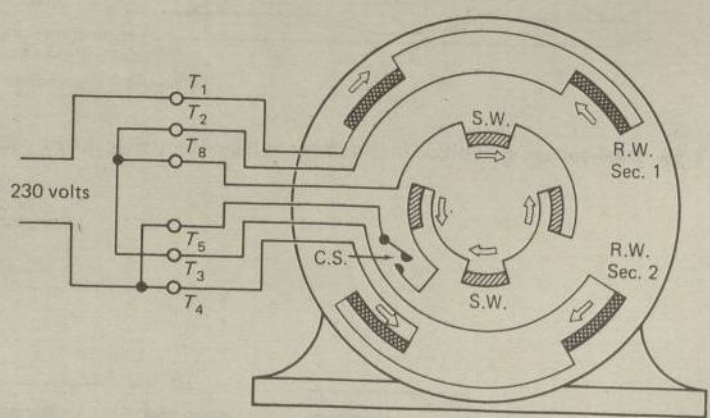


Fig. 1-61. 4-pole dual-voltage split-phase motor. Counterclockwise for 230 volts.

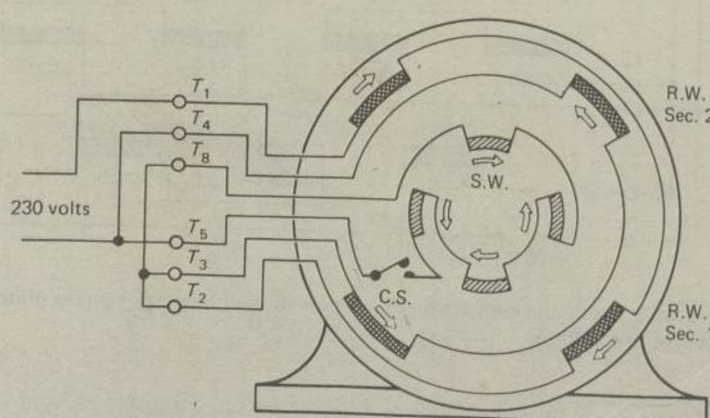


Fig. 1-62. 4-pole dual-voltage split-phase motor – long jumper – counterclockwise for 230 volts.

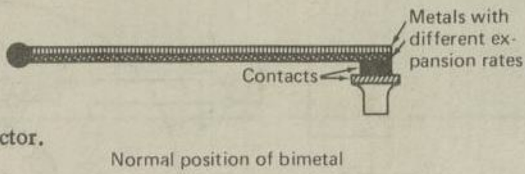


Fig. 1-63a. Bimetal overload protector.

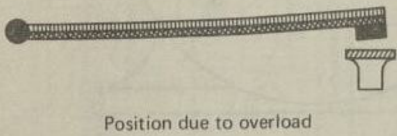
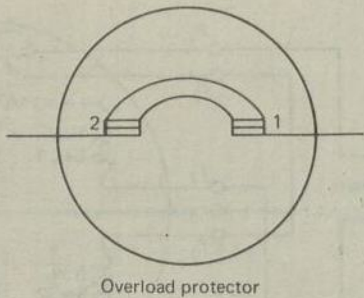


Fig. 1-63b. Bimetal overload protector.

Fig. 1-64. A bimetallic disc with 2 contacts.



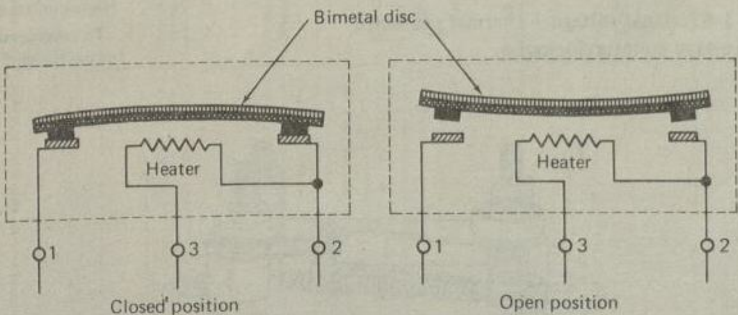


Fig. 1-65. 3 terminal overload protector with heater.

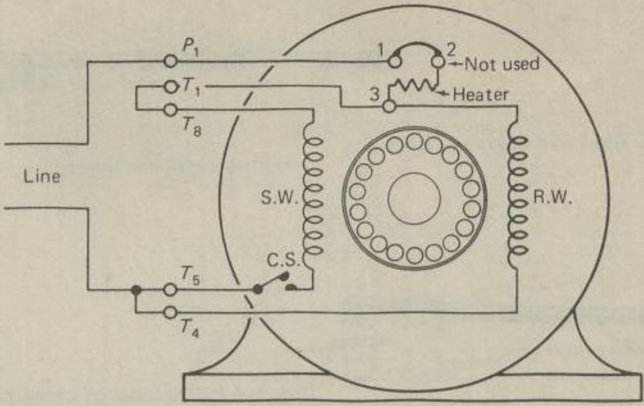


Fig. 1-66. Split-phase motor connected to a 3 terminal overload protector. Counterclockwise rotation. For clockwise rotation interchange T_5 and T_8.

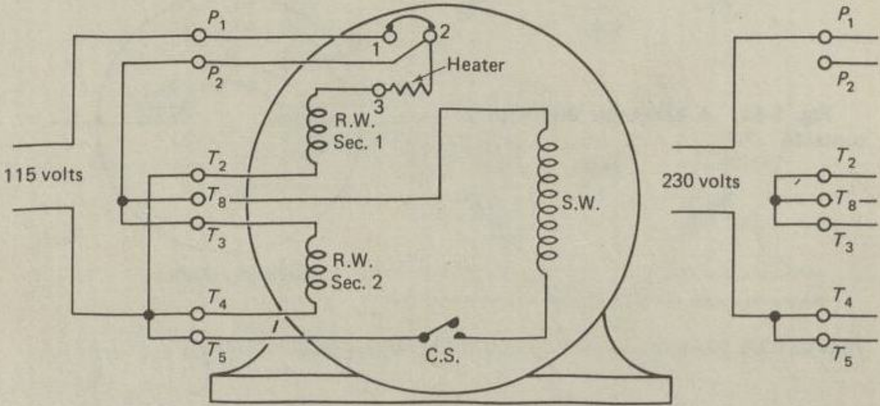


Fig. 1-67. Dual voltage – thermal protector lower voltage counterclockwise.

Higher voltage C.C.W.
To reverse rotation interchange T_5 & T_8.

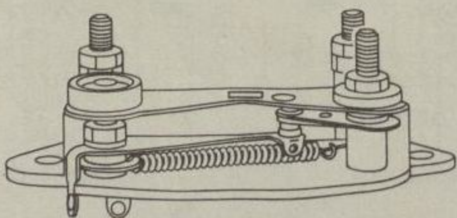


Fig. 1-68. Bimetal type thermotron *(Delco Products)*.

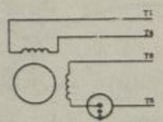
TERMINAL MARKINGS

MG 1-2.47 Schematic Diagrams for Split-Phase Motors—Single Voltage—Reversible

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

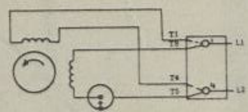
Without Thermal Protector

Line Leads

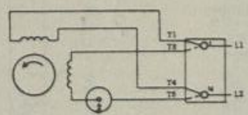


	L1	L2
Counter-clockwise rotation	T1, T8	T4, T5
Clockwise rotation	T1, T5	T4, T8

Terminal Board



To obtain clockwise rotation, interchange leads T5 and T8.

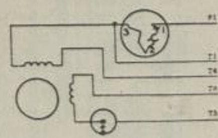


To obtain clockwise rotation, interchange leads T1 and T4.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

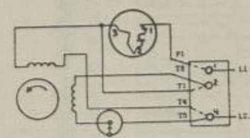
With Thermal Protector

Line Leads

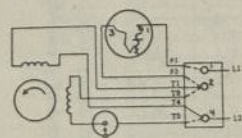


	L1	L2	Join
Counter-clockwise rotation	P1	T4, T5	T1, T8
Clockwise rotation	P1	T4, T8	T1, T5

Terminal Board



To obtain clockwise rotation, interchange leads T5 and T8.



To obtain clockwise rotation, interchange leads T1 and T4.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

Fig. 1-69.

Figure 1-69

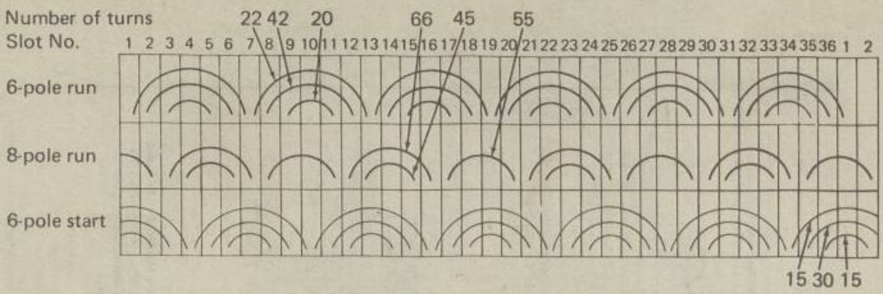


Fig. 1-70. A coil layout of a two-speed, three-winding split-phase motor.

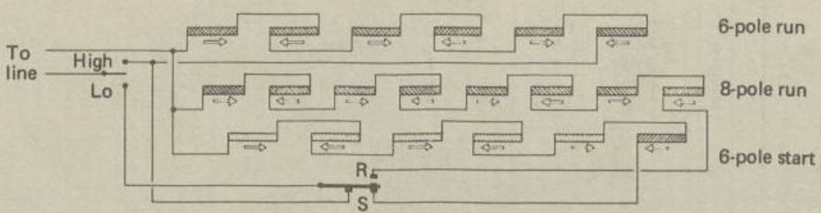


Fig. 1-71. The wiring of a two-speed split-phase motor.

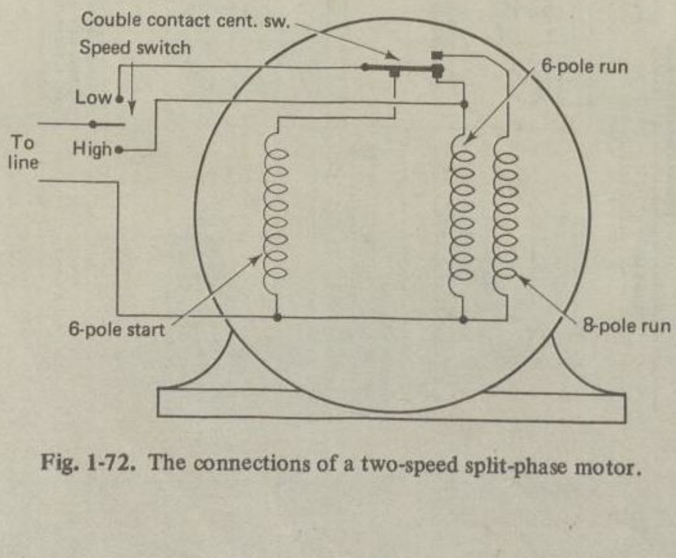


Fig. 1-72. The connections of a two-speed split-phase motor.

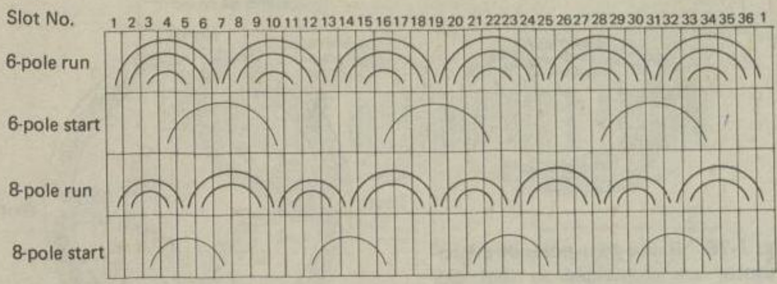


Fig. 1-73. A typical layout of a two-speed split-phase motor using four windings. The starting windings are consequent pole connected.

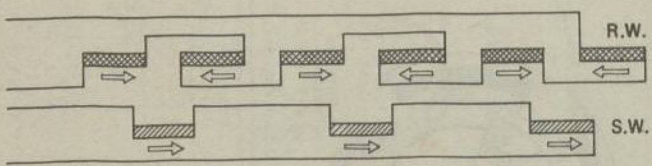


Fig. 1-74. The starting and running winding of the six-pole part of a two-speed motor. The starting-winding poles are connected for like polarity. There are only three wound poles; three more poles of opposite polarity are formed in the stator·frame.

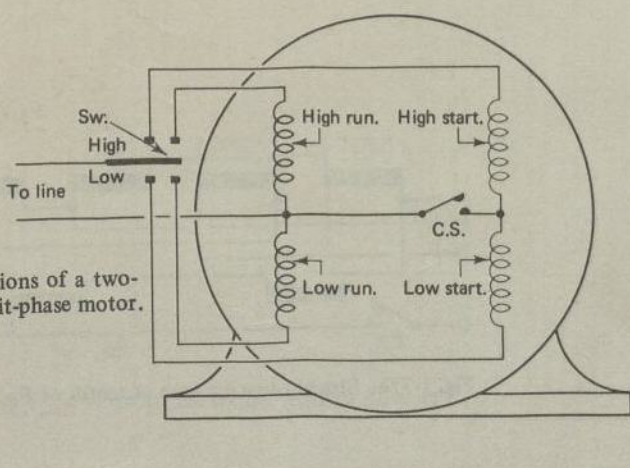


Fig. 1-75. Connections of a two-speed, four-winding split-phase motor.

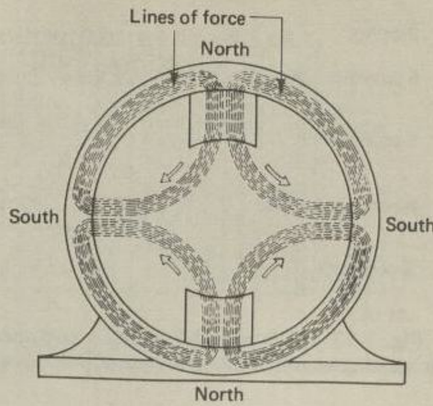


Fig. 1-76. If the two poles of a two-pole motor are connected so that like polarity results, two more poles will be formed by the lines of force entering the frame.

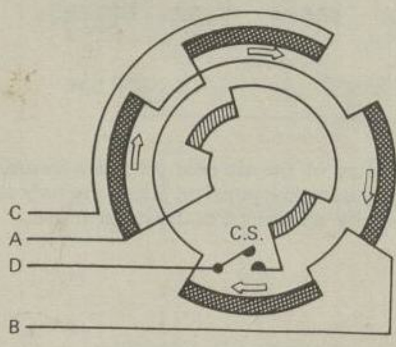


Fig. 1-77a. Circular diagram of a two-speed, two-winding, split-phase motor.

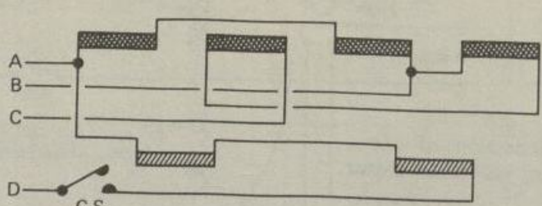
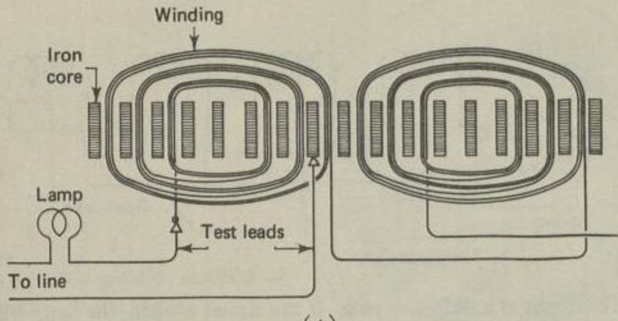
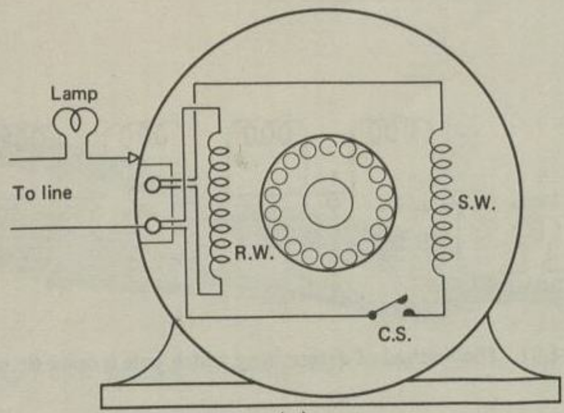


Fig. 1-77b. Straight-line diagram of motor of **Fig. 77a.**



(A)



(B)

Fig. 1-78. To determine whether winding is grounded, connect one test lead to the winding and the other test lead to the core. The lighted lamp indicates a ground.

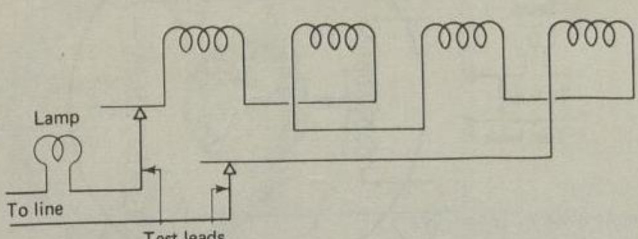
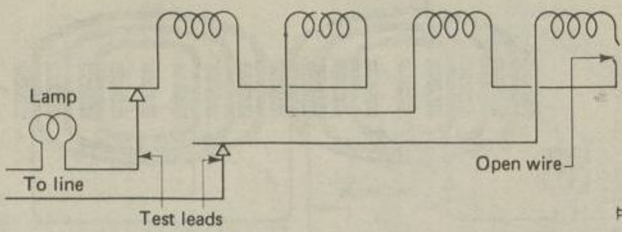


Fig. 1-79. A circuit for testing winding for opens.



FIG

Fig. 1-80. The effect of a defective pole. If the circuit is open, the lamp will not light.

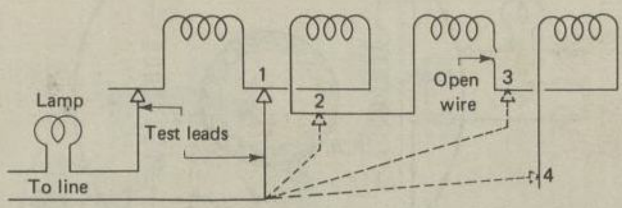


Fig. 1-81. The method of determining which pole is open-circuited.

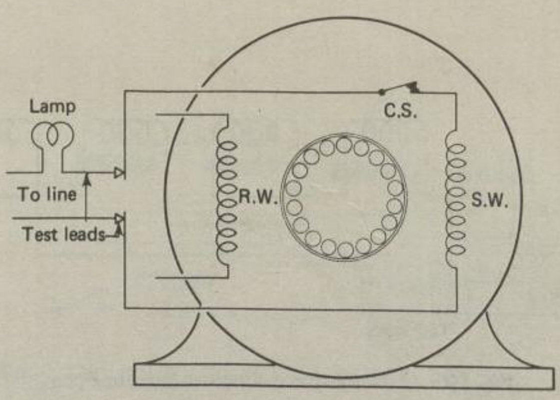


Fig. 1-82. Testing the starting winding circuit for opens.

Figures 1-80; 1-81; 1-82

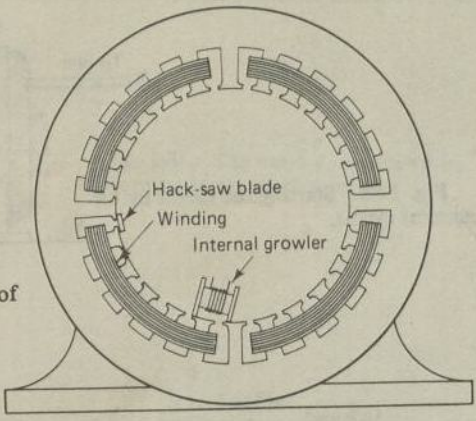


Fig. 1-83a. The growler method of testing for shorts in the stator.

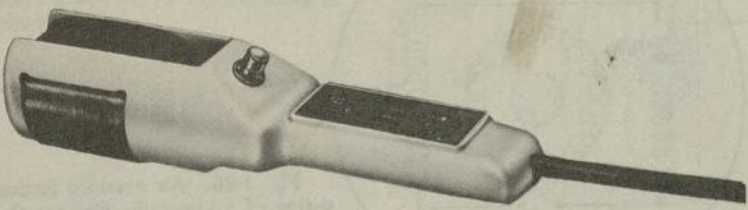


Fig. 1-83b. Internal, external growler. (*Crown Industrial Products*)

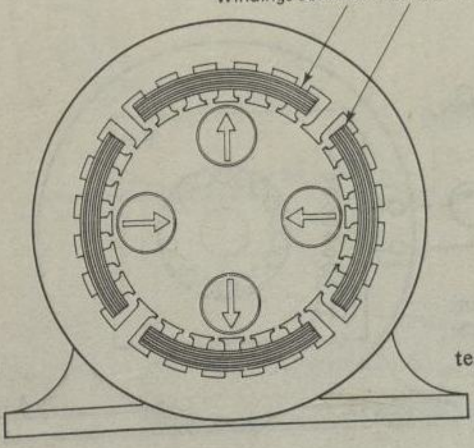


Fig. 1-84. The compass method of testing for reversed poles.

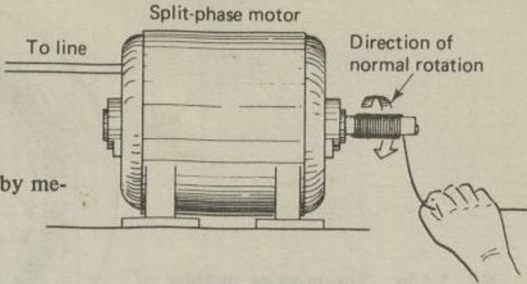


Fig. 1-85. Starting the motor by mechanical means.

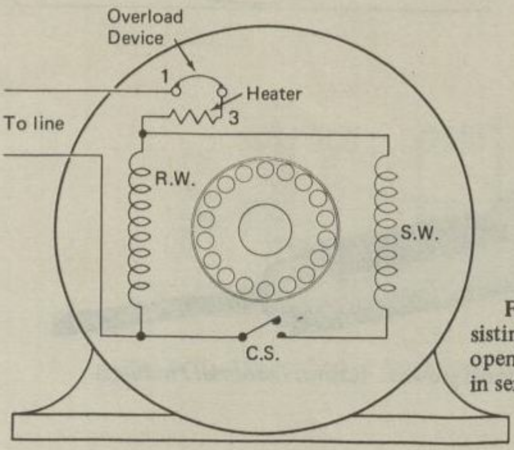


Fig. 1-86. An overload device, consisting of a bimetallic element that will open circuit on overload. It is connected in series with the line.

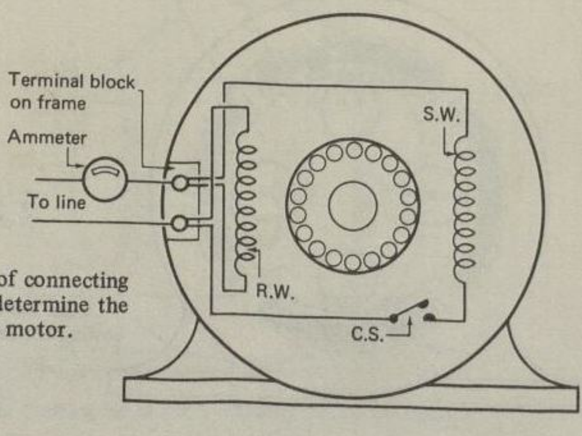


Fig. 1-87. The method of connecting an ammeter in circuit to determine the current flowing through the motor.

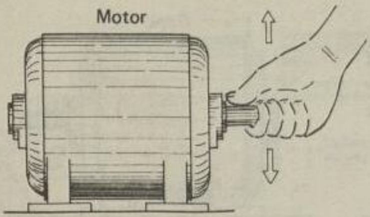


Fig. 1-88. The bearings are tested by trying to move the shaft vertically.

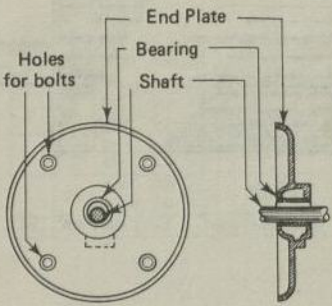


Fig. 1-89. If the shaft can be moved vertically, it indicates a worn bearing or worn rotor shaft.

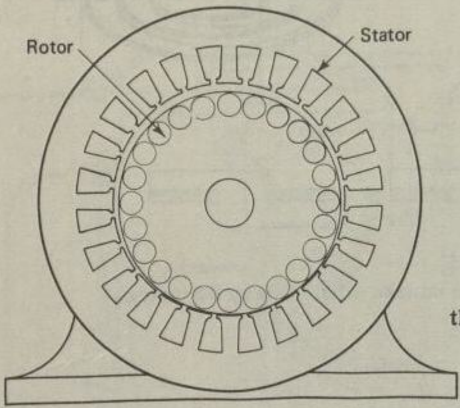


Fig. 1-90. A worn bearing may cause the rotor to rub on the stator core.

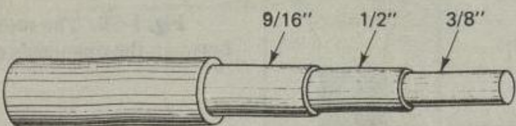


Fig. 1-91. The tool used for forcing bearings out of end plates

Figures 1-88; 1-89; 1-90; 1-91

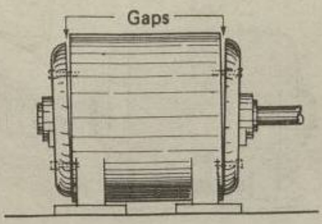


Fig. 1-92. A motor showing end plates not mounted properly. This prevents the rotor from turning. Use a mallet to tap plates into position.

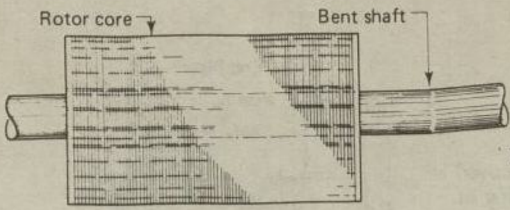


Fig. 1-93. The bent shaft of a rotor.

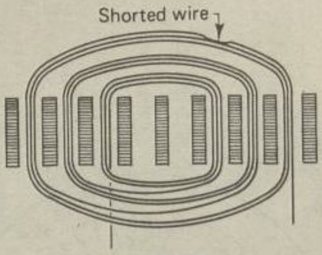


Fig. 1-94. Two turns making electrical contact.

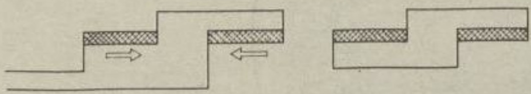


Fig. 1-95. A connection mistake often made by beginners.

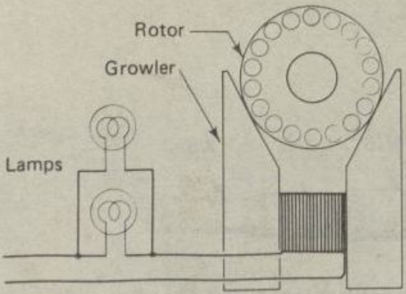


Fig. 1-96. The rotor under test placed between the open ends of the growler core.

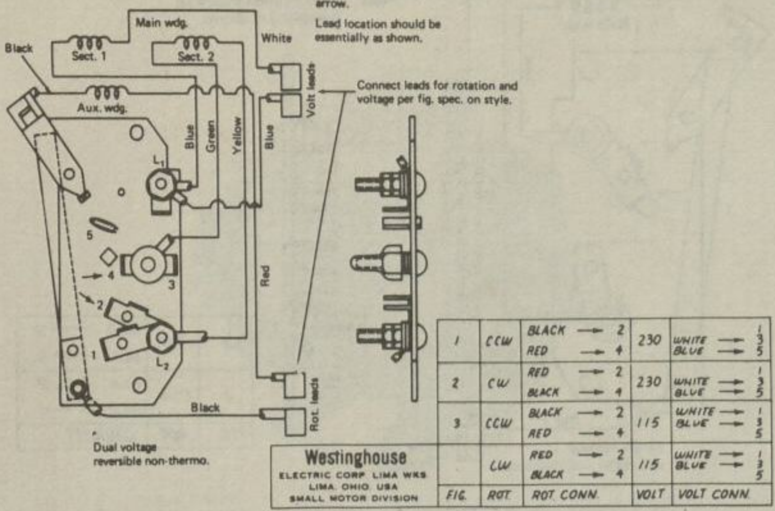


FIG.	ROT.	ROT. CONN.	VOLT	VOLT CONN.
1	CCW	BLACK → 2 RED → 4	230	1 WHITE → 3 BLUE → 5
2	CW	RED → 2 BLACK → 4	230	1 WHITE → 3 BLUE → 5
3	CCW	BLACK → 2 RED → 4	115	WHITE → 1 BLUE → 3 5
	CW	RED → 2 BLACK → 4	115	WHITE → 1 BLUE → 3 5

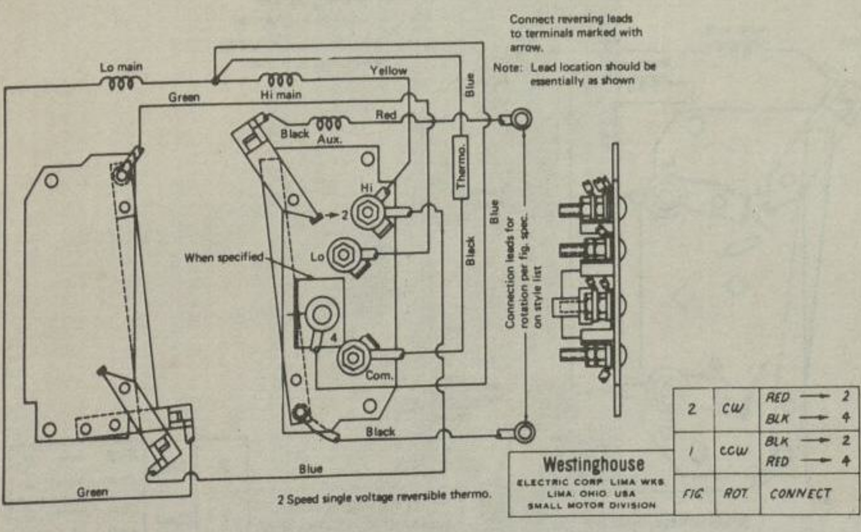
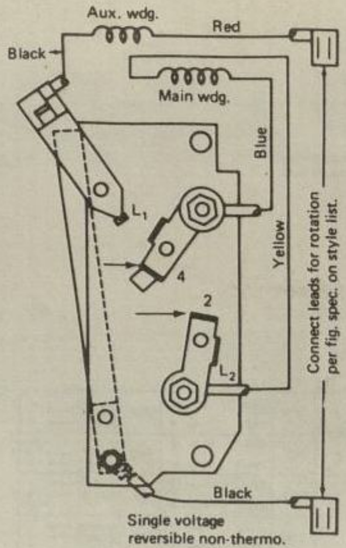


FIG.	ROT.	CONNECT
2	CW	RED → 2 BLK → 4
1	CCW	BLK → 2 RED → 4

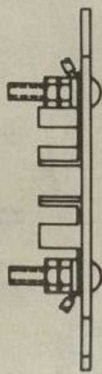
Fig. 1-97. Miscellaneous diagrams

Figure 1-97

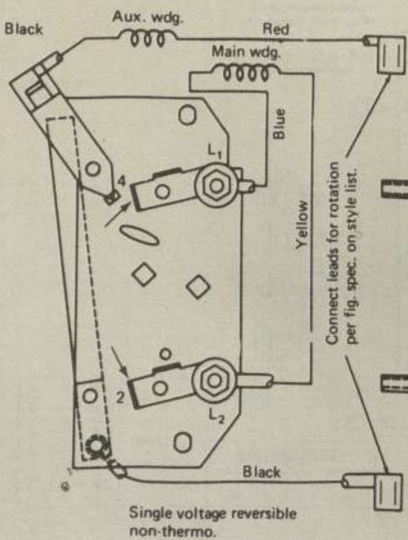


Connect reversing leads to terminals marked with arrow.

Note: Lead location should be essentially as shown.

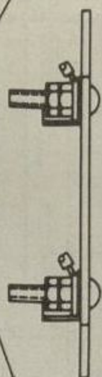


2	CW	RED → 2 BLK → 4
1	CCW	BLK → 2 RED → 4
FIG.	ROT	CONNECT



Connect reversing leads to terminals marked with arrow.

Note: Lead location should be essentially as shown.



	2	CW	RED → 2 BLK → 4
Westinghouse ELECTRIC CORP. LIMA WKS. LIMA, OHIO USA INDUSTRIAL MOTOR DEPT.	1	CCW	BLK → 2 RED → 4
	FIG.	ROT	CONNECT

Fig. 1-97. Miscellaneous diagrams. *(continued)*

Figure 1-97

CHAPTER 2

Capacitor Motors

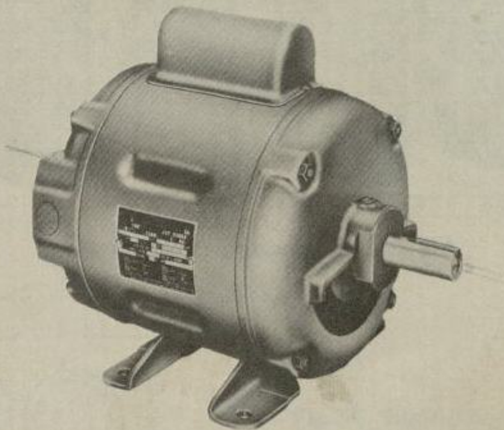


Fig. 2-1. Capacitor start motor. (*Wagner Electric Co.*)

Fig. 2-2. A.C. capacitors with mounting hardware and accessories. (*P.R. Mallory & Co.*)

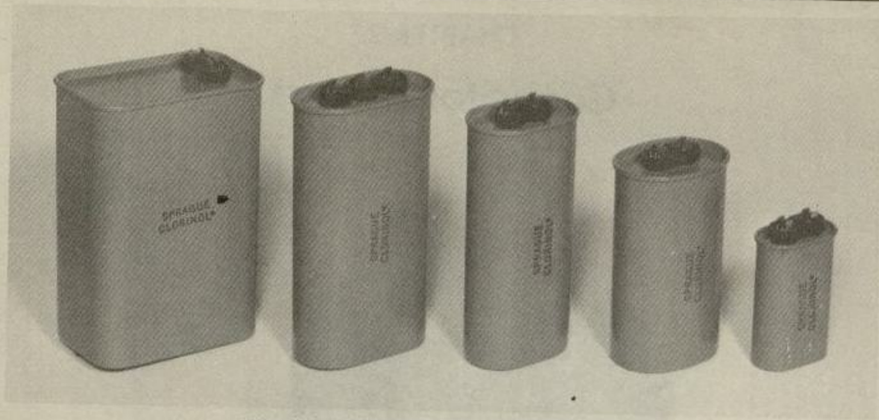


Fig. 2-3. Oil capacitors. *(Sprague Electric)*

Fig. 2-4. Electrolytic capacitor. *(Sprague Electric)*

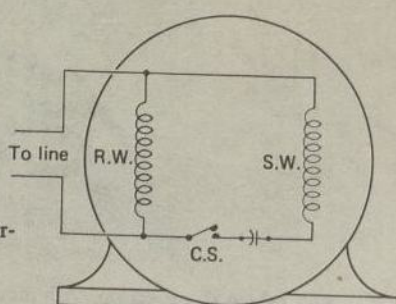


Fig. 2-5. Connections of a capacitor-start motor.

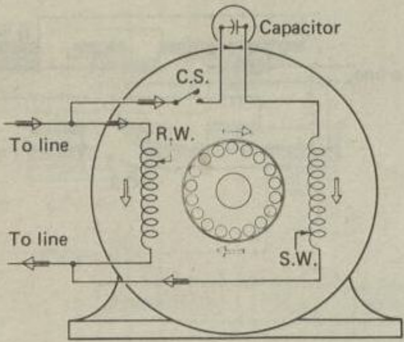


Fig. 2-6. Single voltage capacitor-start motor connected for clockwise rotation. Note direction of current in windings.

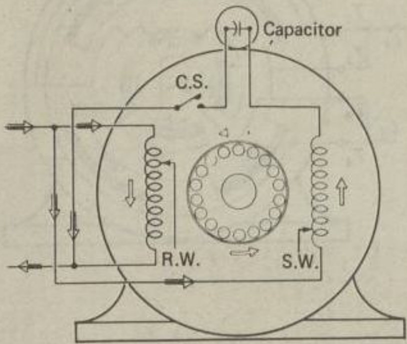


Fig. 2-7. Single-voltage capacitor-start motor connected for counterclockwise rotation. The direction of the current in the starting winding has changed from that shown in **Fig. 2-6.**

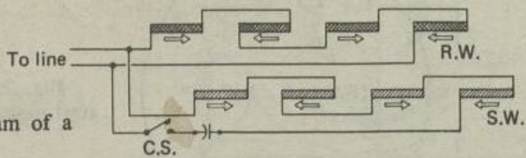


Fig. 2-8. Straight-line diagram of a four-pole capacitor-start motor.

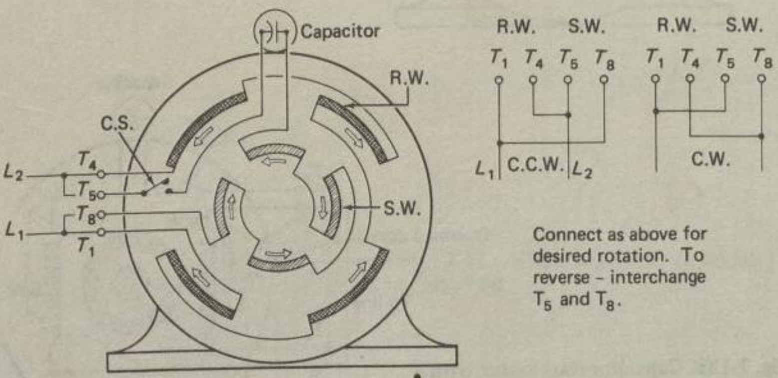


Fig. 2-9. Connection diagram of a four-pole capacitor-start motor.

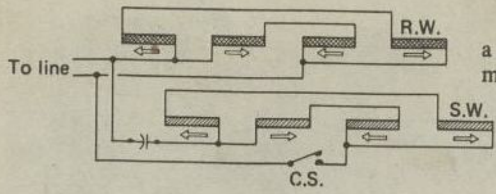


Fig. 2-10. Straight-line diagram of a four-pole, two-circuit capacitor-start motor.

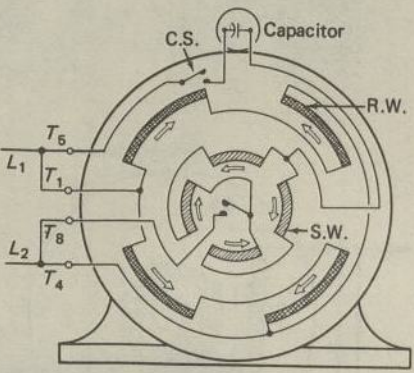


Fig. 2-11. A four-pole, two-circuit capacitor-start motor.

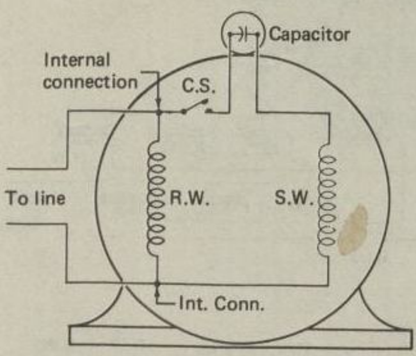


Fig. 2-12. Nonreversible capacitor-start motor.

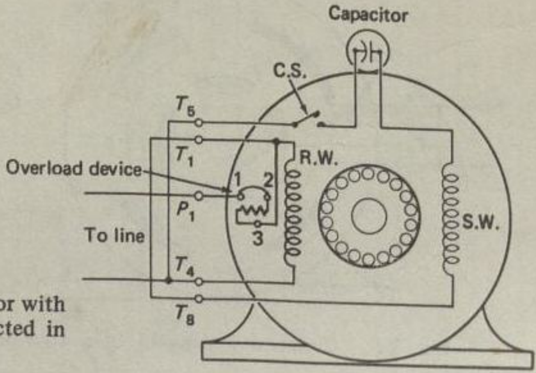


Fig. 2-13a. Capacitor-start motor with bimetallic overload device connected in series with the line.

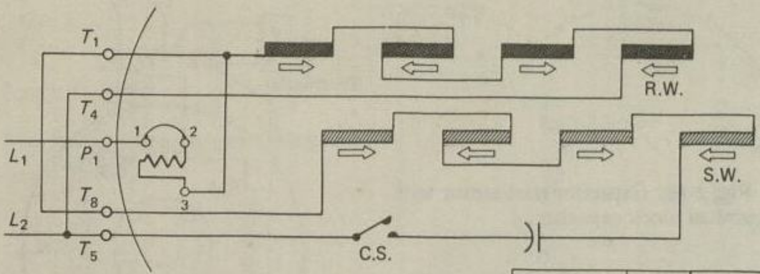


Fig. 2-13b. A four-pole capacitor motor with overload device.

Direction	L_1	L_2	Join
Counter-clockwise	P_1	T_4T_5	T_1T_8
Clockwise	P_1	T_4T_8	T_1T_5

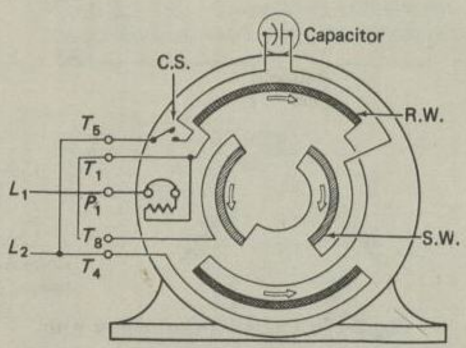


Fig. 2-14. Connection diagram of a two-pole capacitor-start motor with an overload device.

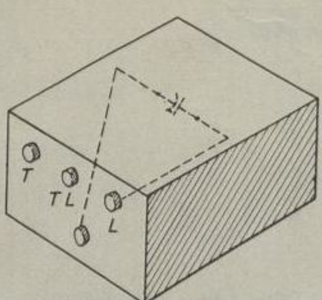


Fig. 2-15. Capacitor with terminal block attached.

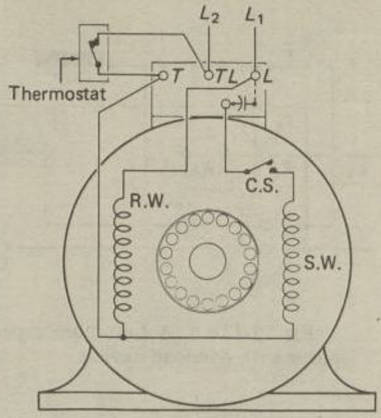


Fig. 2-16. Capacitor-start motor with a terminal block capacitor.

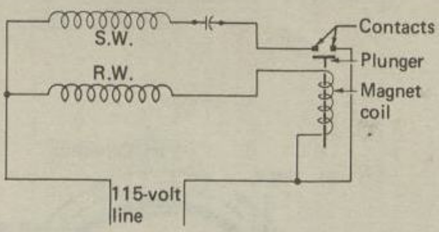


Fig. 2-17a. Diagram of a capacitor-start motor using a current relay instead of a centrifugal switch.

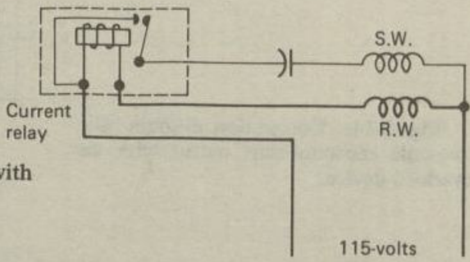


Fig. 2-17b. Capacitor-start motor with current relay.

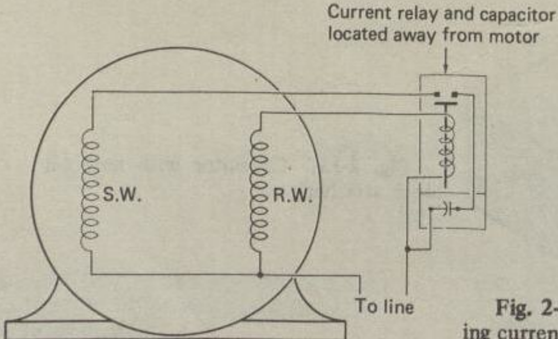


Fig. 2-18a. Capacitor-start motor using current relay.

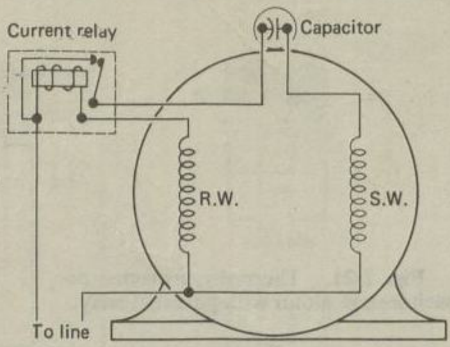


Fig. 2-18b. Capacitor-start motor using a current relay.

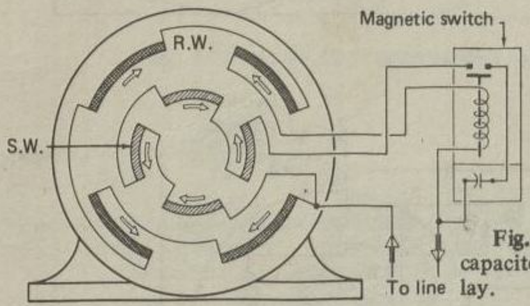


Fig. 2-19a. Connections of four-pole capacitor-start motor using a current relay.

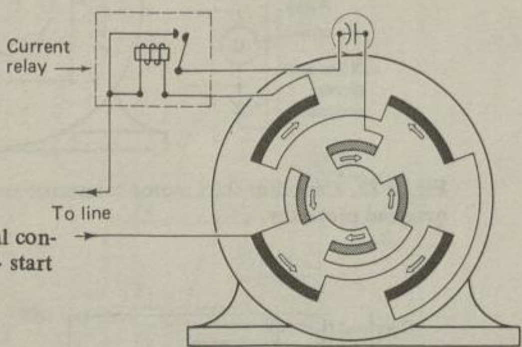


Fig. 2-19b. Internal and external connections of a four-pole capacitor- start motor with current relay.

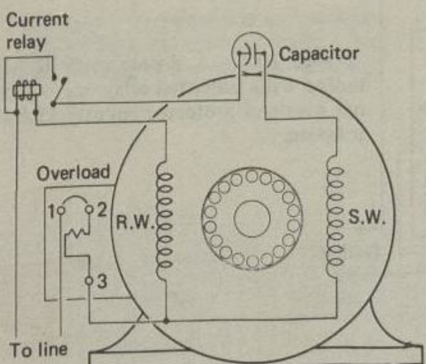


Fig. 2-20. Capacitor-start motor with current relay and 2 terminal overload protector.

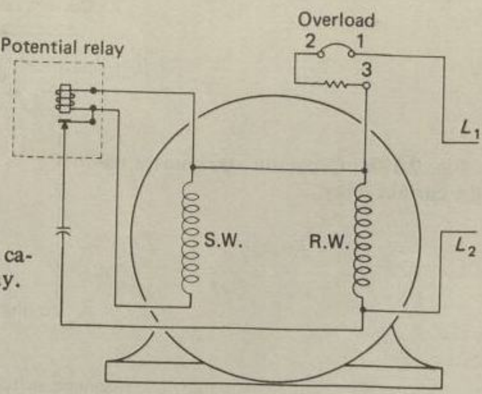


Fig. 2-21. Thermally protected capacitor-start motor with potential relay.

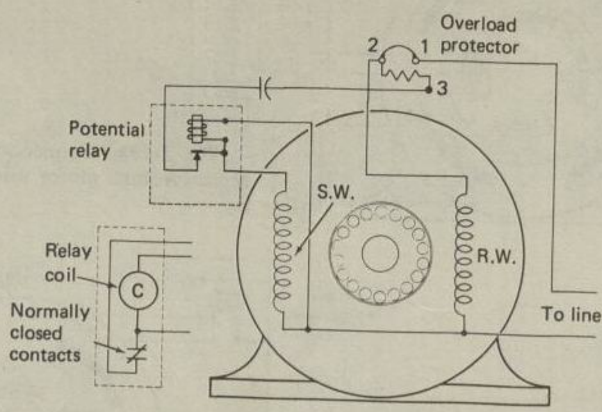


Fig. 2-22. Capacitor-start motor connected to potential relay and 3 terminal overload protector.

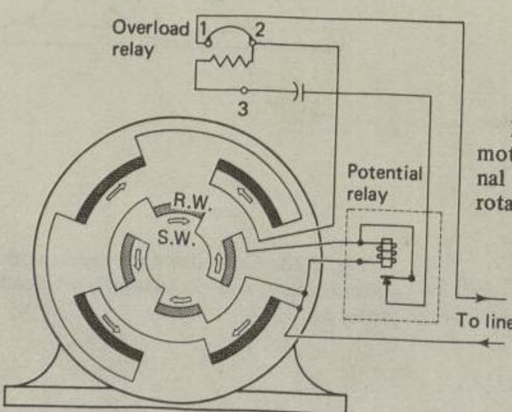


Fig. 2-23. A 4-pole capacitor-start motor with potential relay and 3 terminal overload protector counterclockwise rotation.

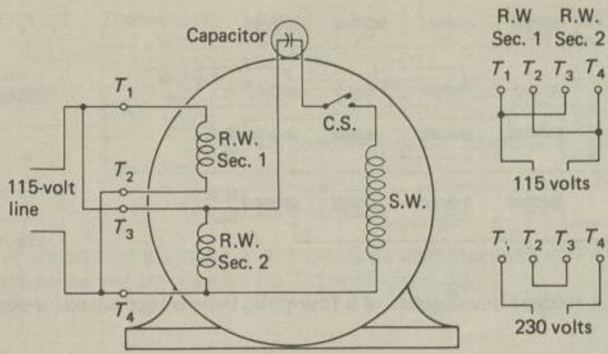


Fig. 2-24. Dual-voltage nonreversible capacitor-start motor.

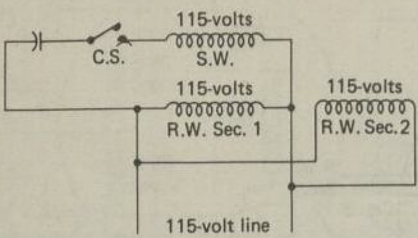


Fig. 2-25. A schematic diagram of a two-voltage capacitor-start motor connected for 115-volt operation.

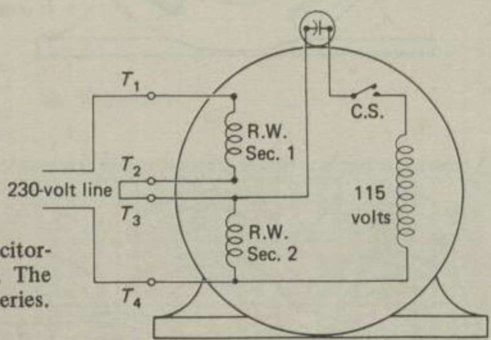


Fig. 2-26. A two-voltage capacitor-start motor connected for 230 volts. The running windings are connected in series.

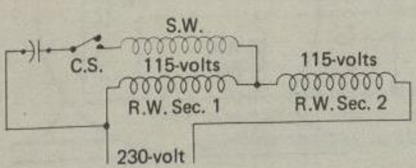


Fig. 2-27. A schematic diagram of a two-voltage capacitor-start connection for 230 volts.

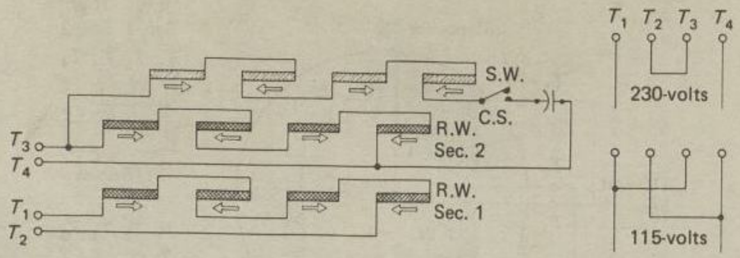


Fig. 2-28. A straight-line diagram of a four-pole, two-voltage capacitor-start motor.

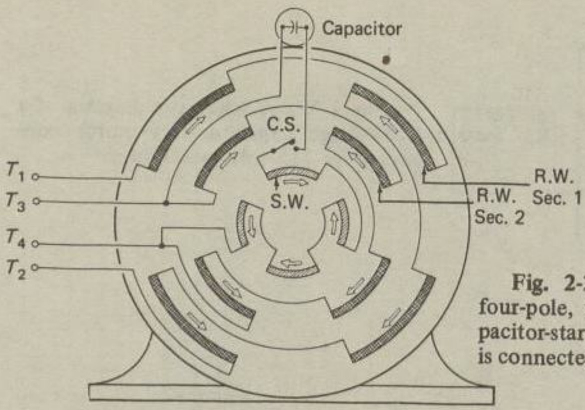


Fig. 2-29. A wiring diagram of a four-pole, two-voltage, nonreversible capacitor-start motor. The starting winding is connected across one running winding.

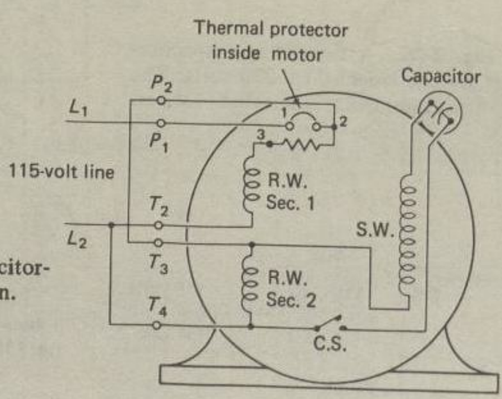


Fig. 2-30. A two-voltage capacitor-start motor with overload protection.

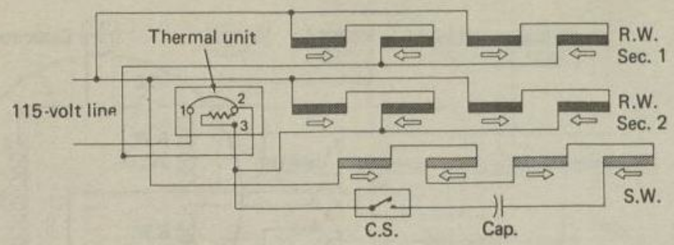
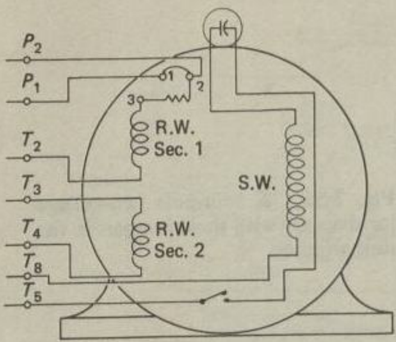


Fig. 2-31. A connection diagram for a two-voltage capacitor-start motor. The running windings are connected two-parallel for 115-volt operation.



		L_1	L_2	Join	Join
H.V.	Counter-clockwise	P_1	T_4	P_2T_8	$T_2T_3T_5$
	Clockwise	P_1	T_4	P_2T_5	$T_2T_3T_8$
L.V.	Counter-clockwise	P_1	$T_2T_4T_5$	$P_2T_3T_8$	
	Clockwise	P_1	$T_2T_4T_8$	$P_2T_3T_5$	

Fig. 2-32. Externally reversible – dual voltage with thermal protector.

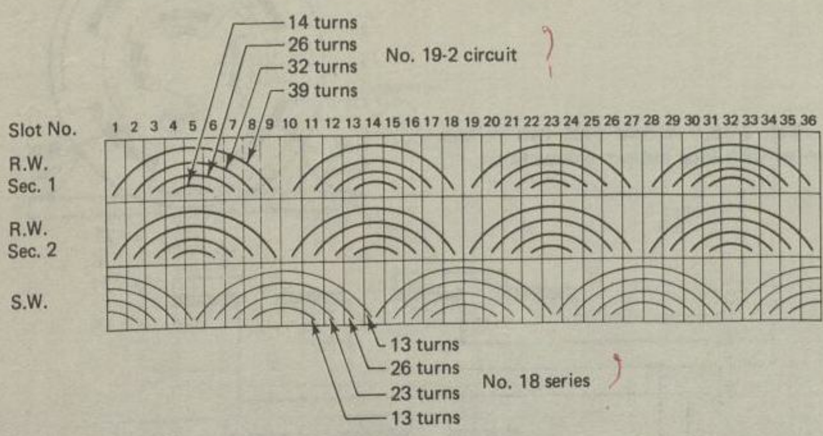


Fig. 2-33. The layout of coils for the two-voltage motor of **Fig. 2-31.** The running winding sections are similar.

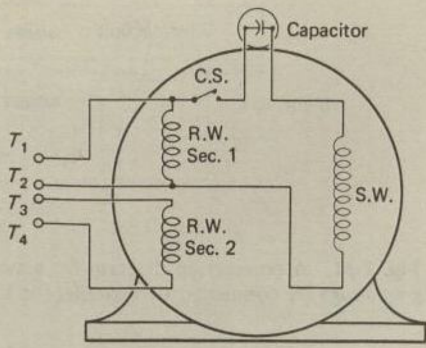


Fig. 2-34. A two-voltage motor having one running winding of two sections.

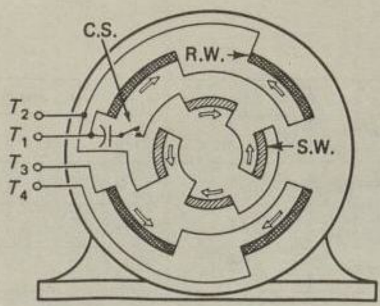


Fig. 2-35. A four-pole two-voltage motor diagram with short jumpers in the running winding.

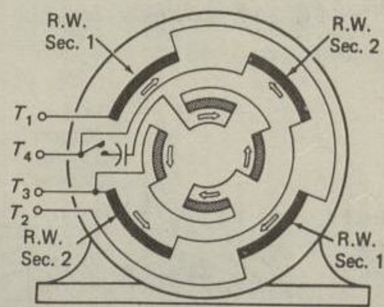


Fig. 2-36. A four-pole two-voltage motor with long jumper connections.

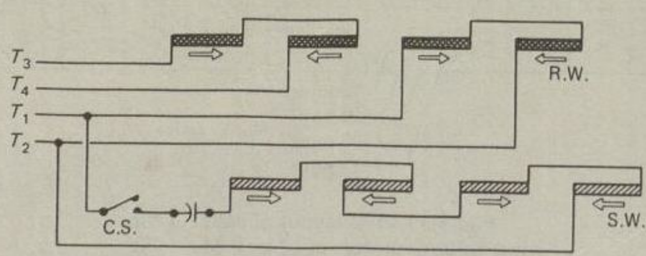


Fig. 2-37. A straight-line diagram of the motor of Fig. 2-35.

Figures 2-34; 2-35; 2-36; 2-37

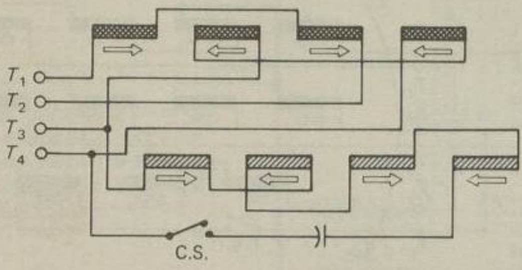


Fig. 2-38. A four-pole two-voltage motor with long jumpers.

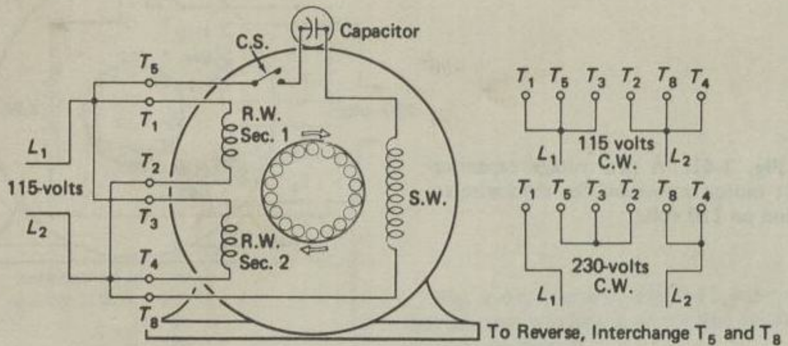


Fig. 2-39. A two-voltage capacitor- start motor connected for clockwise rotation on 115 volts.

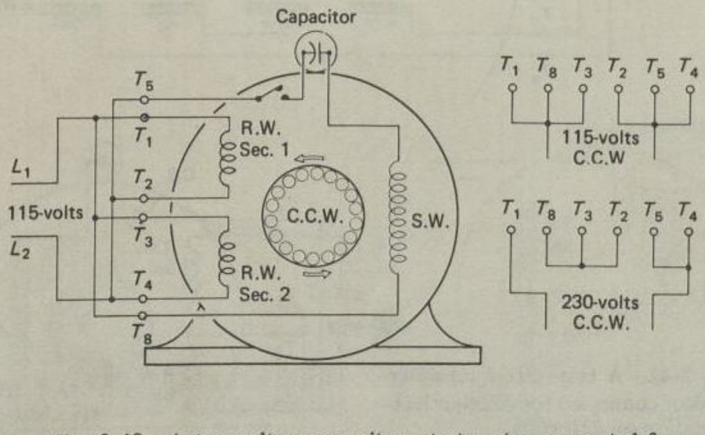
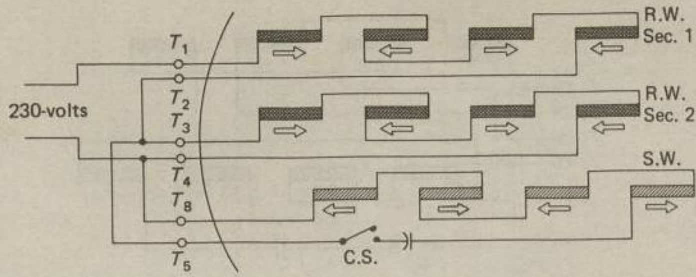


Fig. 2-40. A two-voltage capacitor- start motor connected for counterclock- wise rotation on 115 volts.



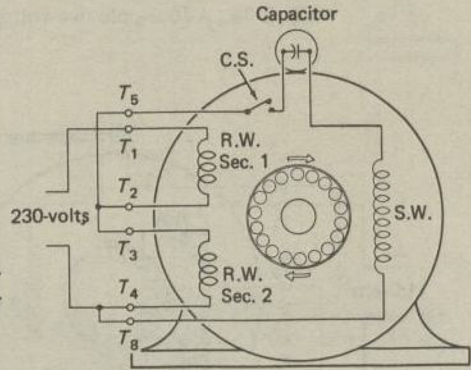
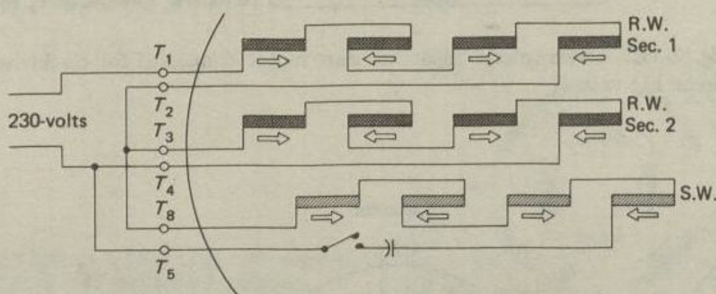


Fig. 2-41. A two-voltage capacitor-start motor connected for clockwise rotation on 230 volts.



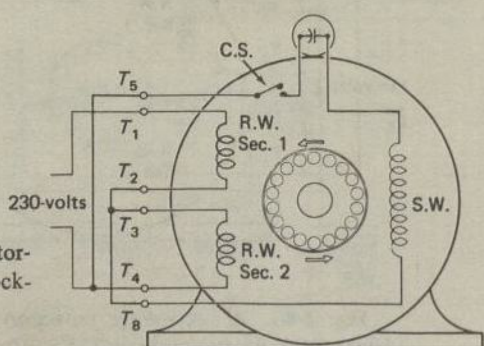


Fig. 2-42. A two-voltage capacitor-start motor connected for counterclockwise rotation on 230 volts.

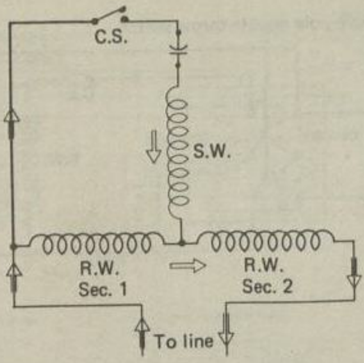


Fig. 2-43. A schematic diagram of a three-lead, reversible capacitor-start motor showing how current in starting winding flows when it is connected across running winding.

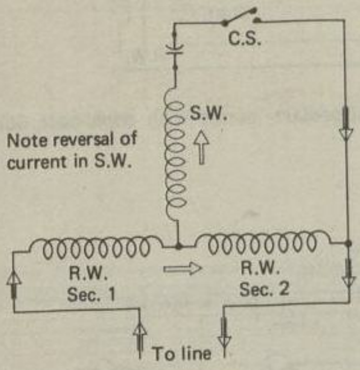


Fig. 2-44. Same as **Fig. 2-43,** except that starting winding is connected across running winding 2.

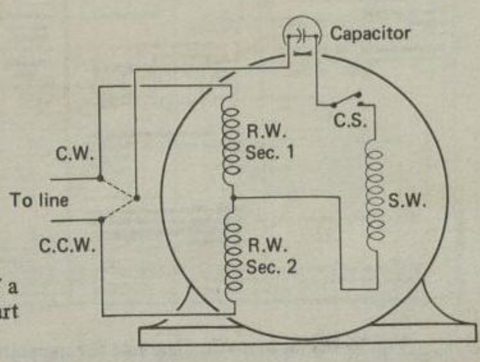


Fig. 2-45. A wiring diagram of a three-lead, reversible capacitor-start motor.

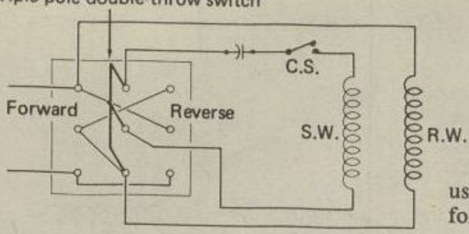


Fig. 2-46. A capacitor-start motor using a triple-pole, double-throw switch for reversing.

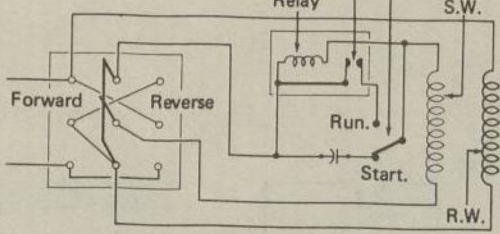
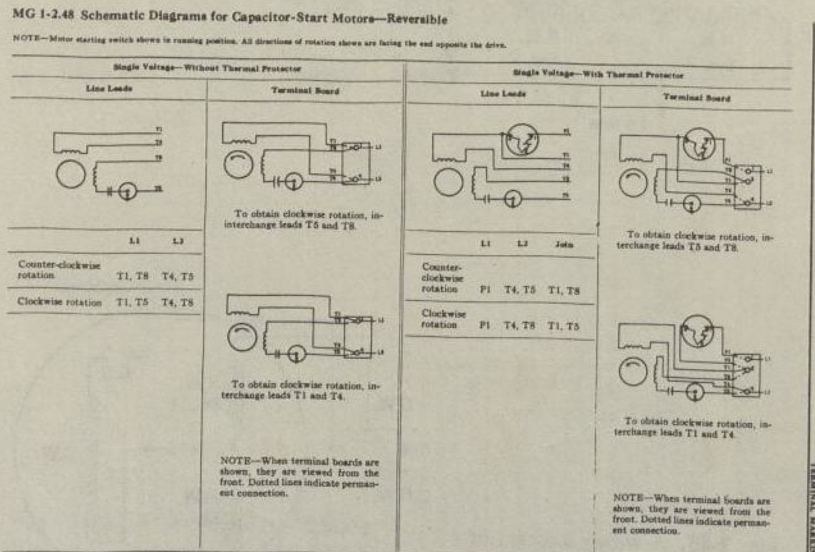


Fig. 2-47. An instantly reversible capacitor-start motor with triple-pole, double-throw switch for reversing.



MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

Single Voltage—Without Thermal Protector

Line Leads

	L1	L2
Counter-clockwise rotation	T1, T8	T4, T5
Clockwise rotation	T1, T5	T4, T8

Terminal Board

To obtain clockwise rotation, interchange leads T5 and T8.

To obtain clockwise rotation, interchange leads T1 and T4.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

Single Voltage—With Thermal Protector

Line Leads

	L1	L2	Join
Counter-clockwise rotation	P1	T4, T5	T1, T8
Clockwise rotation	P1	T4, T8	T1, T5

Terminal Board

To obtain clockwise rotation, interchange leads T5 and T8.

To obtain clockwise rotation, interchange leads T1 and T4.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

TERMINAL MARKINGS

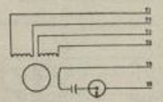
Fig. 2-48. Schematic diagrams for capacitor-start motors–reversible.

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—*(Continued)*

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

DOUBLE VOLTAGE—WITHOUT THERMAL PROTECTOR

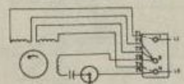
Line Leads



		L1	L2	Join
Higher name-plate voltage	Counter clockwise rotation	T1	T4, T5	T2, T3 and T8
	Clockwise rotation	T1	T4, T8	T2, T3 and T5
Lower name-plate voltage	Counter-clockwise rotation	T1, T3, T8	T2, T4, T5	
	Clockwise rotation	T1, T3, T5	T2, T4, T8	

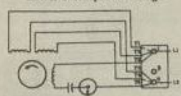
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage

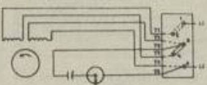


To obtain clockwise rotation, interchange leads T5 and T8

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

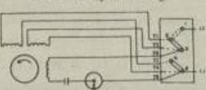
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

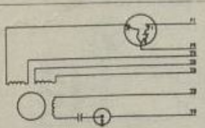
NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—*(Continued)*

NOTE I—The design proportions for dual-voltage, reversible, capacitor-start motors are such that three different groups of diagrams are necessary to show the means for obtaining adequate protection for these motors. These three groups of diagrams (I, II, and III) insert the thermal protector at different points in the circuit; therefore, different currents are provided to actuate the thermal protector.
NOTE II—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

GROUP I—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

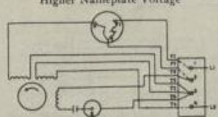
Line Leads



		L1	L2	Join	Join
Higher name-plate voltage	Counter-clockwise rotation	P1	T4	P2, T8	T2, T3 T5
	Clockwise rotation	P1	T4	P2, T5	T2, T3, T8
Lower name-plate voltage	Counter-clockwise rotation	P1	T2, T4, T5	P2, T3, T8	...
	Clockwise rotation	P1	T2, T4, T8	P2, T3, T5	...

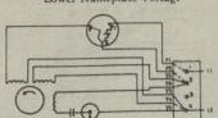
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage

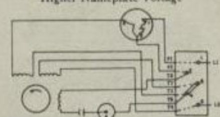


To obtain clockwise rotation, interchange leads T5 and T8.

NOTE III—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.
NOTE IV—Proper connection depends upon design of motor and thermal protector; refer to motor manufacturers' information for proper diagram.

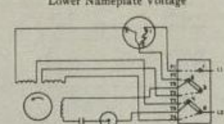
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

Fig. 2-48. Schematic diagrams for capacitor-start motors–reversible. *(continued)*

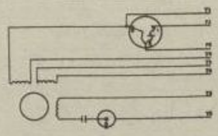
Figure 2-48

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—*(Continued)*

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

GROUP II—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

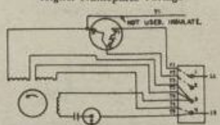
Line Leads



		L1	L2	Join	Join	Insulate Separately
Higher nameplate voltage	Counter-clockwise rotation	P1	T4, T5	T2, T3, T8	...	P2, T1
	Clockwise rotation	P1	T4, T8	T2, T3, T5	...	P2, T1
Lower nameplate voltage	Counter-clockwise rotation	P1	T2, T4, T5	P2, T3	T1, T8	...
	Clockwise rotation	P1	T2, T4, T8	P2, T3	T1, T5	...

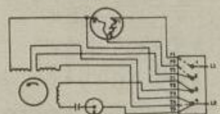
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage

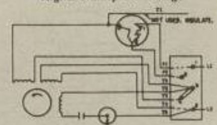


To obtain clockwise rotation, interchange leads T5 and T8.

NOTE I—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.
NOTE II—Proper connection depends upon design of motor and thermal protector; refer to motor manufacturers' information for proper diagram.

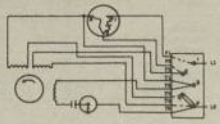
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

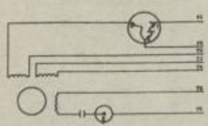
TERMINAL MARKINGS

MG 1-2.48 Schematic Diagrams for Capacitor-Start Motors—Reversible—*(Continued)*

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

GROUP III—DOUBLE VOLTAGE—WITH THERMAL PROTECTOR

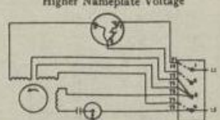
Line Leads



		L1	L2	Join	Insulate Separately
Higher nameplate voltage	Counter-clockwise rotation	P1	T4, T5	T2, T3, T8	P2
	Clockwise rotation	P1	T4, T8	T2, T3, T5	P2
Lower nameplate voltage	Counter-clockwise rotation	P1	T2, T4, T5	P2, T3, T8	...
	Clockwise rotation	P1	T2, T4, T8	P2, T3, T5	...

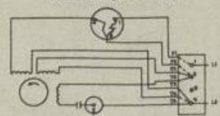
Terminal Board

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage

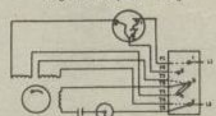


To obtain clockwise rotation, interchange leads T5 and T8.

NOTE I—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.
NOTE II—Proper connection depends upon design of motor and thermal protector; refer to motor manufacturers' information for proper diagram.

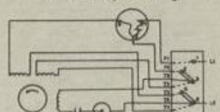
Terminal Board with Links

Higher Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

Lower Nameplate Voltage



To obtain clockwise rotation, interchange leads T5 and T8.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

NEMA Standard 11-16-1967.

TERMINAL MARKINGS

Fig. 2-48. Schematic diagrams for capacitor-start motors – reversible. *(continued)*

Figure 2-48

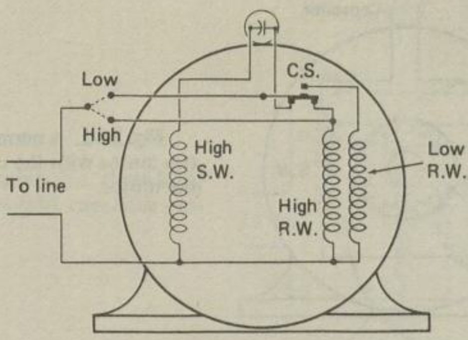


Fig. 2-49. A two-speed capacitor-start motor. This motor always starts on high speed.

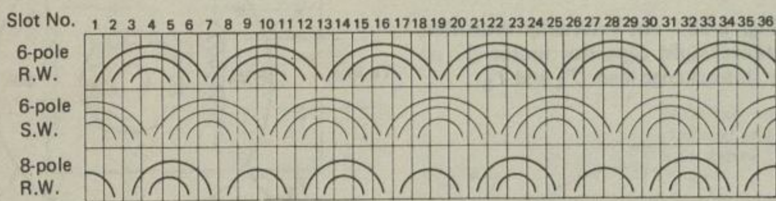


Fig. 2-50. A typical layout of coils in a two-speed capacitor-start motor.

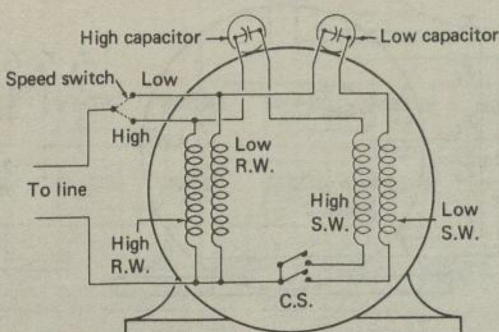


Fig. 2-51. A two-speed capacitor-start motor using two capacitors.

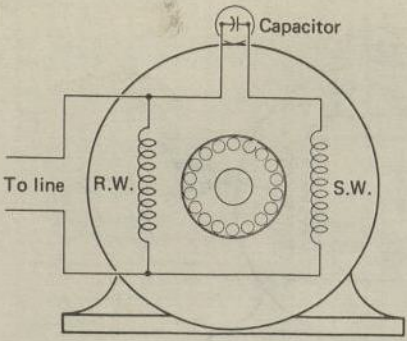
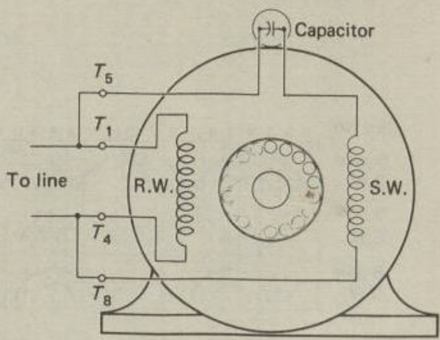


Fig. 2-52. A permanent-split capacitor-run motor with the capacitor mounted on the motor.

Fig. 2-53. An externally reversible, permanent-split capacitor motor. To reverse, interchange leads T_5 and T_8.



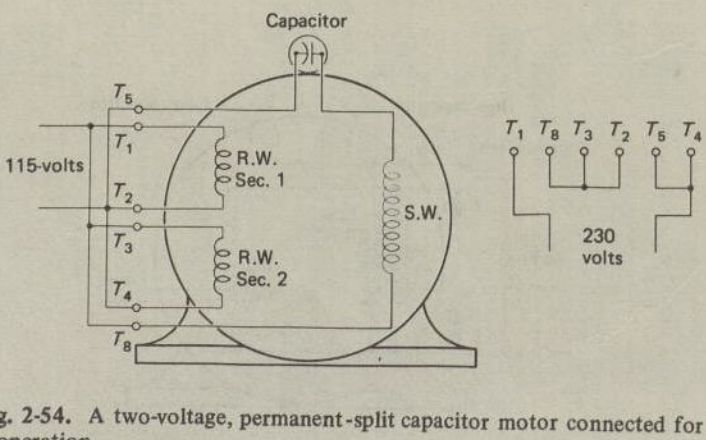


Fig. 2-54. A two-voltage, permanent-split capacitor motor connected for 115 volt operation.

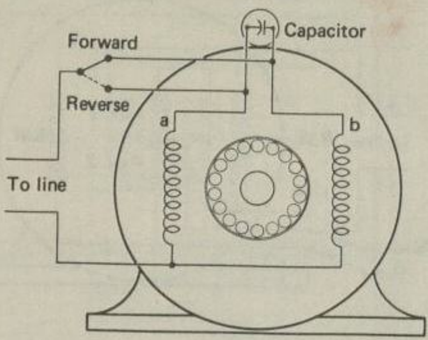


Fig. 2-55. A single-value, three-lead, reversible permanent-split capacitor motor.

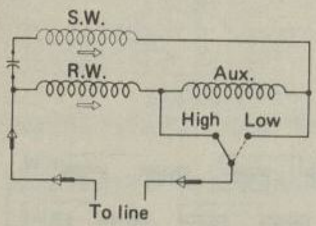


Fig. 2-56. A schematic diagram of a two-speed permanent-split capacitor motor with switch in high-speed position.

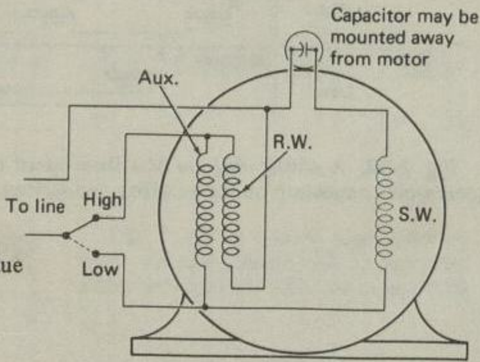


Fig. 2-57. A two-speed, single-value capacitor-run motor.

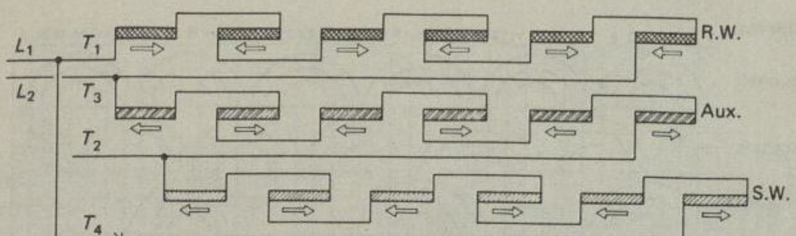


Fig. 2-58. A two-speed, six-pole, single-value capacitor-run motor connected for high-speed operation. For high speed: line L_1 connects to T_1 and T_4; line L_2 connects to T_3. For low speed: line L_1 connects to T_1 and T_4; line L_2 connects to T_2.

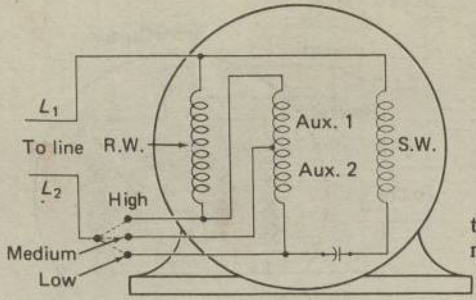


Fig. 2-59. A schematic diagram of a three-speed, single-voltage capacitor-run motor.

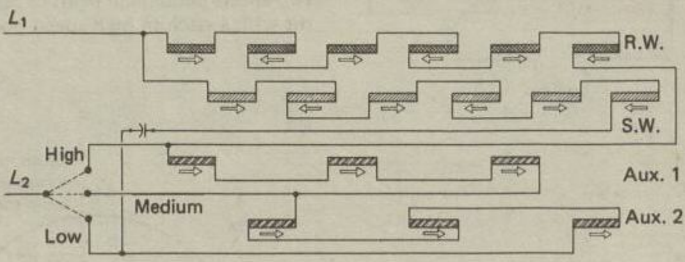


Fig. 2-60. A wiring diagram of a three-speed capacitor-run motor. Note the consequent-pole connection on the auxiliary connection.

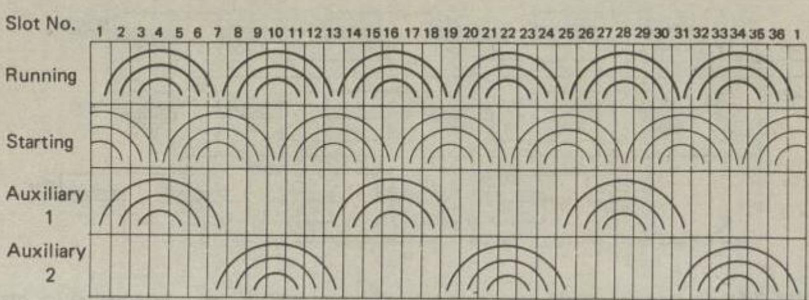


Fig. 2-61. A typical layout of a three-speed capacitor-run motor.

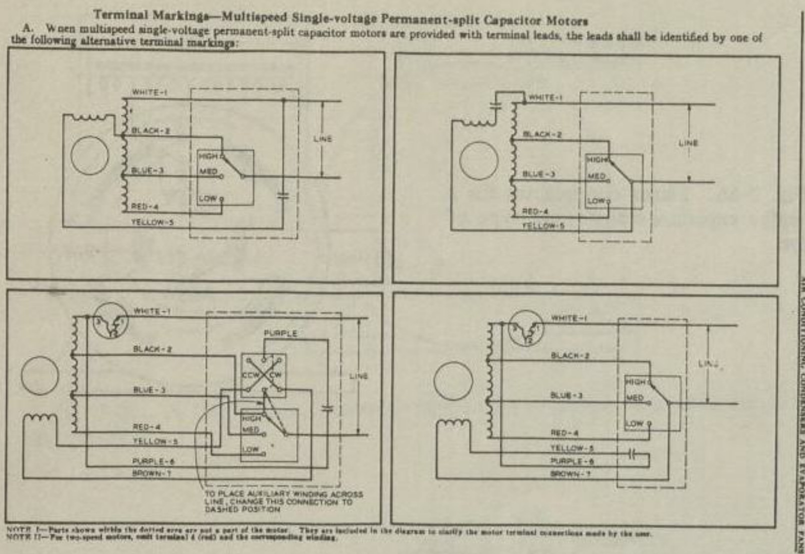
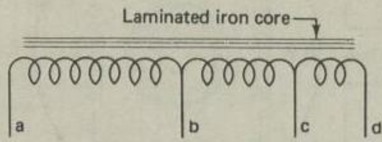


Fig. 2-62. Terminal markings–multispeed single-voltage permanent-split capacitor motors.

Fig. 2-63. An autotransformer consisting of a coil of wire wound on a laminated core. The coil is tapped at several points to obtain different voltages.



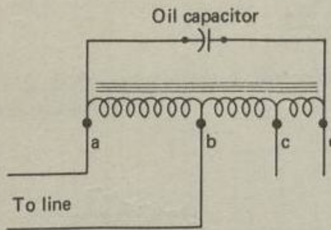
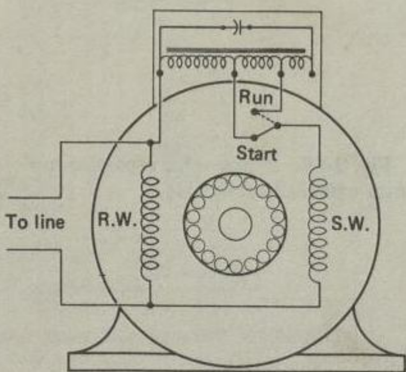


Fig. 2-64. A voltage approximately twice the line voltage will be produced across the capacitor with this connection.

Fig. 2-65. A two-value capacitor-run motor using a capacitor transformer to change the effective capacitor value.



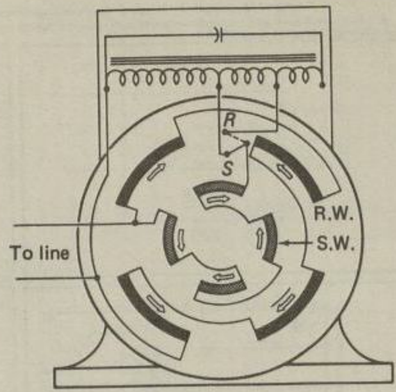


Fig. 2-66. Stator connections for a two-value capacitor-transformer type of motor.

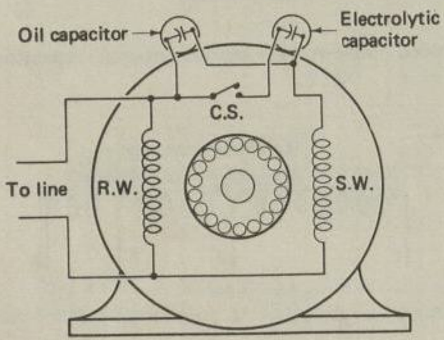


Fig. 2-67. A two-value capacitor-run motor using two capacitors.

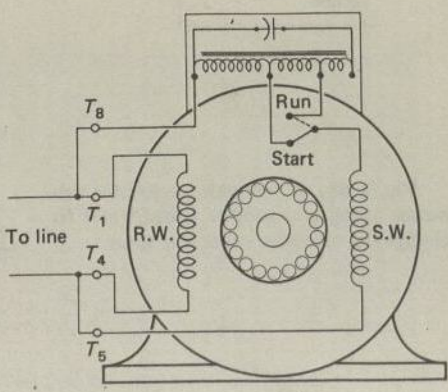


Fig. 2-68. A two-value capacitor-run motor externally reversible.

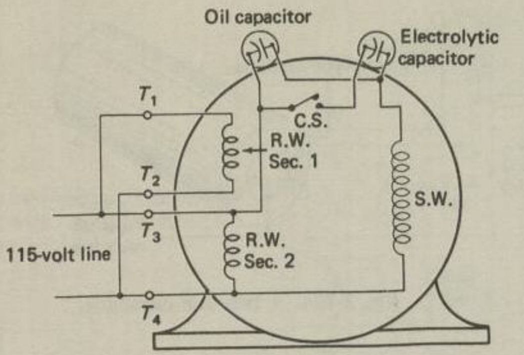


Fig. 2-69. A two-voltage, two-value capacitor-run motor connected for 115-volt operation.

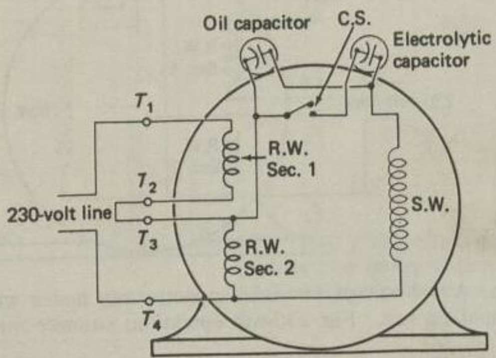


Fig. 2-70. Connections of two-voltage, two-value capacitor-run motor for 230-volt operation.

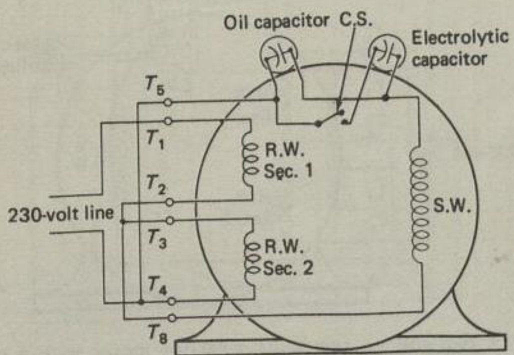


Fig. 2-71. Two-voltage, two-value, reversible capacitor-run motor.

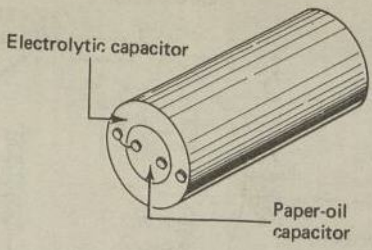


Fig. 2-72a. A two-unit capacitor.

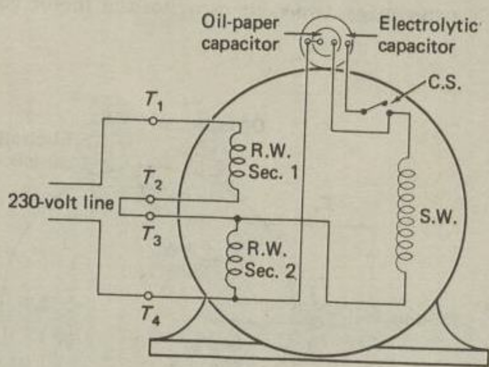


Fig. 2-72b. A two-voltage, two-value capacitor-run motor with a two-unit capacitor mounted on top. For 230-volt operation, connect running windings in series.

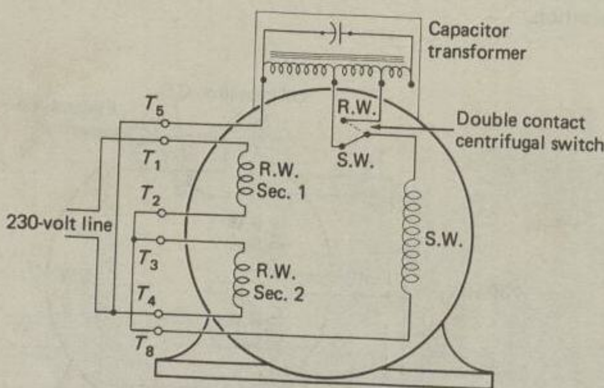


Fig. 2-73. A two-voltage, two-value capacitor motor with a capacitor transformer mounted on the motor. For 230 volts, connect running windings in series externally.

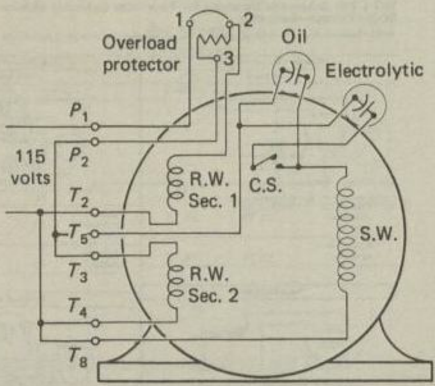


Fig. 2-74. A two-voltage, two-value capacitor motor with overload device. Lower voltage connection.

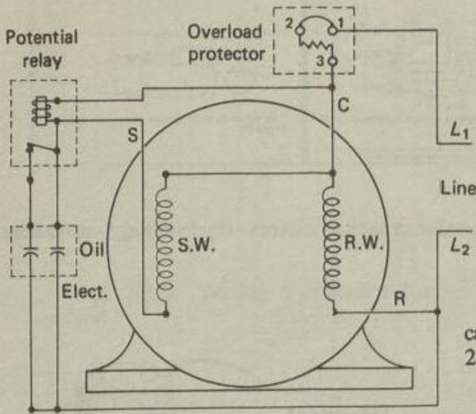


Fig. 2-75. Single-voltage, two-value capacitor motor with potential relay and 2 terminal overload protector.

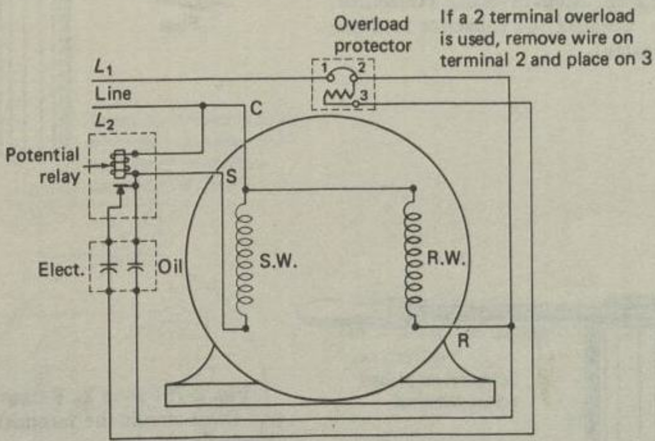
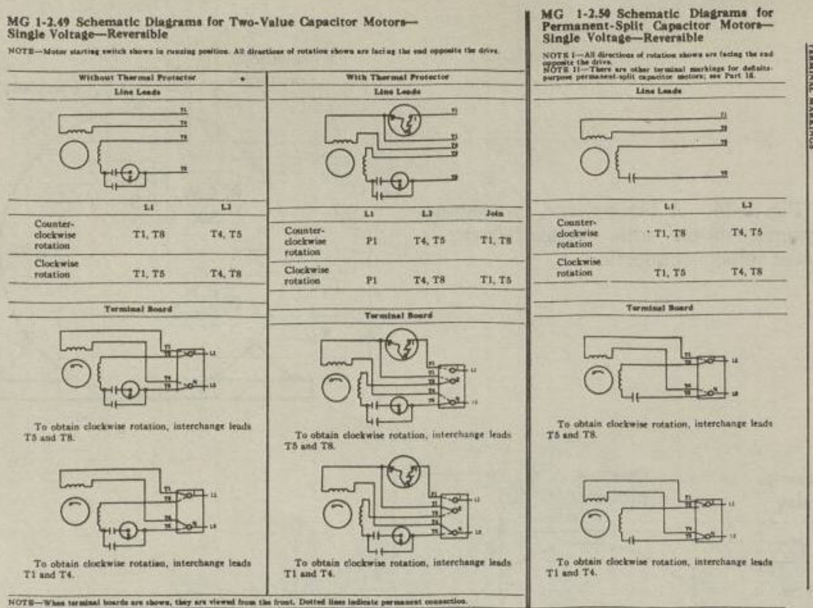


Fig. 2-76. Single-voltage, two-value capacitor motor with potential relay and 3 terminal overload protector.



MG 1-2.49 Schematic Diagrams for Two-Value Capacitor Motors—Single Voltage—Reversible

NOTE—Motor starting switch shown in running position. All directions of rotation shown are facing the end opposite the drive.

Without Thermal Protector — Line Leads

	L1	L2
Counter-clockwise rotation	T1, T8	T4, T5
Clockwise rotation	T1, T5	T4, T8

Terminal Board

To obtain clockwise rotation, interchange leads T5 and T8.

To obtain clockwise rotation, interchange leads T1 and T4.

With Thermal Protector — Line Leads

	L1	L2	Join
Counter-clockwise rotation	P1	T4, T5	T1, T8
Clockwise rotation	P1	T4, T8	T1, T5

Terminal Board

To obtain clockwise rotation, interchange leads T5 and T8.

To obtain clockwise rotation, interchange leads T1 and T4.

NOTE—When terminal boards are shown, they are viewed from the front. Dotted lines indicate permanent connection.

MG 1-2.50 Schematic Diagrams for Permanent-Split Capacitor Motors—Single Voltage—Reversible

NOTE I—All directions of rotation shown are facing the end opposite the drive.
NOTE II—There are other terminal markings for definite-purpose permanent-split capacitor motors; see Part 18.

Line Leads

	L1	L2
Counter-clockwise rotation	T1, T8	T4, T5
Clockwise rotation	T1, T5	T4, T8

Terminal Board

To obtain clockwise rotation, interchange leads T5 and T8.

To obtain clockwise rotation, interchange leads T1 and T4.

TERMINAL MARKINGS

Fig. 2-77. Schematic diagrams for two-value capacitor motors—single-voltage—reversible.

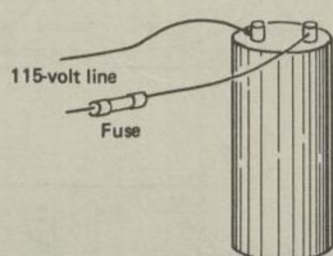


Fig. 2-78. Steps in testing a capacitor: Step 1. Connect the capacitor to a line for an instant.

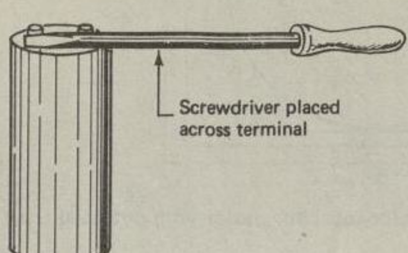


Fig. 2-79. Step 2. Remove line wires and short-circuit the terminals. A spark should be visible.

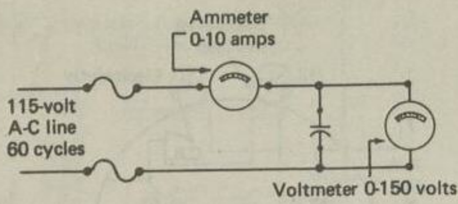


Fig. 2-80. A circuit for capacity test.

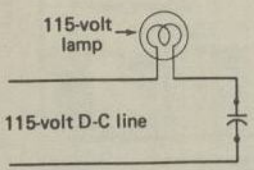


Fig. 2-81. Testing a capacitor for short circuit: If the lamp lights, the capacitor is shorted. Note the use of direct current.

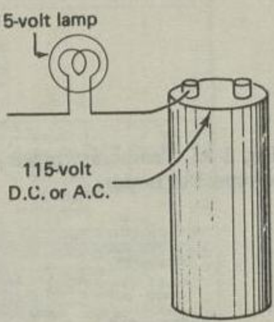


Fig. 2-82. Testing a capacitor for ground.

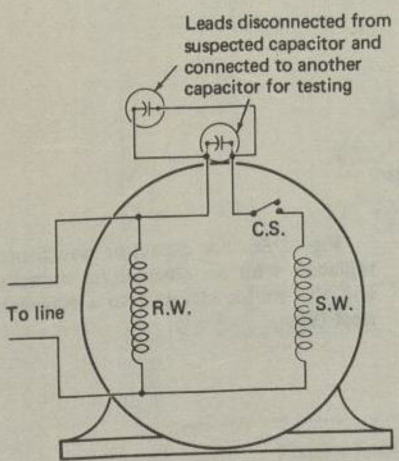


Fig. 2-83. Testing a capacitor motor for a defective capacitor by the substitution method.

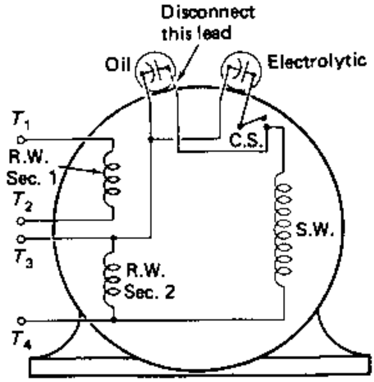


Fig. 2-84. Changing a two-value motor into a capacitor-start motor. This can also be done if the two capacitors are in one container.

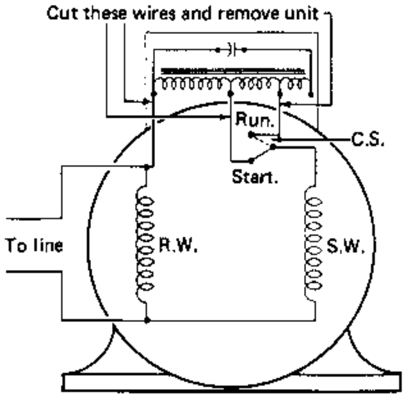


Fig. 2-85. Temporary repair of a two-value capacitor motor.

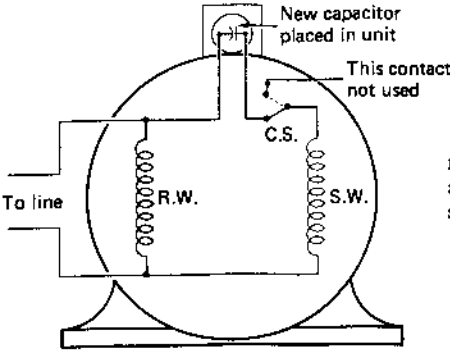
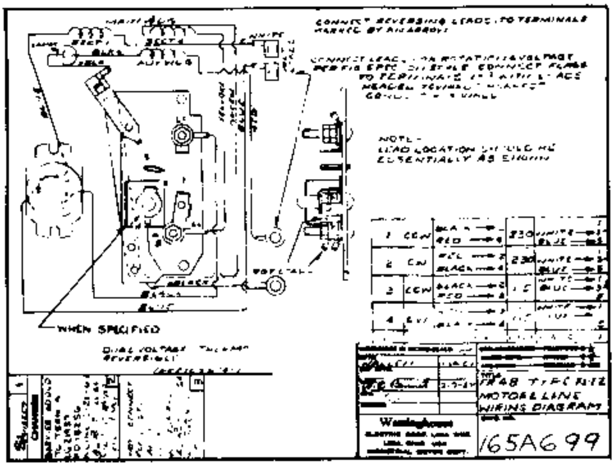
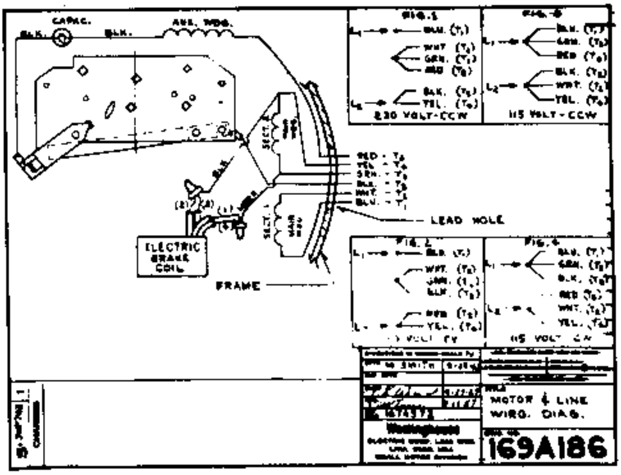


Fig. 2-86. A capacitor transformer replaced with an electrolytic capacitor and the motor changed to a capacitor-start type.





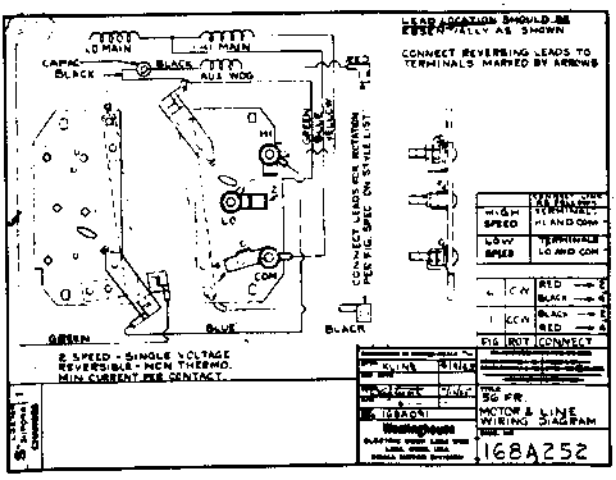
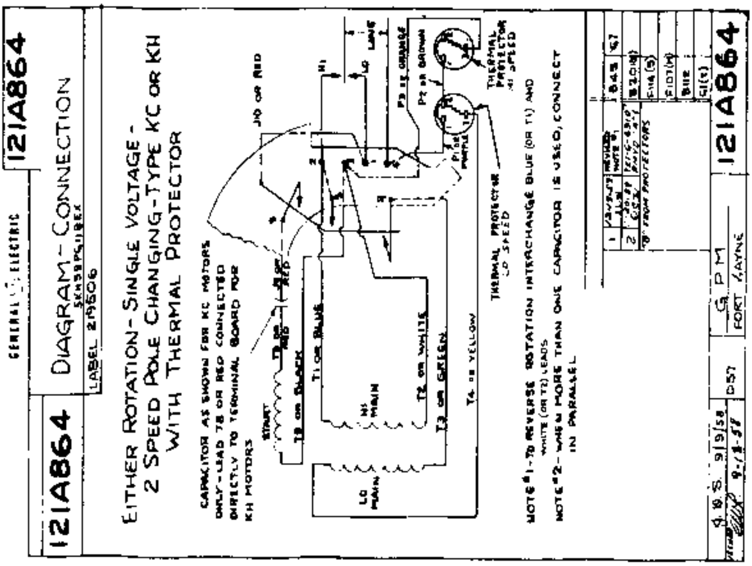
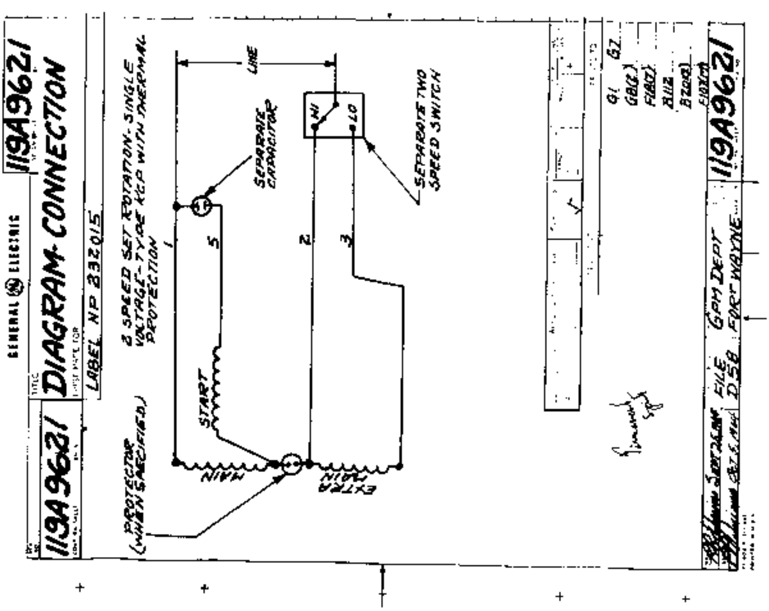


Fig. 2-87. Miscellaneous diagrams.

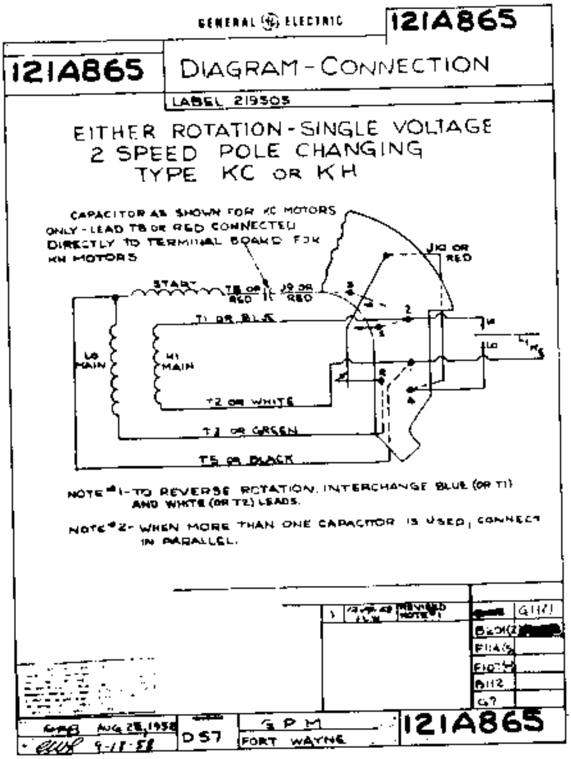
Figure 2-87

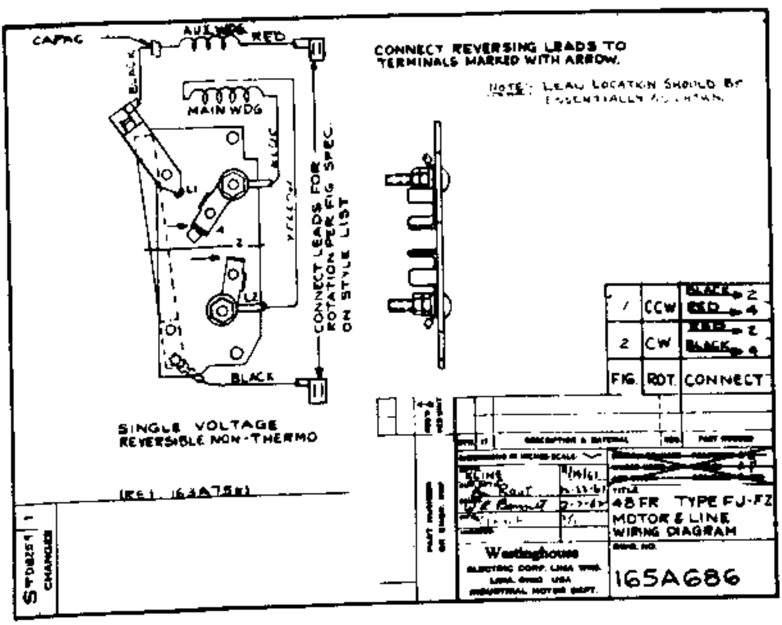




Miscellaneous diagrams

Figures 2-87





Miscellaneous diagrams

CHAPTER 3

Repulsion-type Motors

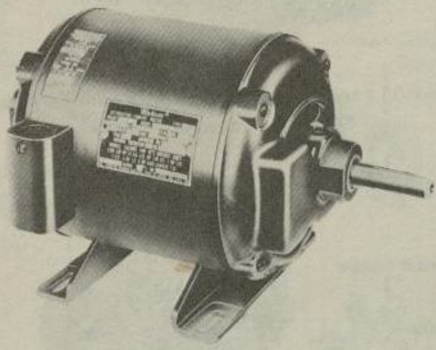


Fig. 3-1. A repulsion-start induction motor. (*Wagner Electric Co.*)

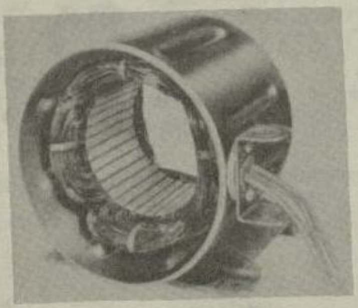


Fig. 3-2. Stator and winding of a repulsion-start, induction motor. (*Wagner Electric Co.*)

Fig. 3-3. The rotor of a repulsion induction motor. The axial commutator has bars parallel to the shaft.

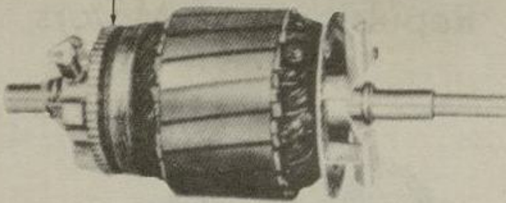


Fig. 3-4. A rotor having a radial commutator with bars perpendicular to the shaft. *(Wagner Electric Company)*

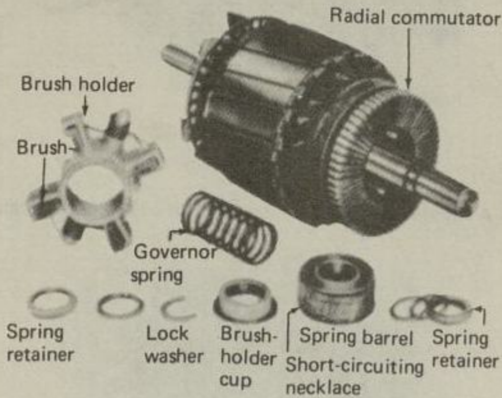


Fig. 3-5. A partly dismantled rotor and parts of the centrifugal mechanism. *(Wagner Electric Company)*

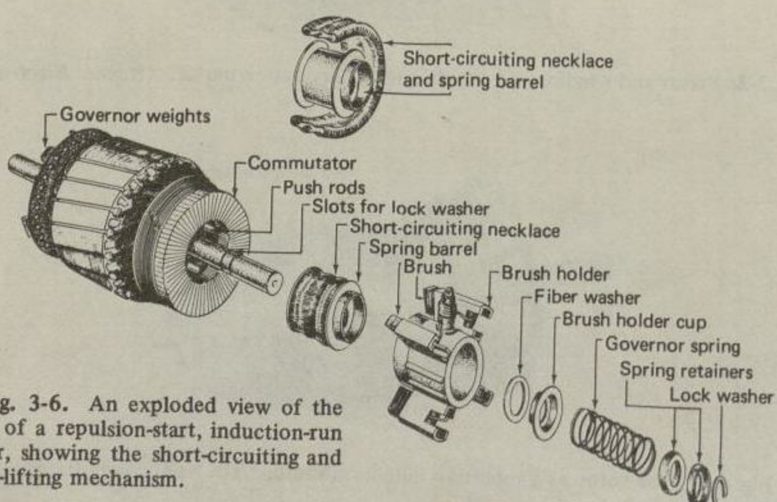


Fig. 3-6. An exploded view of the rotor of a repulsion-start, induction-run motor, showing the short-circuiting and brush-lifting mechanism.

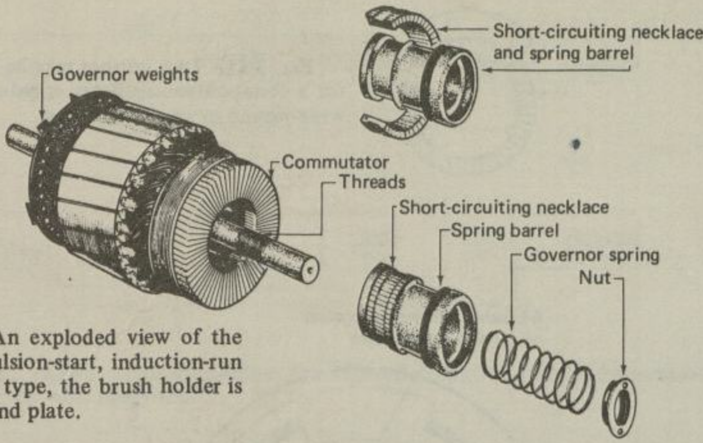


Fig. 3-7. An exploded view of the rotor of a repulsion-start, induction-run motor. In this type, the brush holder is located in the end plate.

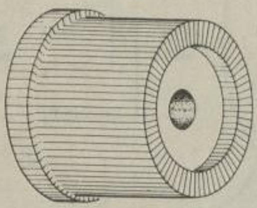


Fig. 3-8. A commutator for a brush-riding, repulsion-start, induction-run motor.

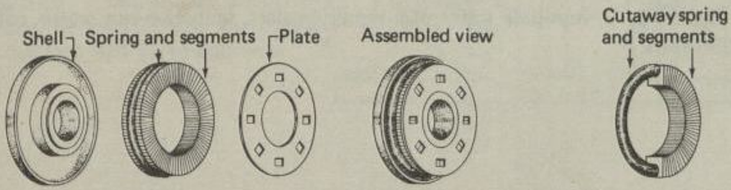
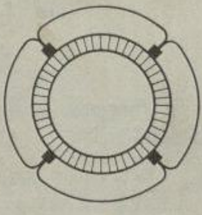


Fig. 3-9. The assembly of the short-circuiting device of a brush-riding, repulsion-start, induction-run motor.

Fig. 3-10. Four brushes are used on this four-pole motor. All brushes are connected together by a one-piece metal brush holder rigging and the pigtails on the brushes.



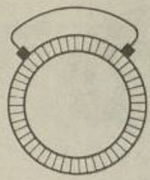


Fig. 3-11. Two brushes may be used for a four-pole motor if the armature is wave-wound or cross-connected.

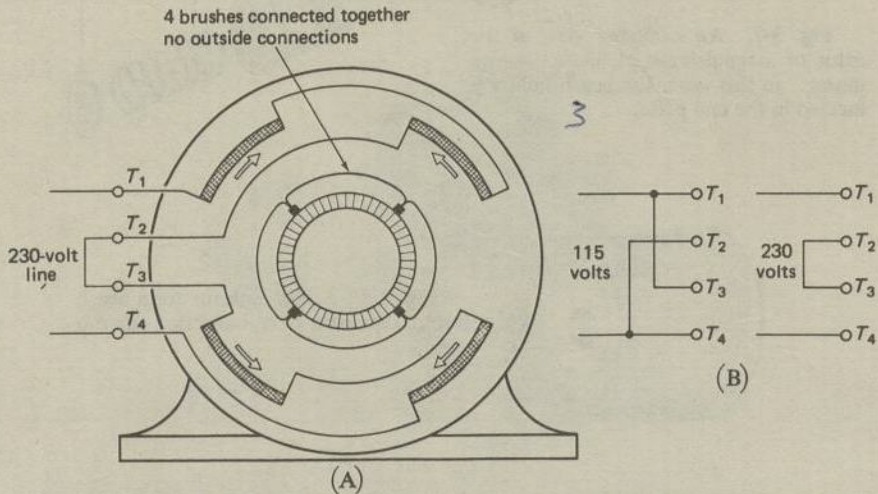


Fig. 3-12. A four-pole stator of a repulsion-start, induction-run motor, connected for 230 volts.

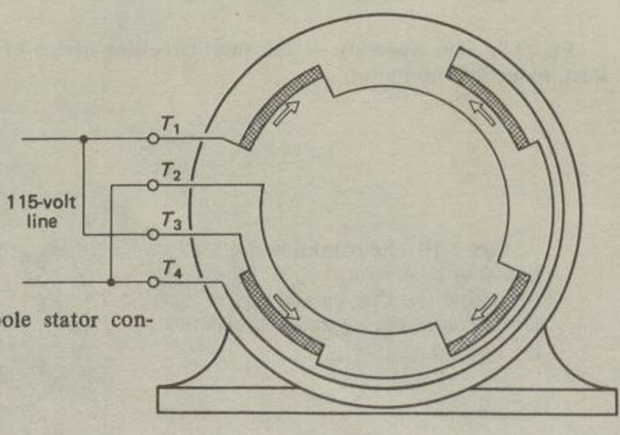


Fig. 3-13. A four-pole stator connected for 115 volts.

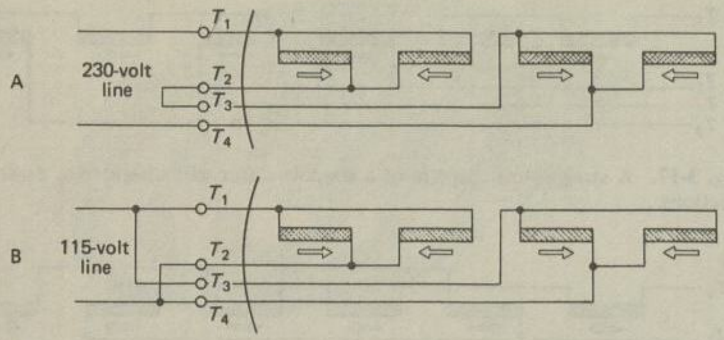


Fig. 3-14-A. A two-circuit connection for 230-volt operation. **B.** A four-circuit connection for 115-volt operation.

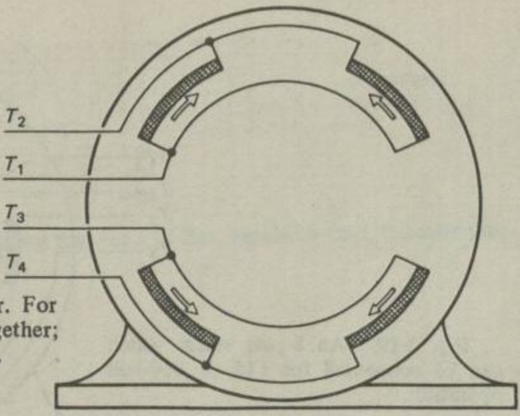


Fig. 3-15. A two-voltage motor. For 230 volts: connect T_2 and T_3 together; T_1 to line lead, and T_4 to line lead.

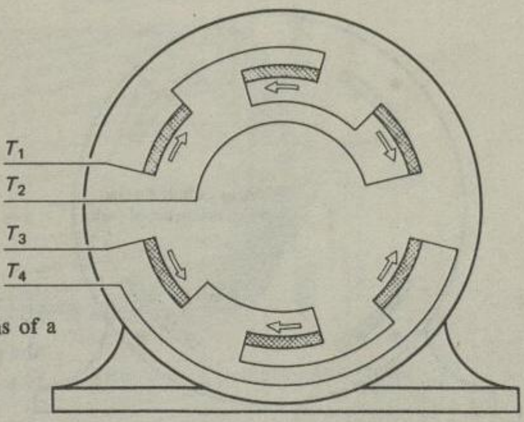


Fig. 3-16. Internal connections of a 6-pole repulsion motor stator.

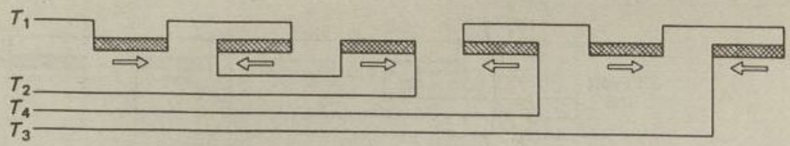


Fig. 3-17. A straight-line diagram of a six-pole stator with alternate or short jumper connections.

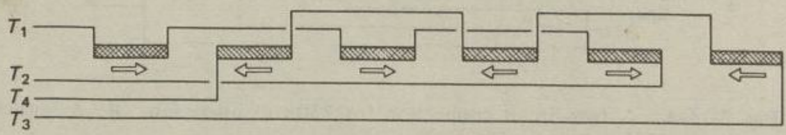


Fig. 3-18. Same as **Fig. 3-17**, except that the skip-group or long jumper connection is used.

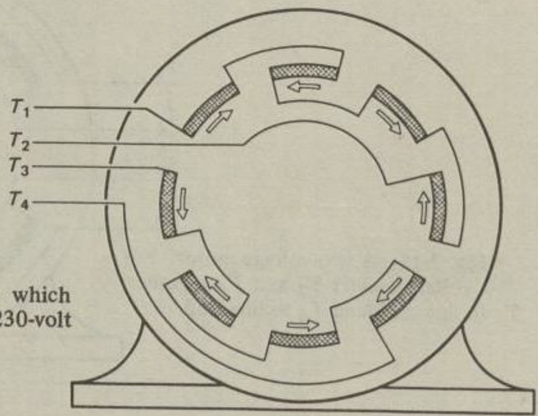


Fig. 3-19. An 8-pole stator which can be connected for 115 or 230-volt operation.

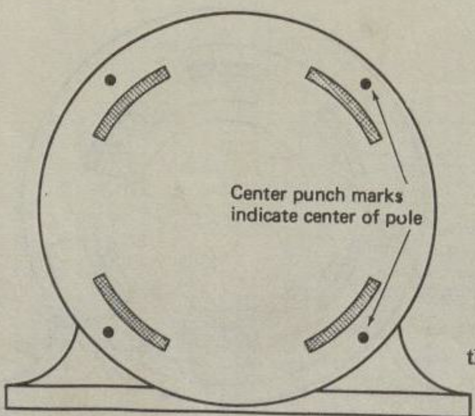


Fig. 3-20. Recording the position of the poles in a repulsion motor.

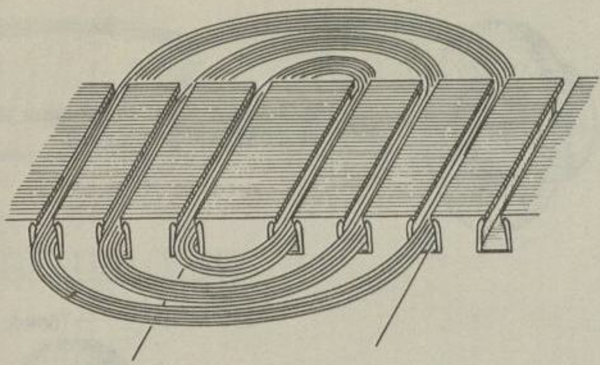


Fig. 3-21. The core section at the center of the pole. It is wider than other sections.

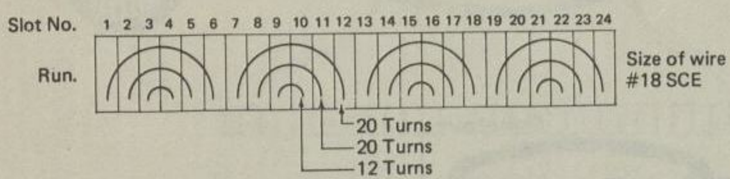


Fig. 3-22. The method of recording data for a 24-slot, repulsion-start, induction-run motor.

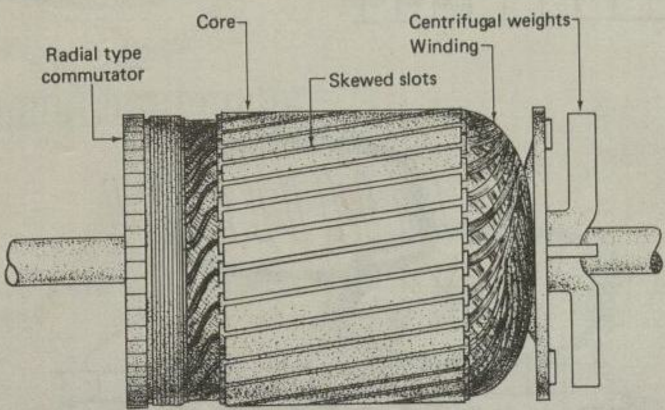


Fig. 3-23. The armature of a repulsion-start, induction-run motor.

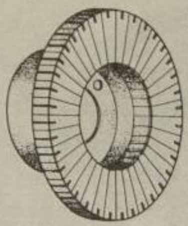
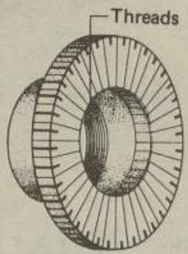


Fig. 3-24. A radial commutator that is pressed on the armature shaft.

Fig. 3-25. A radial commutator that screws onto the armature shaft.



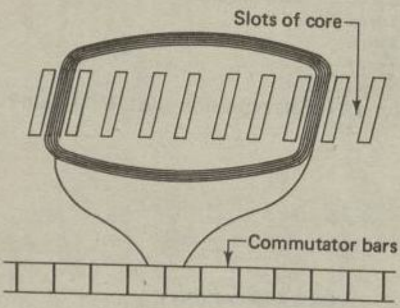


Fig. 3-26. A lap winding with one coil per slot.

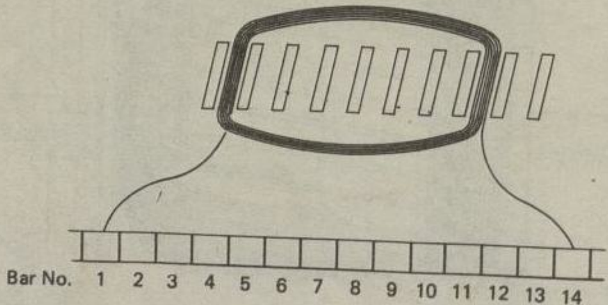


Fig. 3-27. A wave winding with one coil per slot.

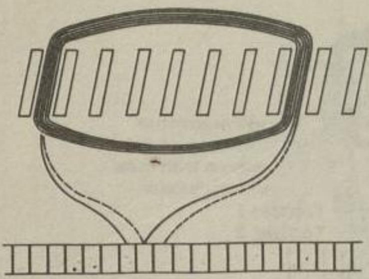
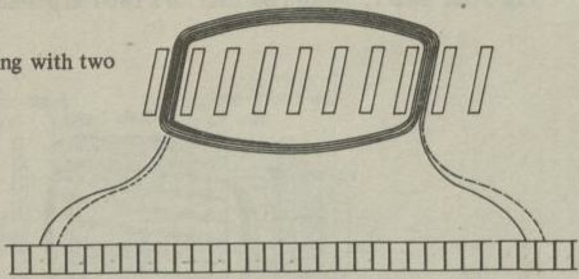


Fig. 3-28. A lap winding with two coils per slot.

Fig. 3-29. A wave winding with two coils per slot.



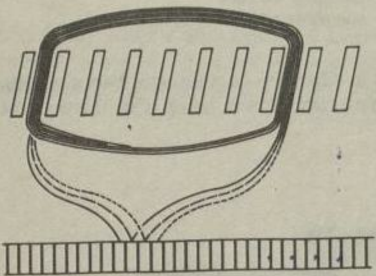
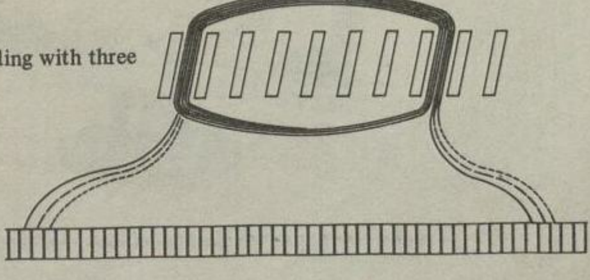


Fig. 3-30. A lap winding with three coils per slot.

Fig. 3-31. A wave winding with three coils per slot.



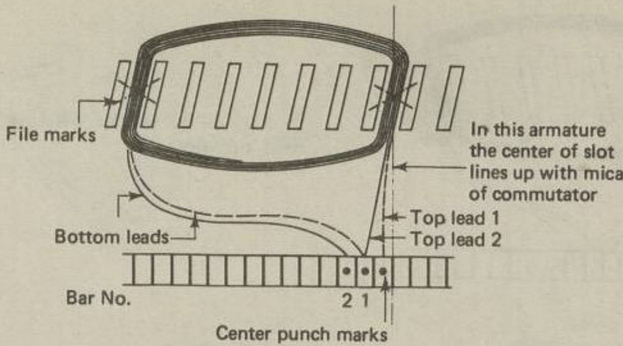


Fig. 3-32. Step 1. Record the data for a two-coil per-slot repulsion armature.

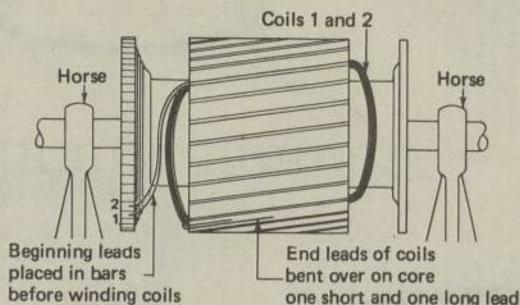


Fig. 3-33A. Step 2. Place beginning leads in adjoining commutator bars according to data and wind the proper number of turns, using two wires in hand. Cut the wires at the last turn and bend them over the core.

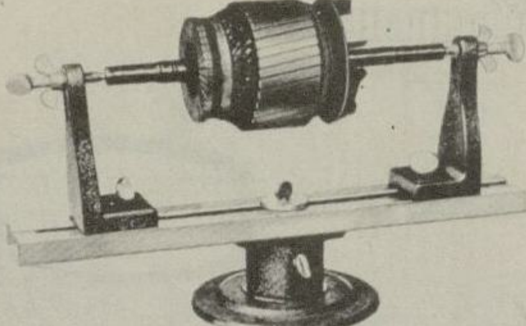


Fig. 3-33B. Armature Holder. (*Crown Industrial Products*)

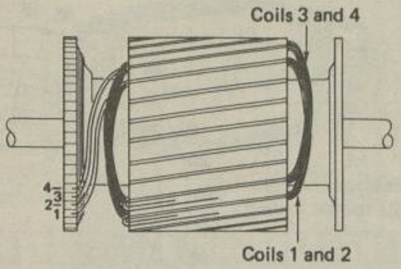


Fig. 3-34. Step 3. Place the beginnings of coils *3* and *4* in bars *3* and *4* and start winding the coils, beginning one slot away from the first coils and using the same pitch as before.

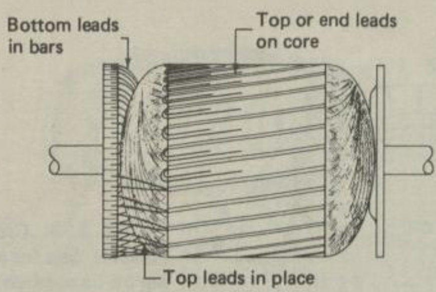


Fig. 3-35. Step 4. Place the top leads in the commutator bars after the armature is completely wound. For a lap winding, the top leads are placed in bars adjacent to the bottom leads of the same coil.

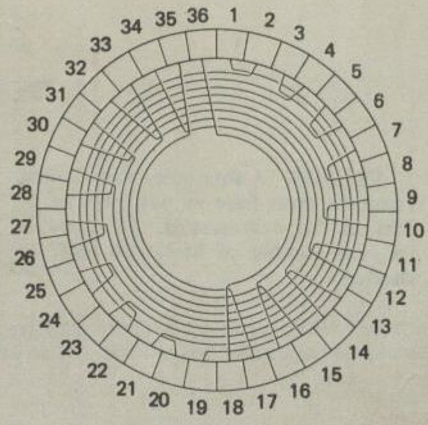


Fig. 3-36. Cross connections of commutator bars for a four-pole motor having 36 bars, pitch 1 and 19.

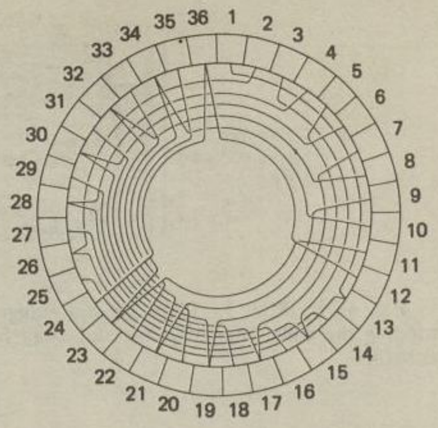


Fig. 3-37. Cross connections of commutator bars for a six-pole motor having 36 bars, pitch 1 and 13.

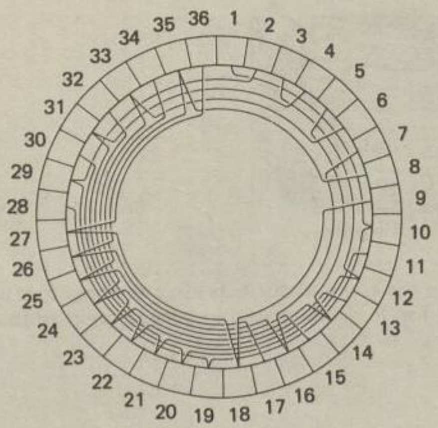


Fig. 3-38. Cross connections of commutator bars for an eight-pole motor having 36 bars, pitch 1 and 10.

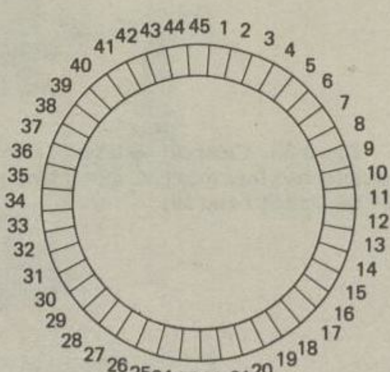


Fig. 3-39. A four-pole, wave-wound armature must have an odd number of bars in the commutator. If there is an even number of bars, two must be shorted.

Figures 3-37; 3-38; 3-39

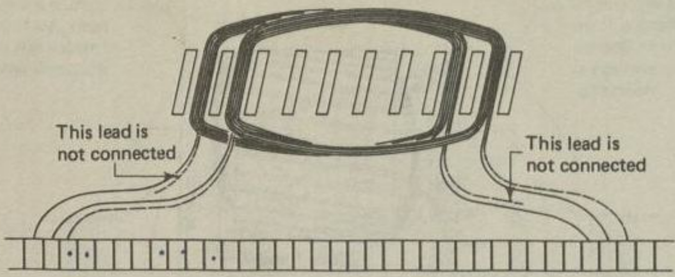


Fig. 3-40. A wave connection showing dead coil. This coil must remain unconnected when there are more coils than bars.

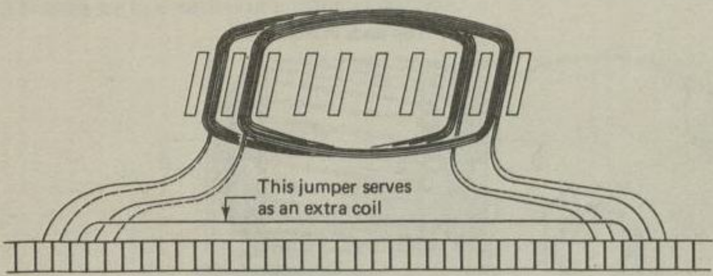


Fig. 3-41. The method of placing a jumper between two bars to take the place of a coil. This is used when there is an even number of coils and one bar more than the number of coils.

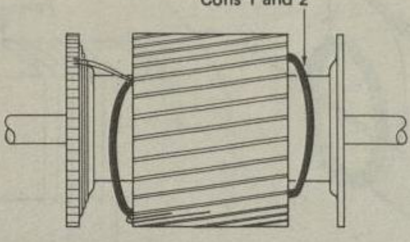


Fig. 3-42. The first two coils of a wave-wound armature in place. Note that this armature is wound exactly as a lap armature, except that the beginning leads are placed away from the center of the coil.

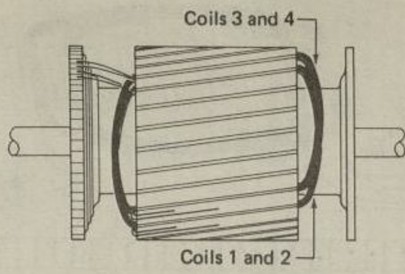


Fig. 3-43. The next two coils placed in the slots exactly as the first two coils, except that they are started in the next slot. The end leads are cut off and left on the core.

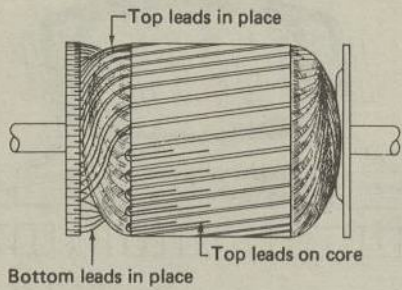


Fig. 3-44. How the top leads are placed in bars for a wave winding.

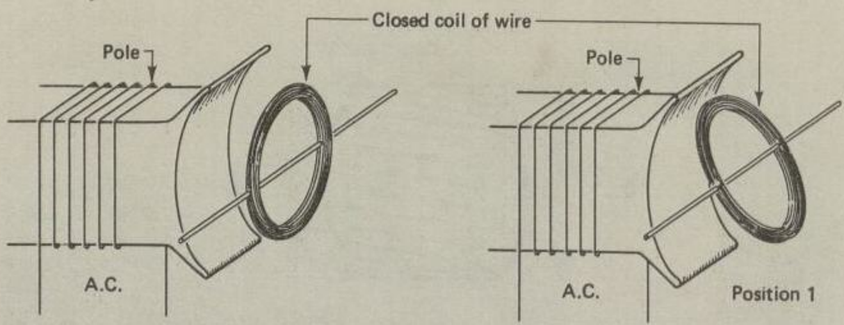


Fig. 3-45. If the coil is in a vertical plane, it will not move. If the coil is tilted off the vertical, it will tend to move.

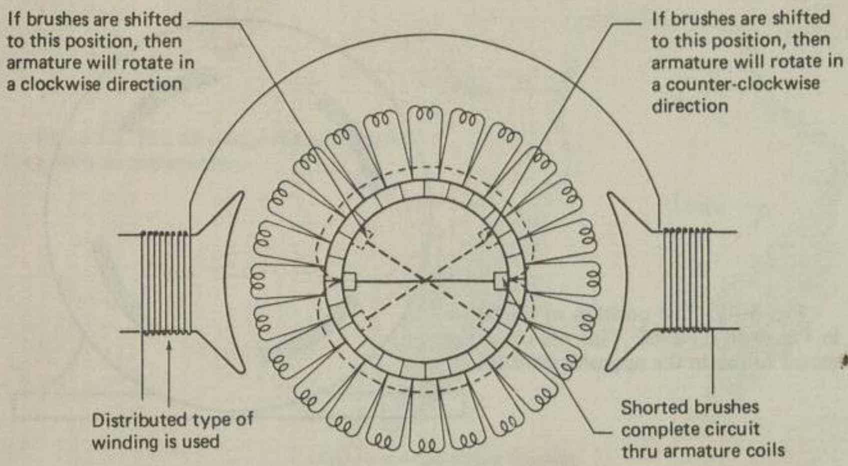


Fig. 3-46. Two closed circuits in an armature similar to two coils. No motion takes place if brushes are in a vertical or horizontal position.

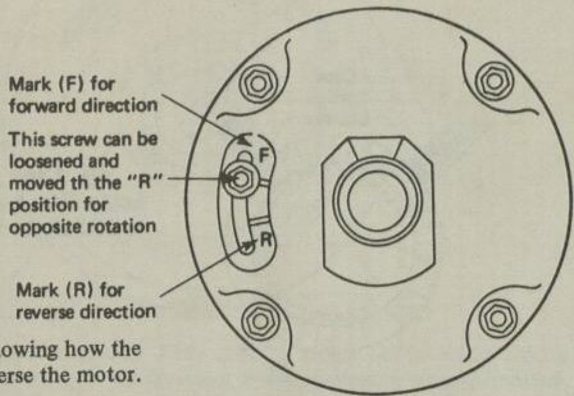


Fig. 3-47. An end plate showing how the brush holder is moved to reverse the motor.

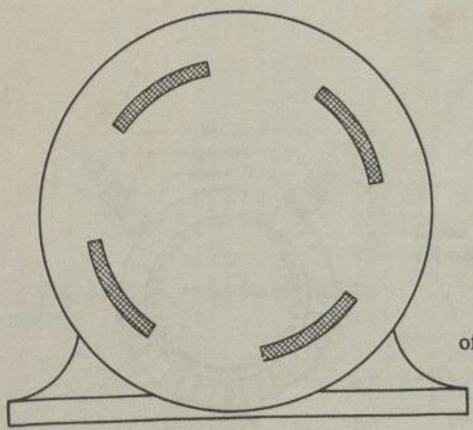


Fig. 3-48. A frame with field poles off center.

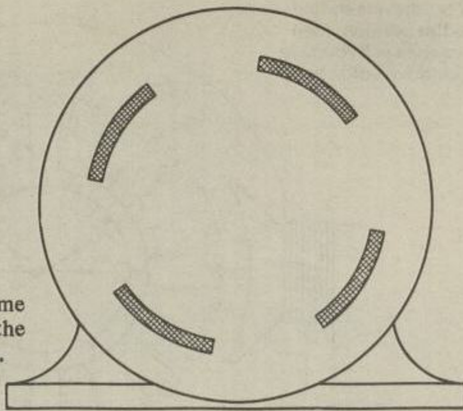


Fig. 3-49. The position of the frame in **Fig. 3-48** reversed. This will cause the motor to run in the opposite direction.

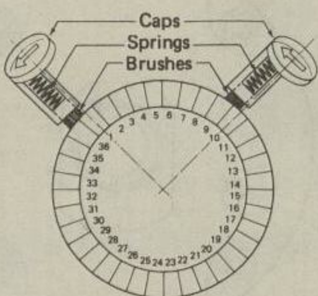


Fig. 3-50. A cartridge type of brush holder with both brushes in position for counterclockwise rotation.

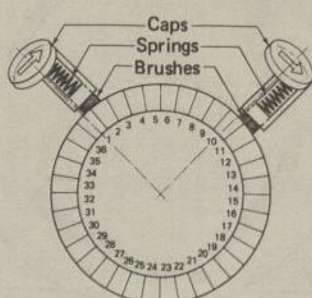


Fig. 3-51. A cartridge type of brush holder with both brushes in position for clockwise rotation.

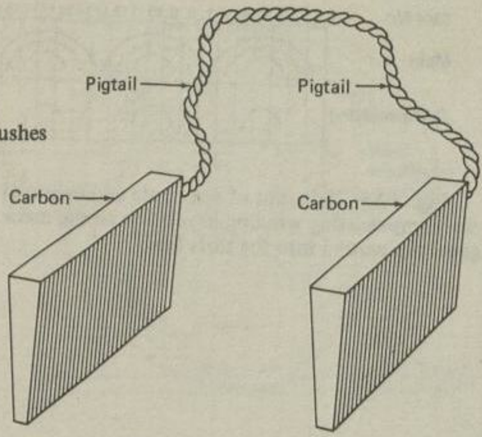


Fig. 3-52. Pair of wedge shaped brushes for a vertical commutator.

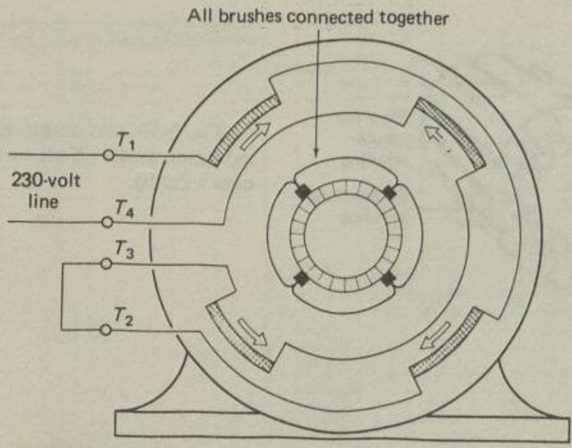


Fig. 3-53. A four-pole repulsion motor. Note that the motor can be connected for two voltages. Four brushes are used. If the armature is wave-wound or cross-connected, two adjacent brushes may be used.

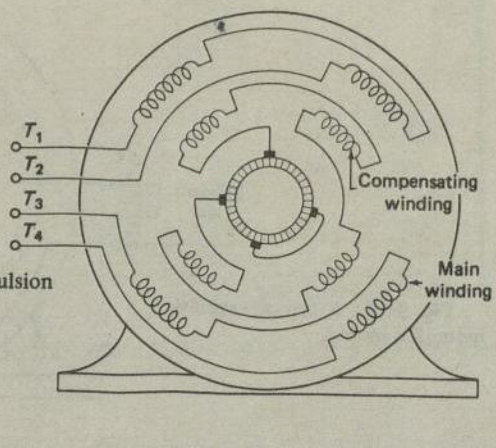


Fig. 3-54. A compensated repulsion motor.

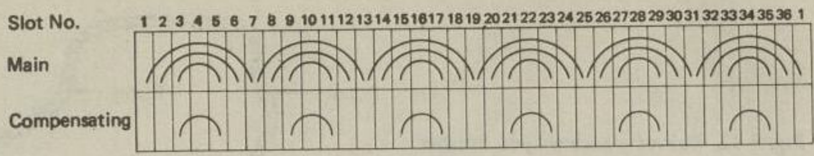


Fig. 3-55. A layout of a six-pole compensated repulsion motor. Note the location of the compensating winding in relation to the main winding. The compensating winding is generally wound into the slots first.

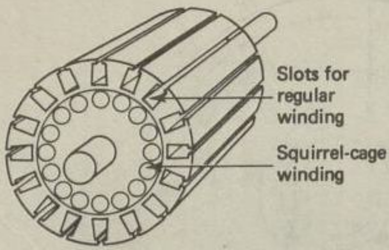


Fig. 3-56. An armature of a repulsion-induction motor. Note slots and squirrel-cage winding.

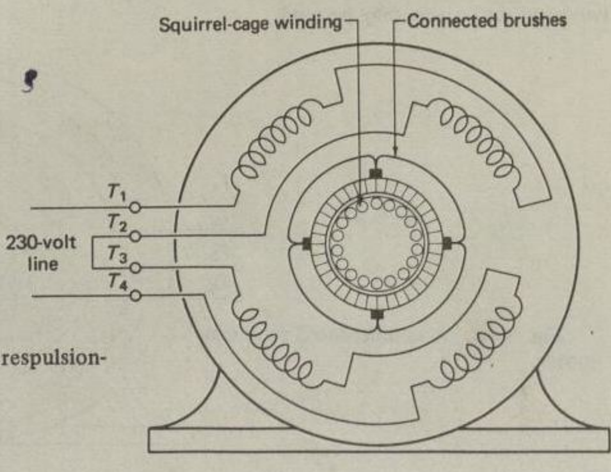


Fig. 3-57. A typical respulsion-induction motor.

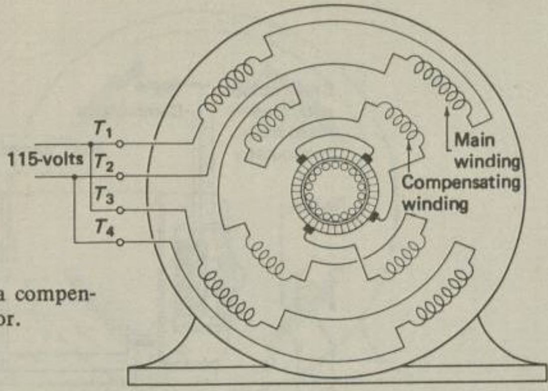
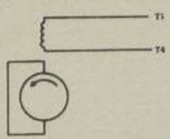


Fig. 3-58. A diagram of a compensated repulsion-induction motor.

MG 1-2.52 Schematic Diagrams for Repulsion, Repulsion-Start Induction and Repulsion-Induction Motors

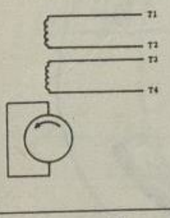
Reversible by Shifting Brushes

Single Voltage



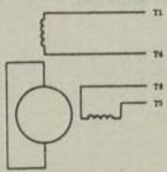
L1 to T1
L2 to T4

Double Voltage

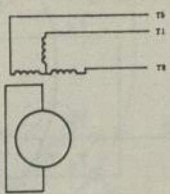


	L1	L2	Join
Higher nameplate voltage	T1	T4	T2, T3
Lower nameplate voltage	T1, T3	T2, T4	. . .

Single Voltage—Externally Reversible



	L1	L2	Join
Counter-clockwise rotation	T1	T5	T4, T8
Clockwise rotation	T1	T8	T4, T5



	L1	L2	Insulate
Counter-clockwise rotation	T1	T5	T8
Clockwise rotation	T1	T8	T5

NEMA Standard 11-16-1967.

Fig. 3-59. Schematic diagrams for repulsion, repulsion-start induction and repulsion-induction motors.

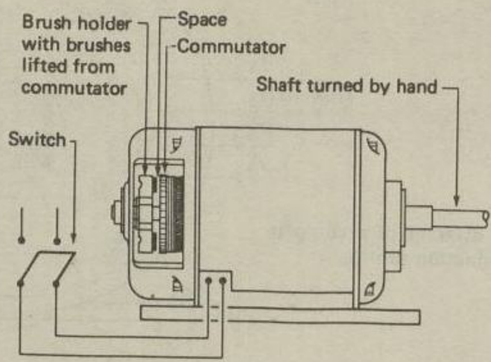


Fig. 3-60. Testing a repulsion motor for a shorted armature. Lift the brushes from the commutator; throw the switch on and turn the armature by hand. If it turns freely, the armature is not shorted.

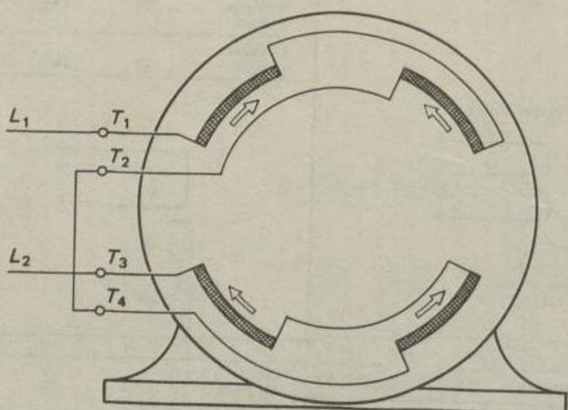


Fig. 3-61. A wrong connection for 230 volts. The current flows through two adjacent poles in the same direction. The motor hums and does not run. To remedy, connect T_2 and T_3 together, L_1 to T_1 and T_4 to L_2.

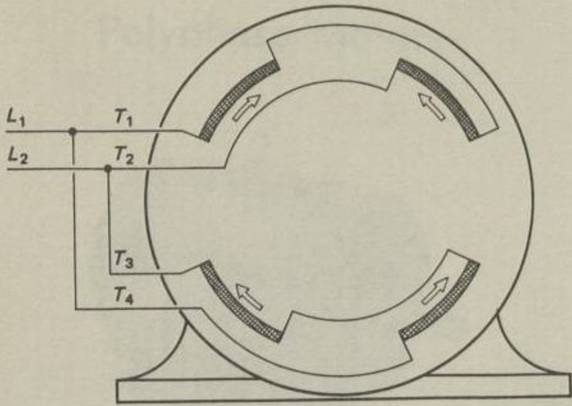


Fig. 3-62. Although connected for 115 volts, adjacent poles have the same polarity. Remedy by connecting T_1 and T_3 to L_1 and T_2 and T_4 to L_2.

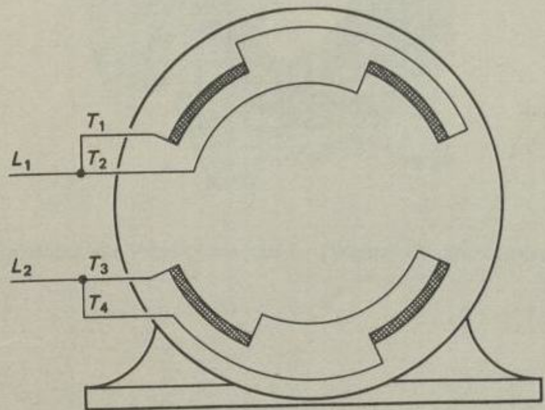


Fig. 3-63. A common mistake. There is no complete circuit across the line, and the motor neither operates nor hums.

CHAPTER 4

Polyphase Motors

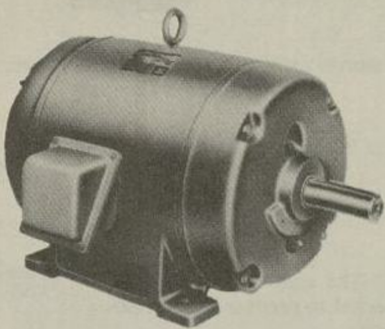


Fig. 4-1. A three-phase motor. *(Wagner Electric Company)*

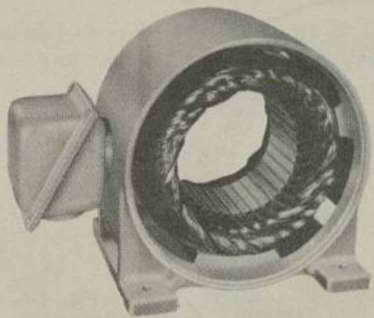


Fig. 4-2. A stator of a three-phase motor. *(Wagner Electric Company)*

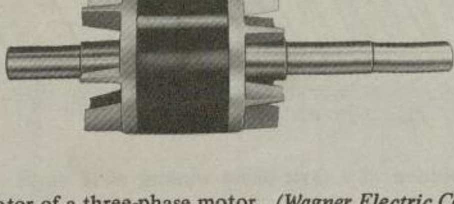


Fig. 4-3. Rotor of a three-phase motor. *(Wagner Electric Company)*

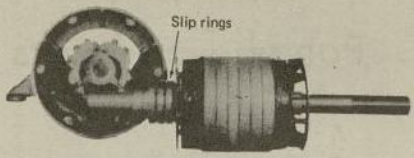


Fig. 4-4. A wound rotor and an end plate of a three-phase motor. *(Wagner Electric Company)*

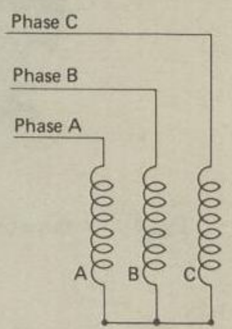


Fig. 4-5. The coils of a three-phase motor connected to produce three windings, or phases.

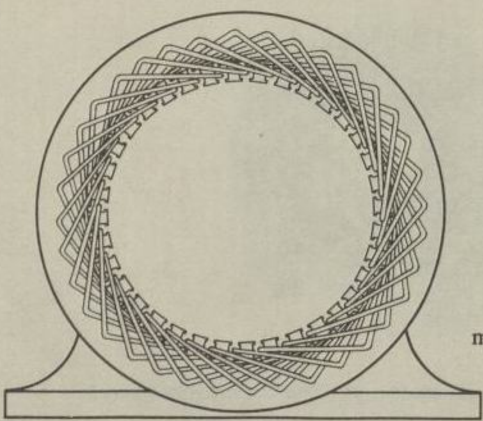


Fig. 4-6. A stator of a three-phase motor with all the coils in their slots.

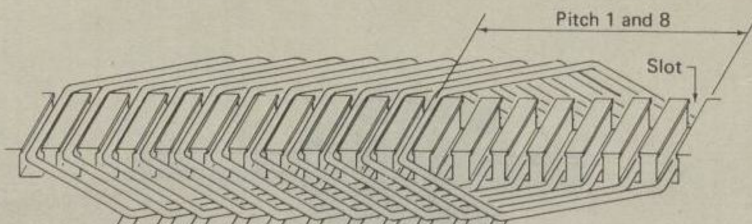


Fig. 4-7. A portion of a three-phase winding as it would appear if the slots were laid flat.

Figures 4-4; 4-5; 4-6; 4-7

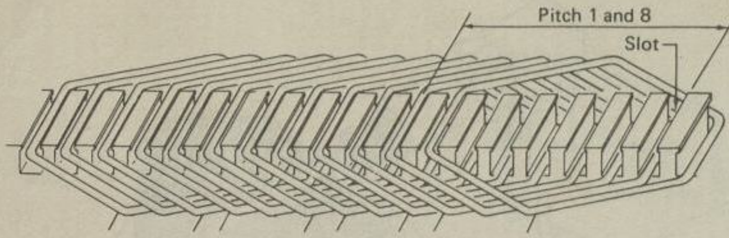
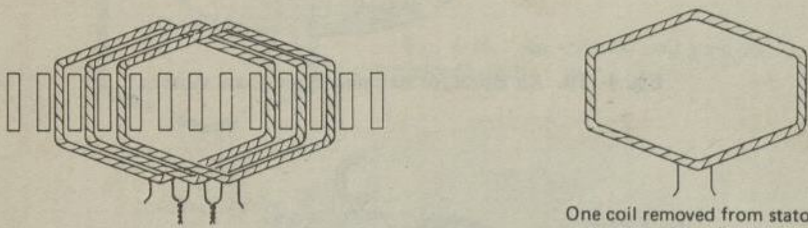


Fig. 4-8. A portion of a three-phase winding as it would appear if the coils were group wound.



Developed view of coils in slots

One coil removed from stator and used as form for new coils

Fig. 4-9. A simplified diagram of the coils and slots. *A* shows three coils connected in series; *B* shows one coil removed.

a) Open-slot stator

b) Semiclosed slot stator

Fig. 4-10. Two types of slots found in the stators of three-phase motors.

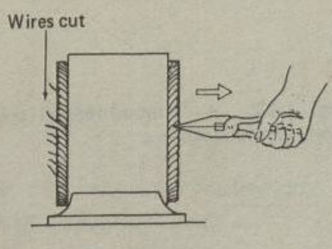


Fig. 4-11A. Stripping the stator by cutting each coil on one side and pulling from the other side.

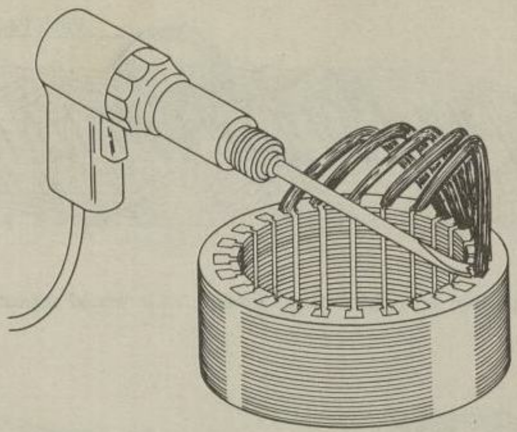


Fig. 4-11B. Air chisel for stripping three-phase motors.

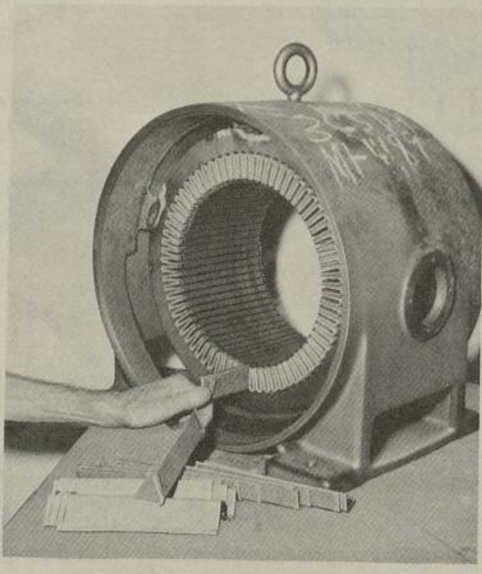


Fig. 4-12. Motor using cuffed insulation in slots. *(Wagner Electric Company)*

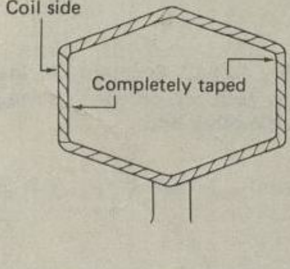


Fig. 4-13. A diamond-shaped coil used on open-slot stators.

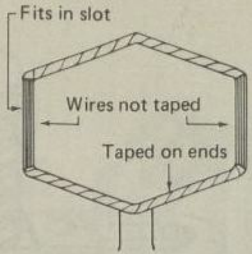


Fig. 4-14. A coil used in semiclosed slots.

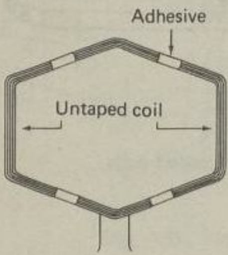


Fig. 4-15. An untaped coil used in semiclosed slots.

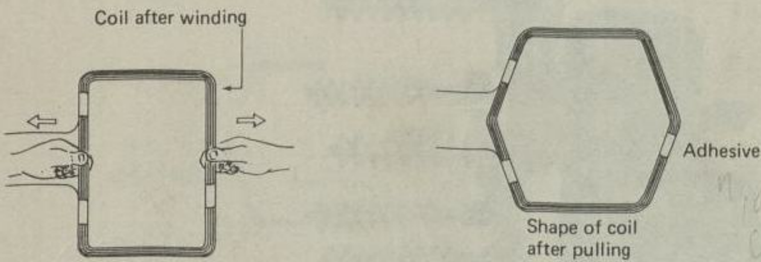


Fig. 4-16. The coils of small motors may be wound in a rectangular shape, which is later formed into a diamond shape by pulling at the center of opposite ends.

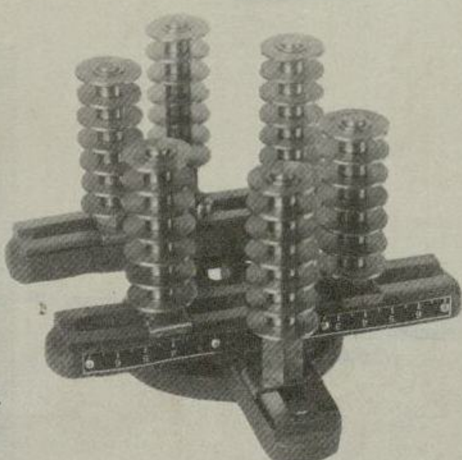


Fig. 4-17. Midget coil winding head. *(Crown Industrial Products Co.)*

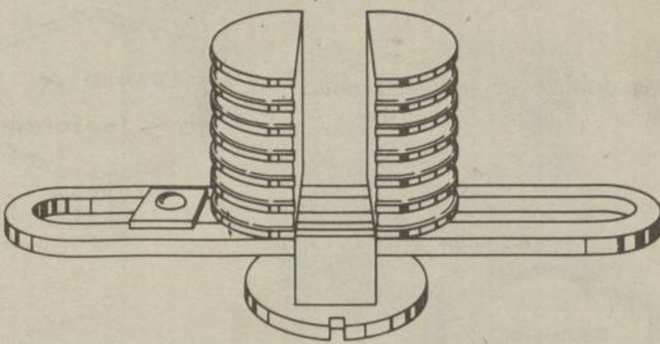


Fig. 4-18. Three-phase head for rounded coils.

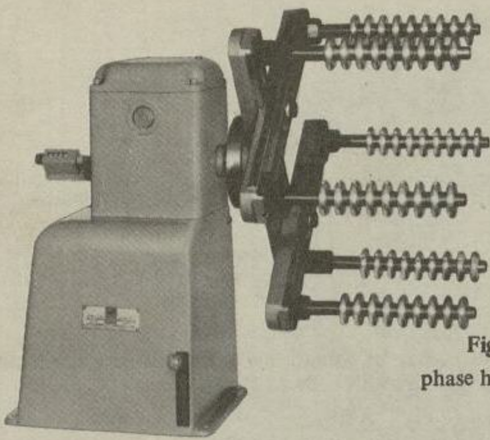


Fig. 4-19. Coil winding drive and three-phase head. *(Crown Industrial Products Co.)*

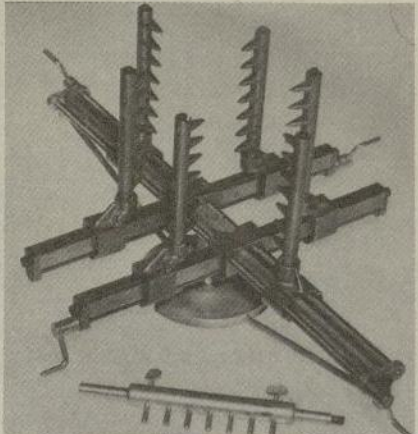


Fig. 4-20. Winding head with permanently attached cranks to adjust winding arms. *(Crown Industrial Products Co.)*

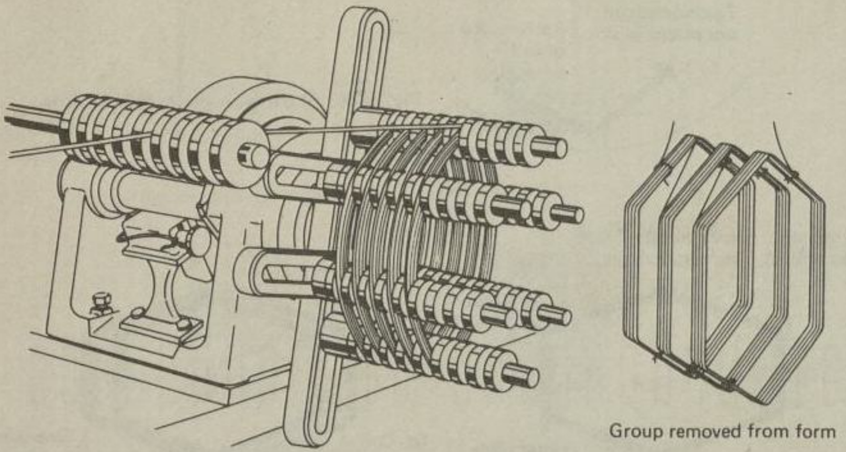


Fig. 4-21. Method of winding coils in groups.

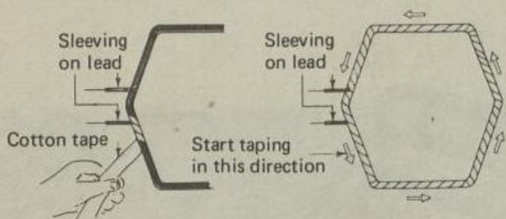


Fig. 4-22. Taping coils to fit open slots.

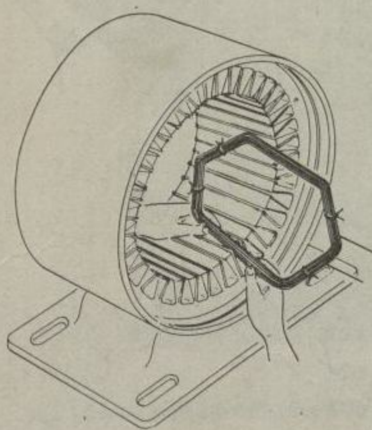


Fig. 4-23. One side of a coil spread so that it can be fed into the slot.

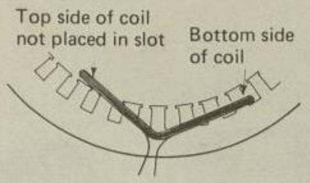


Fig. 4-24. Starting to place coils in slots.

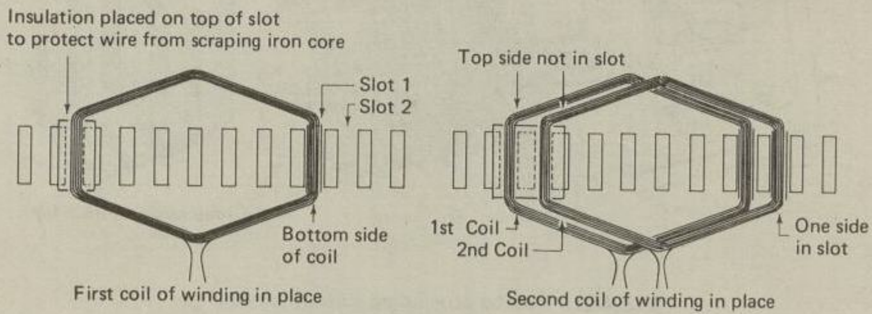


Fig. 4-25. The method of placing one side of each coil in slot.

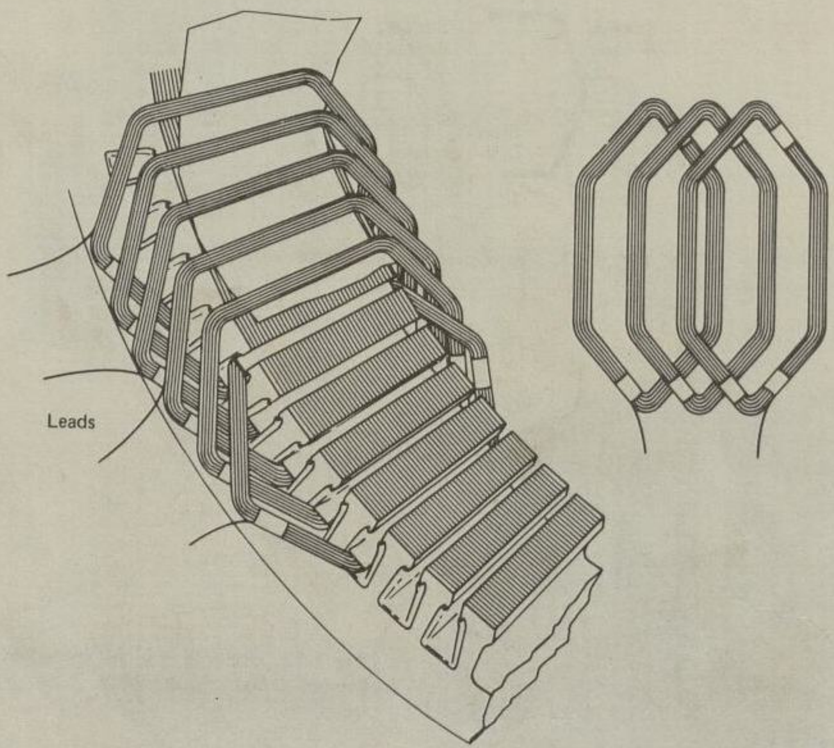


Fig. 4-26. Installing groups of 3 coils into the slots.

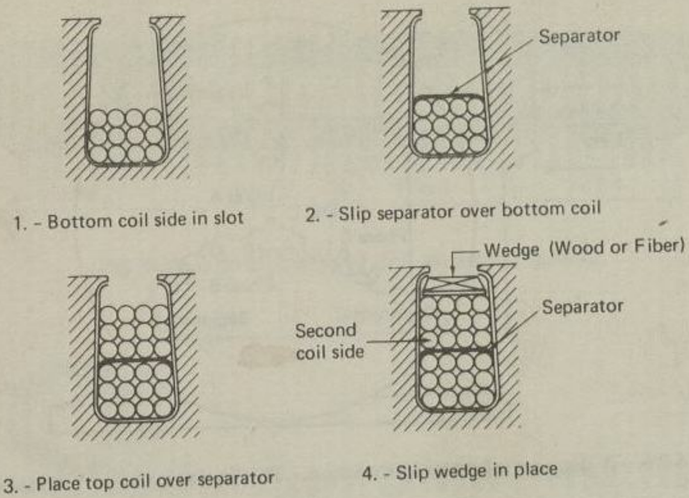


Fig. 4-27. The method of placing the sides of two coils in a slot with insulation.

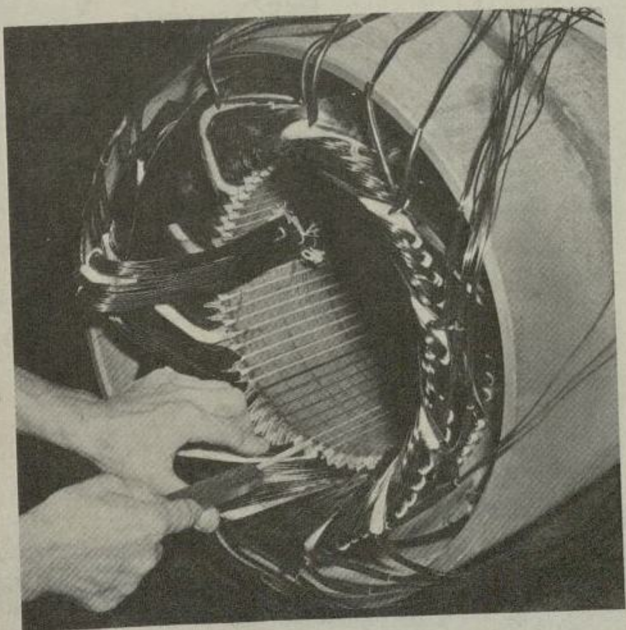


Fig. 4-28. Winding and insulating a three-phase stator. *(Wagner Electric Company)*

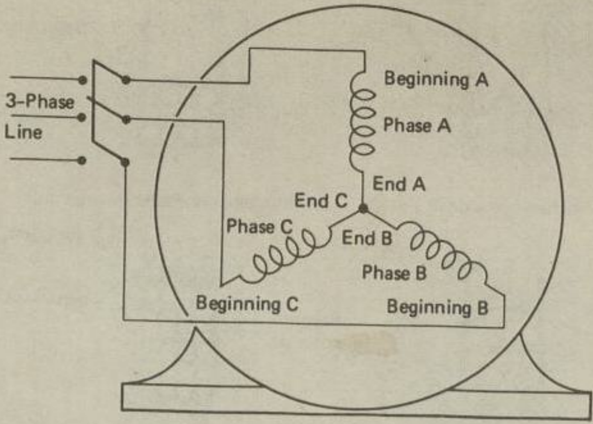


Fig. 4-29. A diagram of a star connection. This is also called a Y connection.

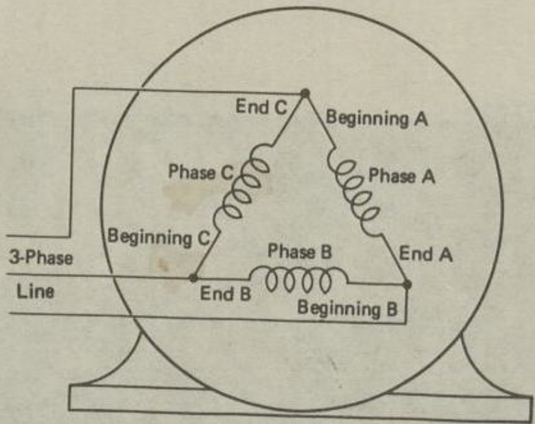


Fig. 4-30. A diagram of a delta connection.

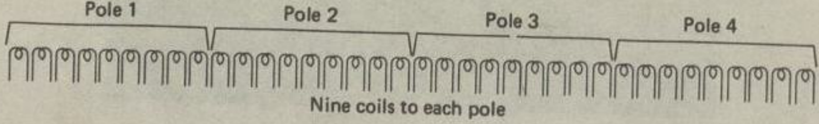


Fig. 4-31. A 36-coil, three-phase motor with coils divided into poles.

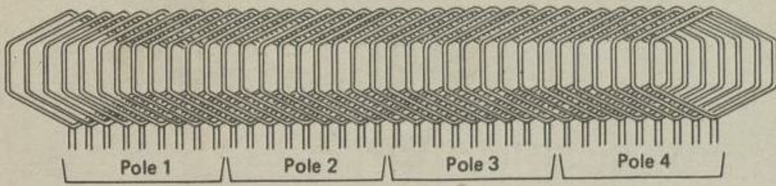


Fig. 4-32. The true shape of coils shown in Fig. 4-31.

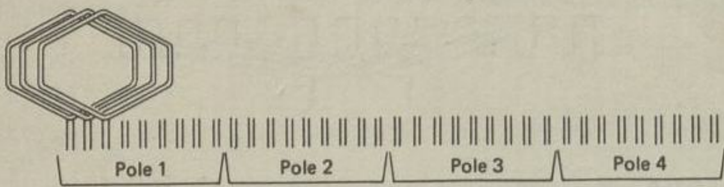


Fig. 4-33. A simplified diagram of the coils in a three-phase, four-pole motor.

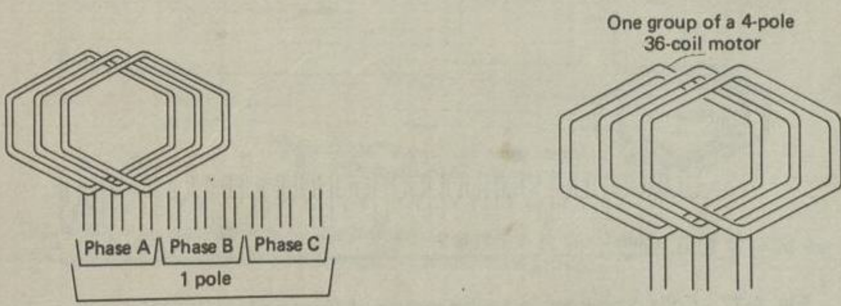
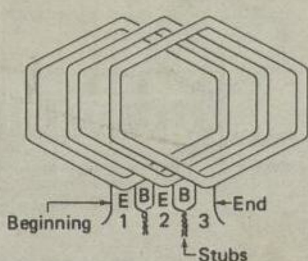


Fig. 4-34. Three groups in one pole. Each group has three coils.

Fig. 4-35. How the coils in a group are connected together.



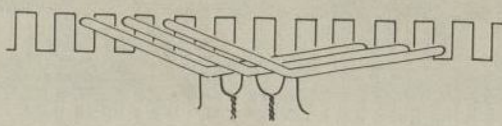


Fig. 4-36A. A side view of the coil connections shown in Fig. 4-35.

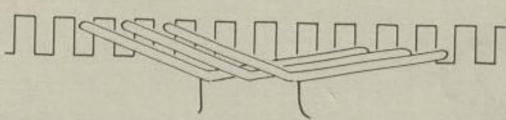


Fig. 4-36B. Three coils are group wound. Connections between coils are automatically made during the winding process.

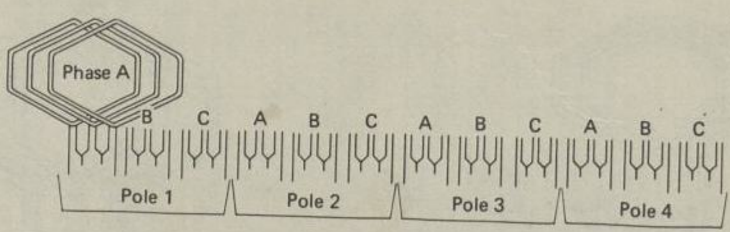


Fig. 4-37. Coils connected in twelve groups of three coils each. Note that all poles are alike.

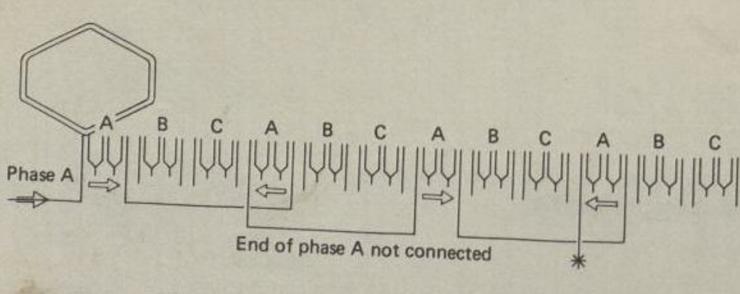


Fig. 4-38. Connections of groups of phase *A*.

Figures 4-36; 4-37; 4-38

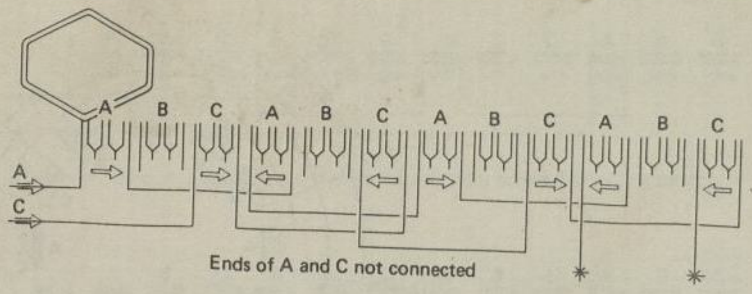


Fig. 4-39. Phase *C* connected exactly like phase *A* and connected before phase *B* to simplify connections.

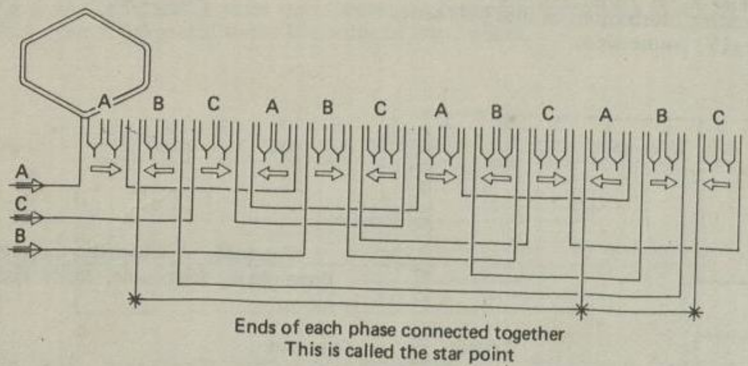


Fig. 4-40. The current flow in the *B* phase is opposite to the current flow in both the *A* and *C* phases. This is shown by the arrows under each group.

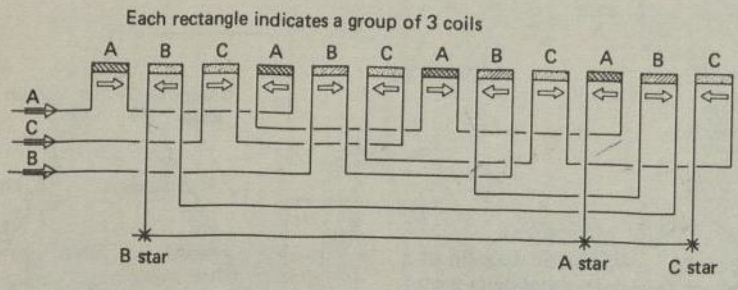


Fig. 4-41. A diagram similar to **Fig. 4-40** except that rectangles are used instead of coils.

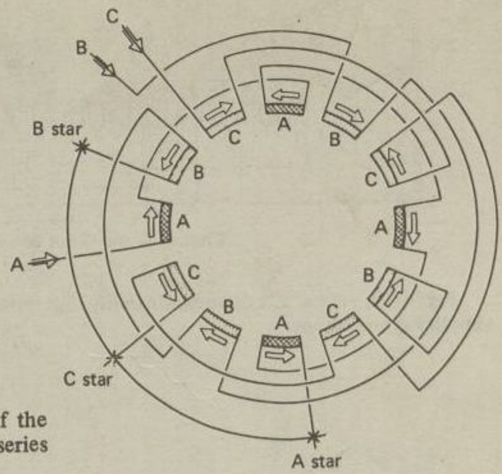


Fig. 4-42. A circular diagram of the preceding illustration. A four-pole series star (1Y) connection.

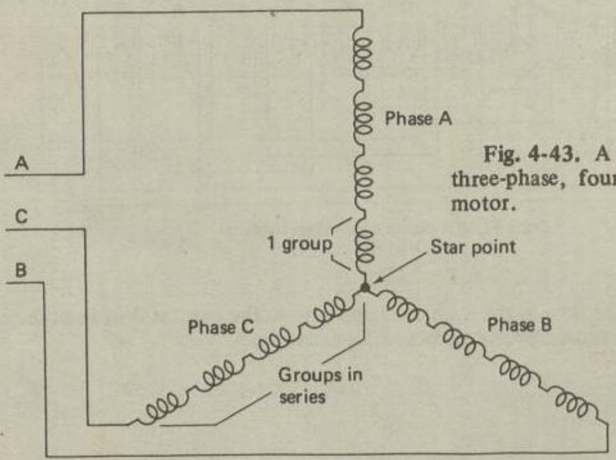


Fig. 4-43. A schematic diagram of a three-phase, four-pole, series star (1Y) motor.

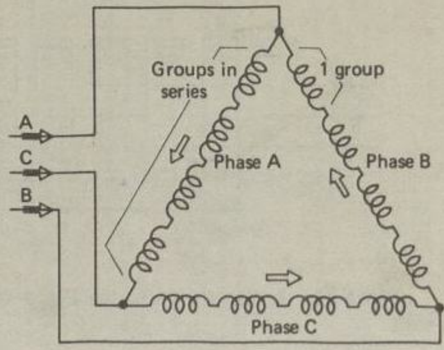


Fig. 4-44. A schematic diagram of a three-phase, four-pole, series delta motor.

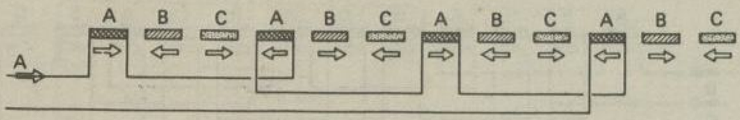


Fig. 4-45. The *A* phase connection in a four-pole, series delta (1△) motor.

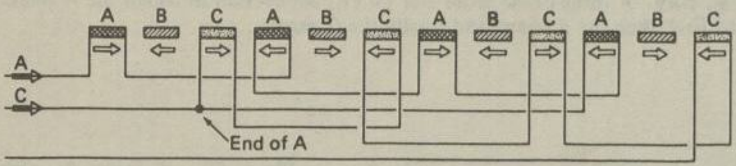


Fig. 4-46. The *C* and *A* phase connections in a four-pole, series delta motor. The end of the *A* phase is connected to the beginning of the *C* phase.

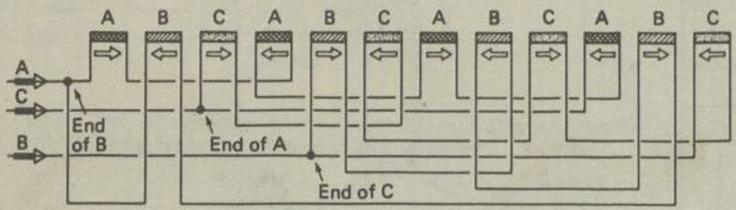


Fig. 4-47. A complete diagram of connections for a three-phase, four-pole, series delta motor.

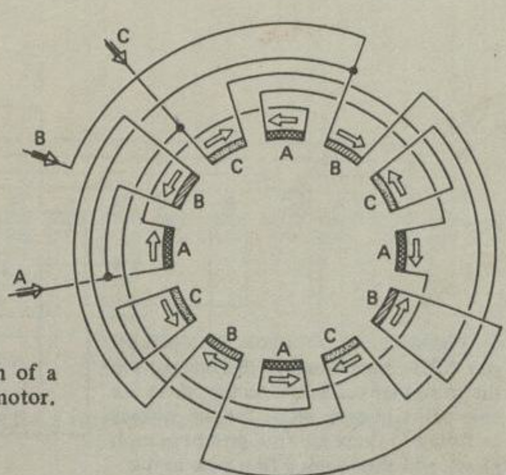


Fig. 4-48. A circular diagram of a four-pole, three-phase, series delta motor.

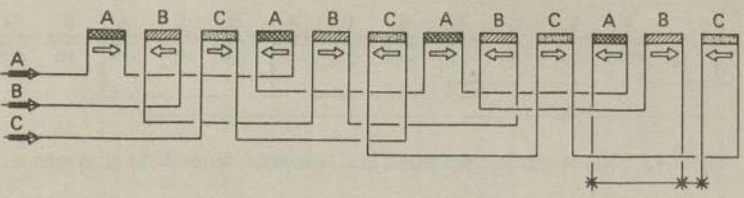


Fig. 4-49. A three-phase series star (WYE) connection in which the *A* phase is connected first, then the *B* phase, and finally the *C* phase.

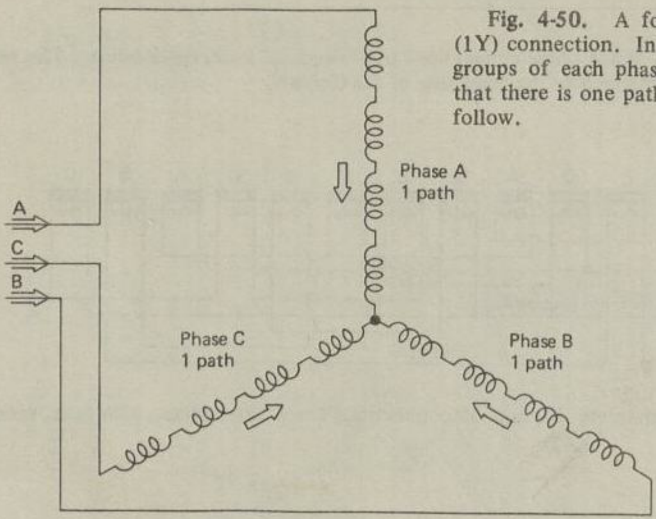


Fig. 4-50. A four-pole, series star (1Y) connection. In this connection the groups of each phase are connected so that there is one path for the current to follow.

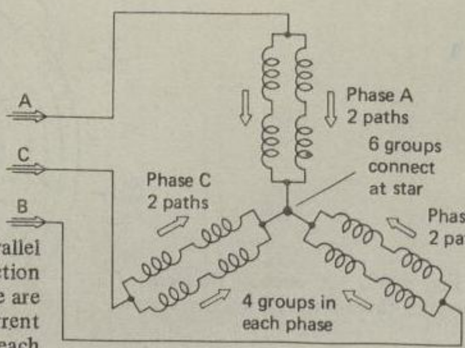


Fig. 4-51. A four-pole, two-parallel star (2Y) connection. In this connection the groups are connected so that there are two paths in each phase for the current to follow. There are four groups in each phase, and this forms a four-pole motor.

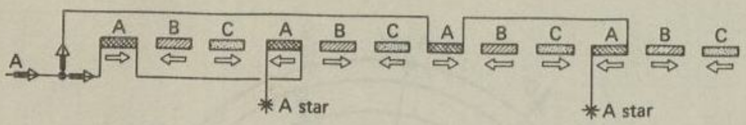


Fig. 4-52. A diagram of connections for the *A* phase of a two-parallel star (2Y) connection. Two wires from the *A* phase connect to the star point.

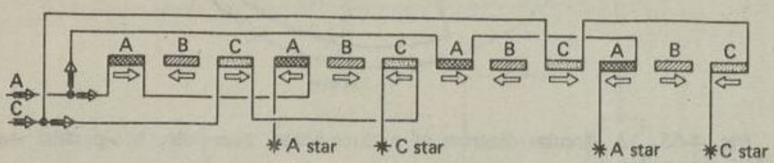


Fig. 4-53. The connections for the *C* and *A* phase of a two-parallel star (2Y) connection. So far, four leads are connected to star points.

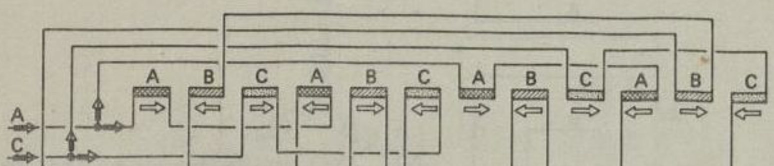


Fig. 4-54. A complete diagram for a three-phase, four-pole, two-parallel star (2Y) connection.

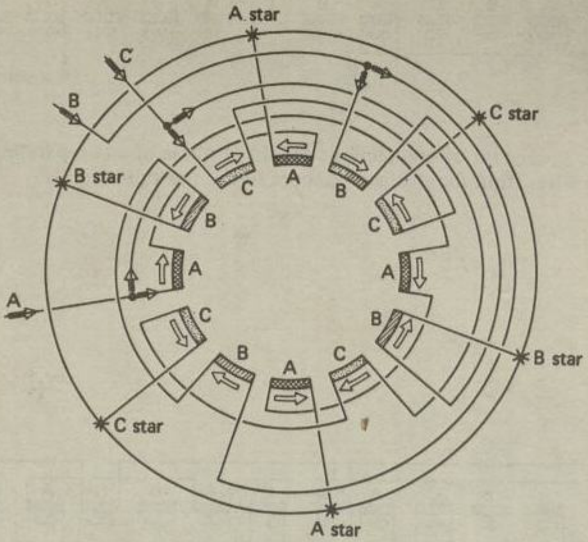


Fig. 4-55. A circular diagram of a three-phase, four-pole, two-parallel star (2Y) connection.

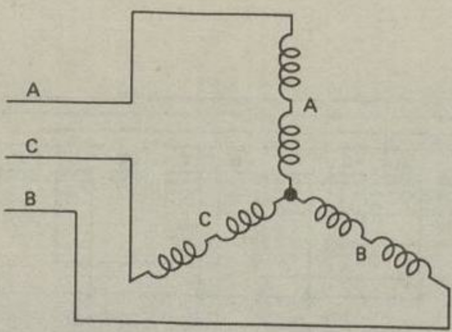


Fig. 4-56. A two-pole, series star (1Y) connection. If only one group is connected to each line, then it is a series star (1Y) connection.

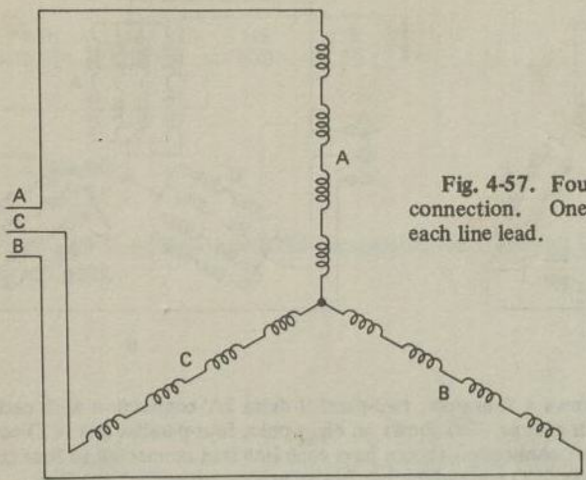


Fig. 4-57. Four-pole series star (1Y) connection. One group connected to each line lead.

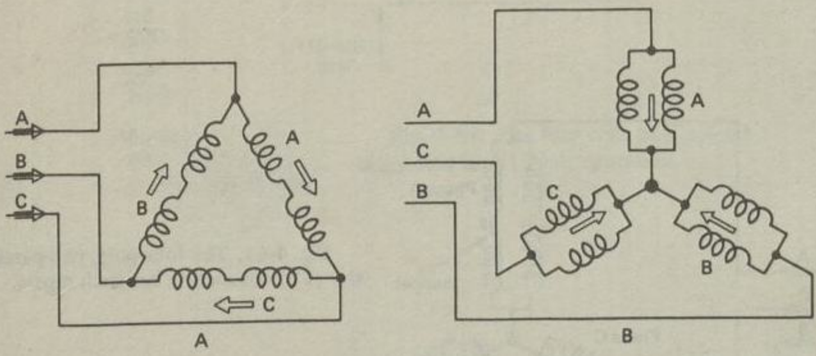
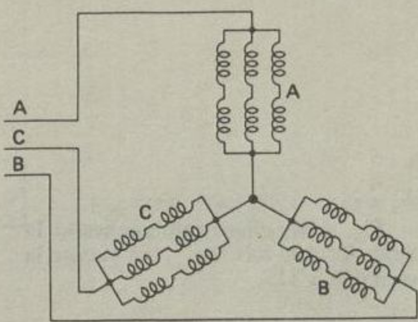


Fig. 4-58. Both methods of connection shown above have each line lead connected to two groups, but the parallel star connection has six groups connected together.

Fig. 4-59. A three-parallel star (3Y) connection. Each line lead connects to three groups.



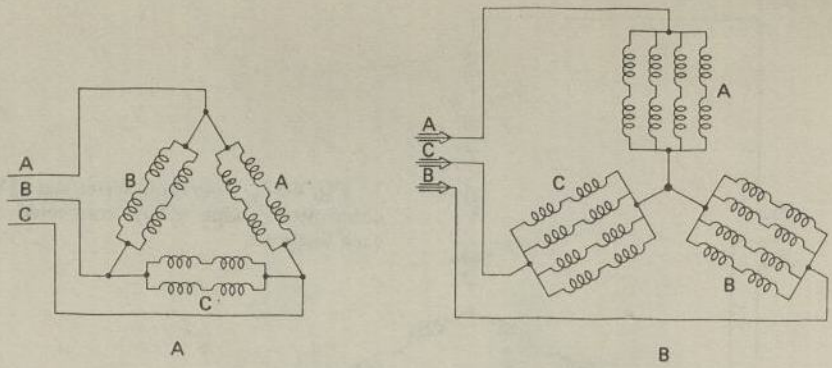


Fig. 4-60. (*A*) shows a four-pole, two-parallel delta 2△ connection with each line lead connected to four groups. (*B*) shows an eight-pole, four-parallel star (4Y) connection. Both methods of connection shown have each line lead connected to four groups, but the four-parallel star (4Y) connection has twelve groups connected together.

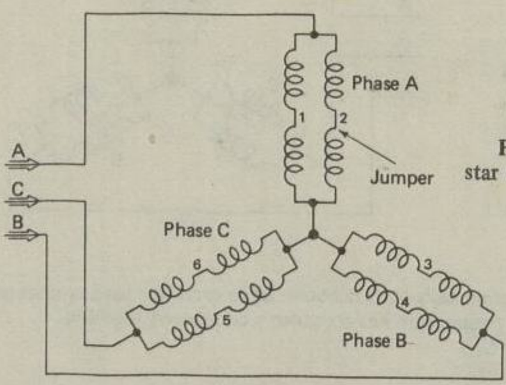
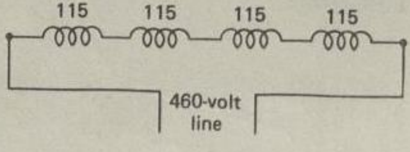


Fig. 4-61. The four-pole, two-parallel star (2Y) connection has six jumpers.

Fig. 4-62. Four coils connected in series for 460-volt line. The voltage in each coil is 115.



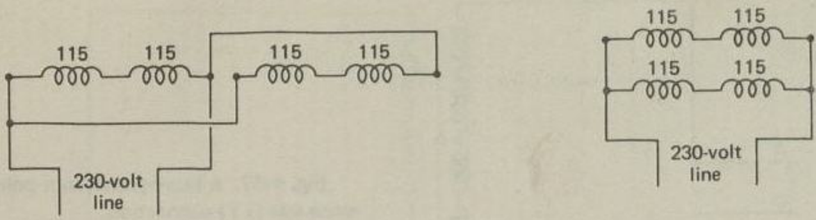


Fig. 4-63. Four coils connected two-parallel for a 230-volt line. Each coil still receives 115 volts.

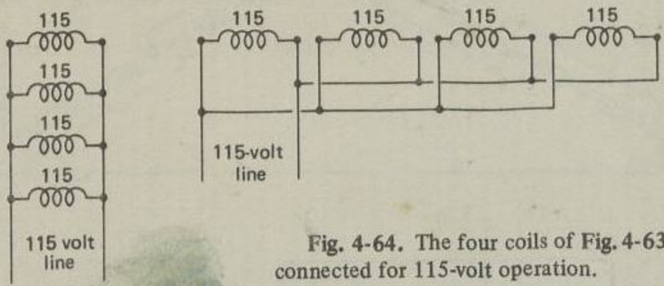
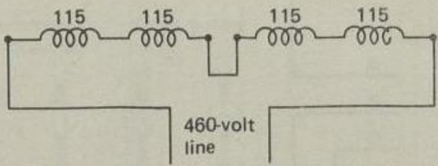


Fig. 4-64. The four coils of **Fig. 4-63** connected for 115-volt operation.

Fig. 4-65. Series connection of coils for 460-volt operation.



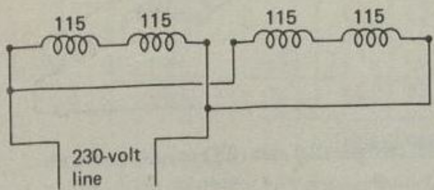


Fig. 4-66. Two sets of coils in parallel for 230-volt operation.

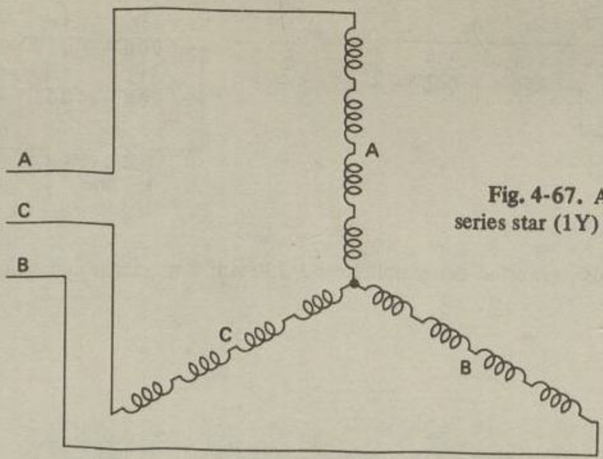


Fig. 4-67. A three-phase, four-pole, series star (1Y) connection.

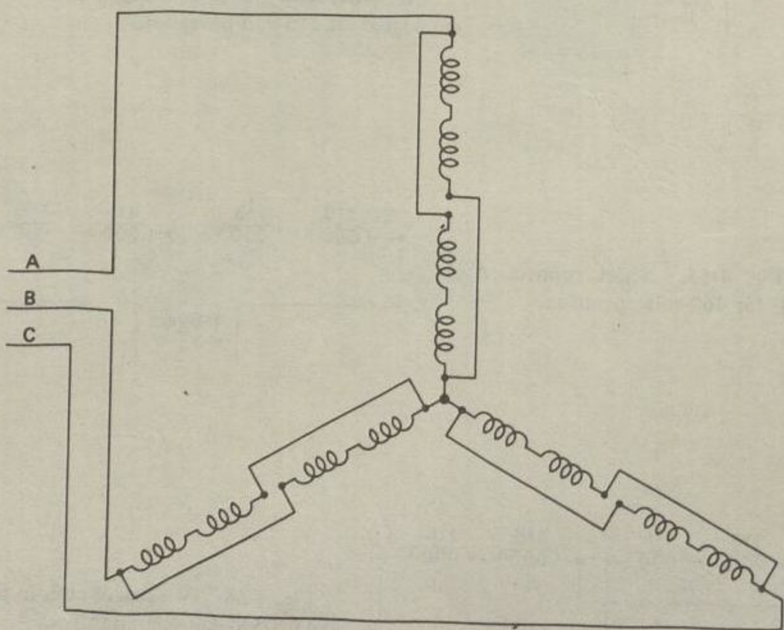


Fig. 4-68. A three-phase, four-pole, two-parallel star (2Y) connection with one star point.

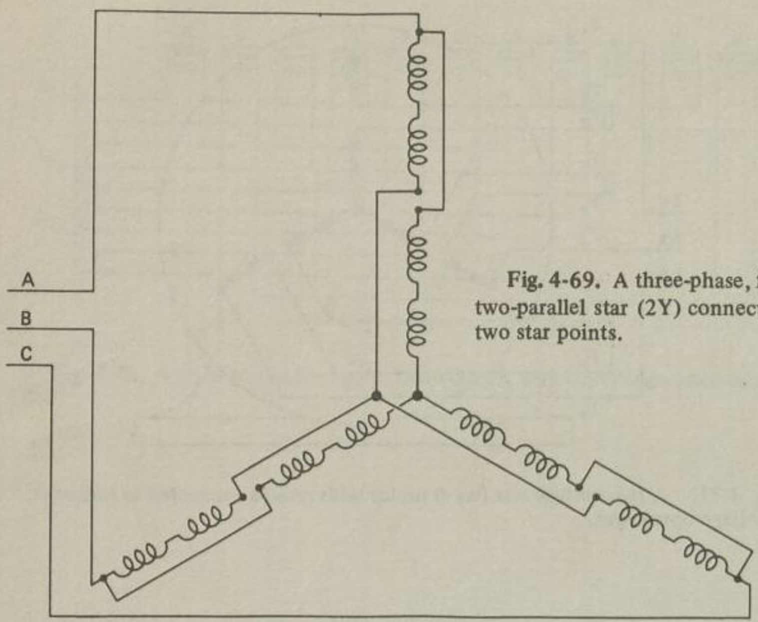
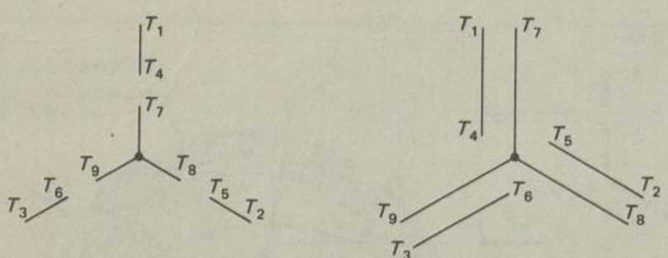
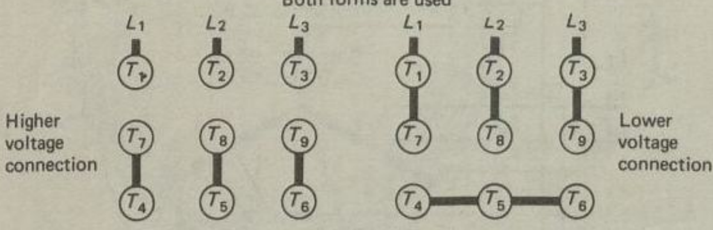


Fig. 4-69. A three-phase, four-pole two-parallel star (2Y) connection with two star points.



Standard markings for Y connected dual voltage motors
Both forms are used



Y connections for dual voltage

Voltage	L_1	L_2	L_3	Tie Together		
Low	$T_1\ T_7$	$T_2\ T_8$	$T_3\ T_9$		$T_4\ T_5\ T_6$	
High	T_1	T_2	T_3	$T_4\ T_7$	$T_5\ T_8$	$T_6\ T_9$

Table of connections

Fig. 4-70. Markings and connections for Y connected dual-voltage motor.

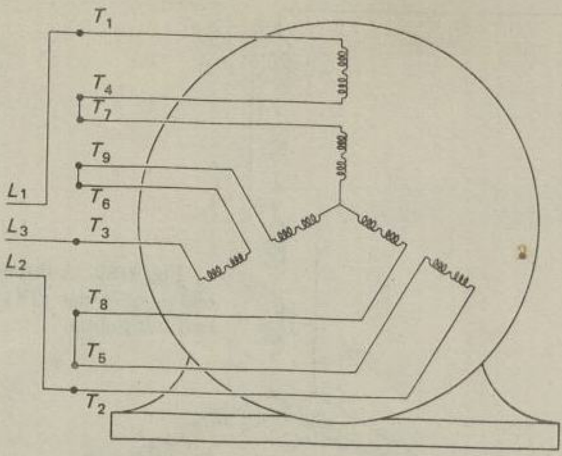


Fig. 4-71. A two-voltage star (wye) motor with groups connected in series for high-voltage operations.

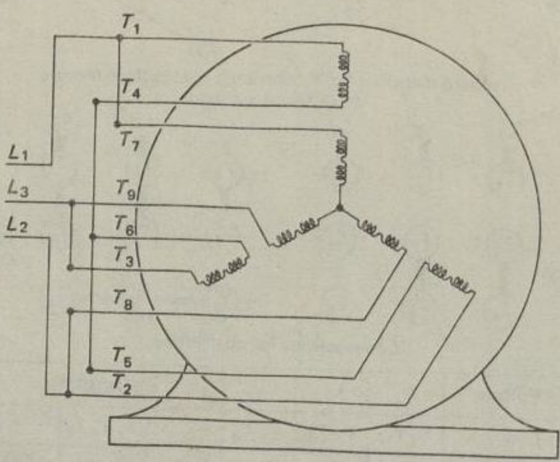


Fig. 4-72. A two-voltage star (wye) motor with groups connected in parallel for low voltage. The common connection of *4, 5,* and *6* forms an external star.

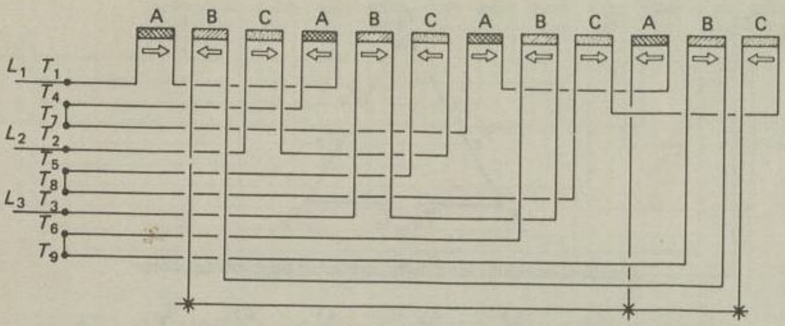


Fig. 4-73. A three-phase, four-pole, two-voltage, star (wye) connected motor.

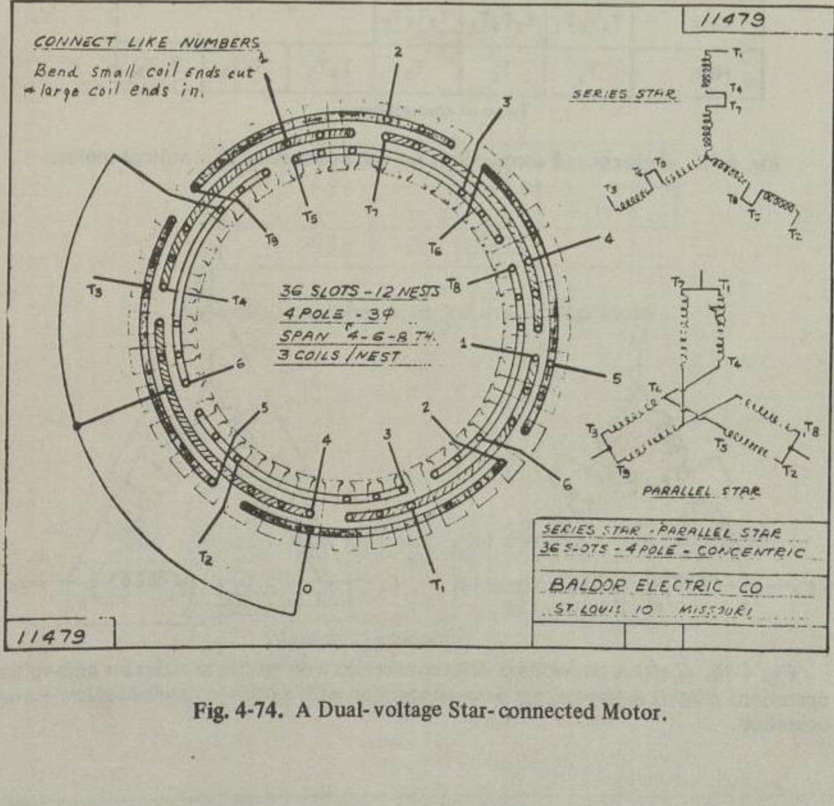
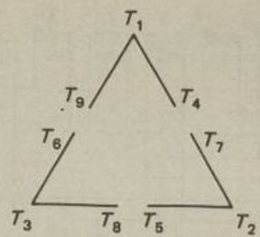
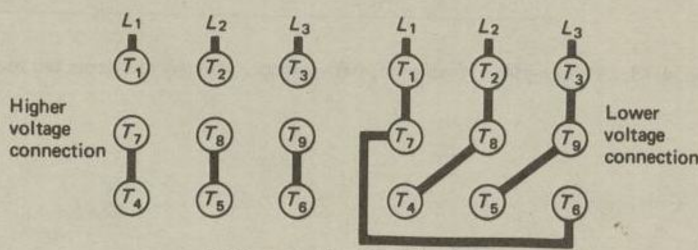


Fig. 4-74. A Dual-voltage Star-connected Motor.



Standard markings for a delta connected dual voltage motor



Delta connection for dual voltage

Voltage	L_1	L_2	L_3	Tie Together		
Low	$T_1T_6T_7$	$T_2T_4T_8$	$T_3T_5T_9$			
High	T_1	T_2	T_3	T_4T_7	T_5T_8	T_6T_9

Table of connections

Fig. 4-75. Markings and connections for delta-connected dual-voltage motor.

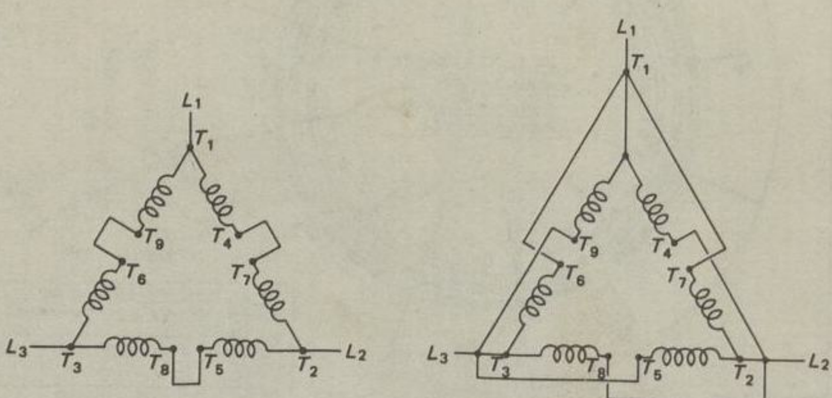


Fig. 4-76. *(Left)* A two-voltage delta connection with groups in series for high-voltage operation. *(Right)* A two-voltage delta connection with groups in parallel for low-voltage operation.

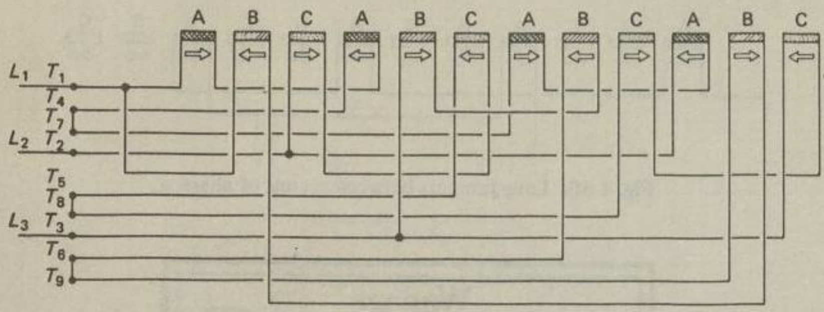
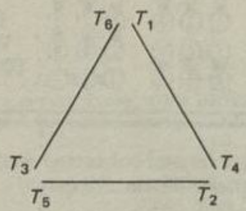


Fig. 4-77. A three-phase, four-pole, two-voltage, delta-connected motor.



Voltage	L_1	L_2	L_3	Tie Together
High	T_1	T_2	T_3	$T_4T_5T_6$
Low	T_1T_6	T_2T_4	T_3T_5	

Fig. 4-78. Wye delta-connected dual-voltage motor.

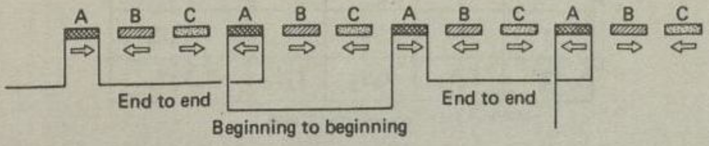


Fig. 4-79. Short jumpers between groups of phase *A*.

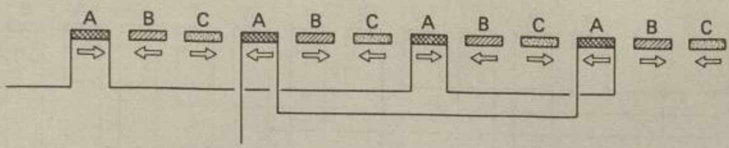


Fig. 4-80. Long jumpers between groups of phase *A*.

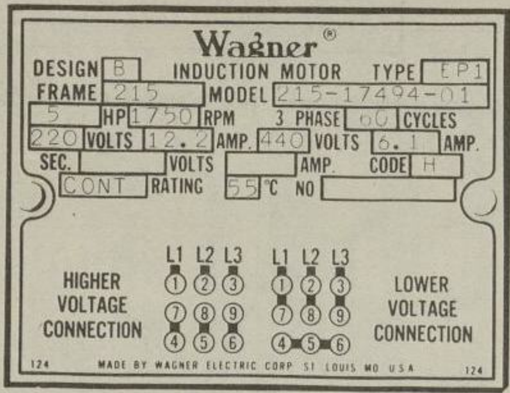
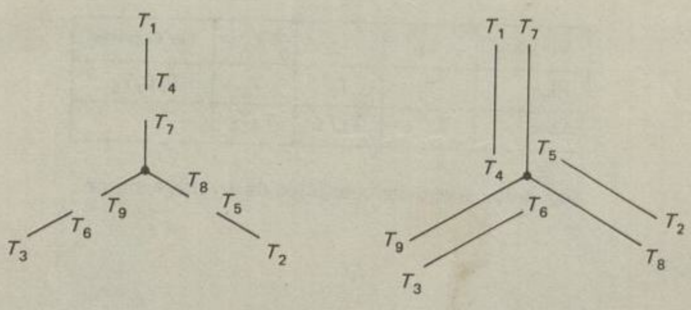


Fig. 4-81. Name plate for star-connected dual-voltage motor. *(Wagner Electric Company)*



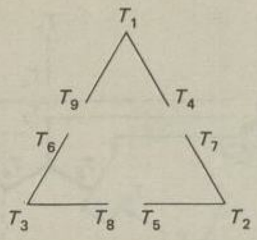
(a) Terminal markings 9 lead star (b)

Step	L_1	L_2	L_3	Tie Together
1	T_1	T_2	T_3	$T_4T_5T_6$
2	T_1T_7	T_2T_8	T_3T_9	$T_4T_5T_6$

Connector Table

Fig. 4-82A and B. Nine-lead wye connected part-winding motor. This is similar to that of a 9-lead dual-voltage motor.

Figures 4-80; 4-81; 4-82



Terminal markings - 9 lead delta

Step	L_1	L_2	L_3	Tie Together
1	T_1T_6	T_2T_4	T_3T_5	
2	$T_1T_6T_7$	$T_2T_4T_8$	$T_3T_5T_9$	

Step	L_1	L_2	L_3	Tie Together		
1	T_1	T_4T_2	T_9	T_4T_8	T_5T_9	T_6T_7
2	T_1T_6	T_4T_2	T_9T_3	T_4T_8	T_5T_9	T_6T_7

Fig. 4-83. Two methods of connecting a 9-lead delta part-winding motor.

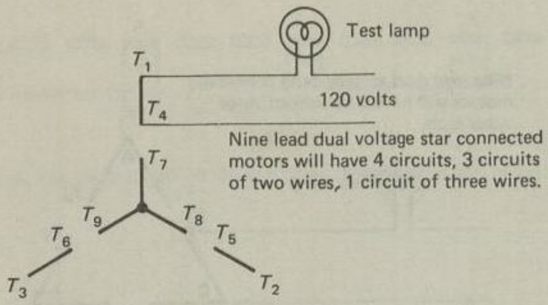


Fig. 4-84A. Testing each circuit for continuity.

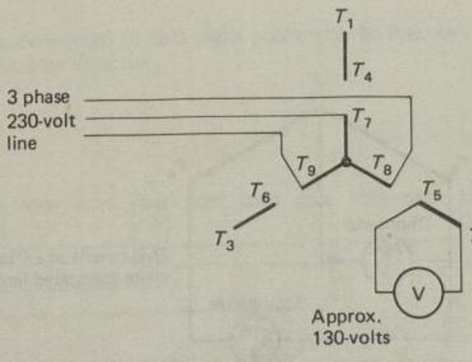


Fig. 4-84B. Run motor using 230 volts 3 phase across T_7, T_8, T_9 to test voltage across each section.

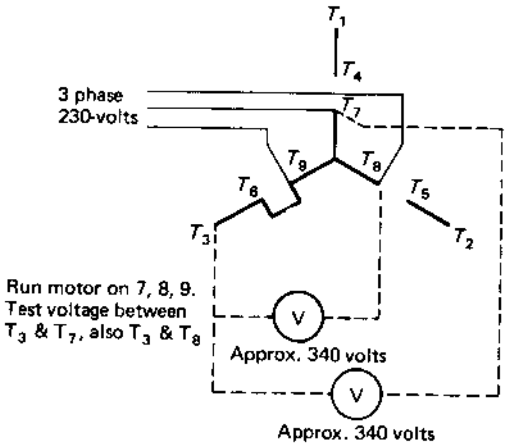


Fig. 4-84C. Testing for correct connections in each phase.

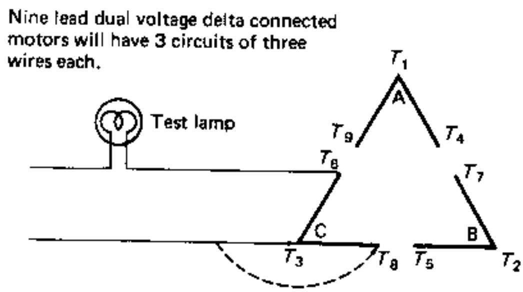


Fig. 4-85A. Test for 3 circuits of 3 leads each.

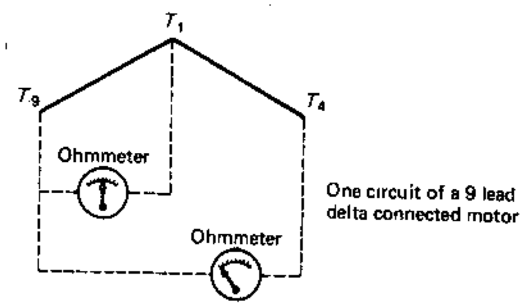


Fig. 4-85B. Measuring resistances with ohmmeter resistance between T_9 and T_4 = 2 times that of T_9 and T_1.

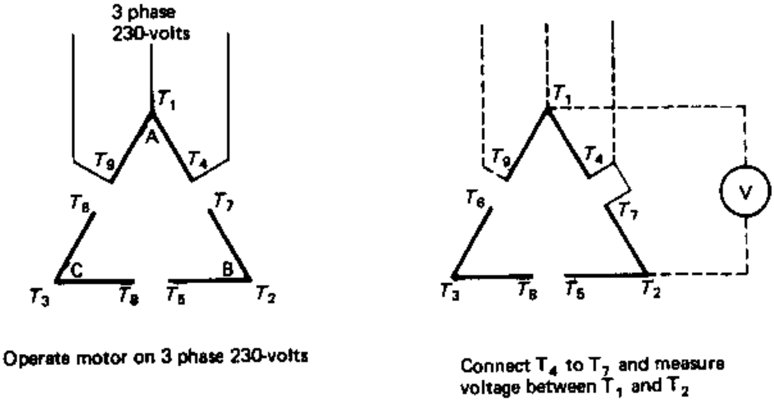


Fig. 4-85C. Connecting circuits to their proper phases.

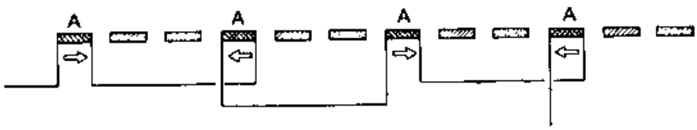


Fig. 4-86. A four-pole motor with *A* phase connected in the usual way.

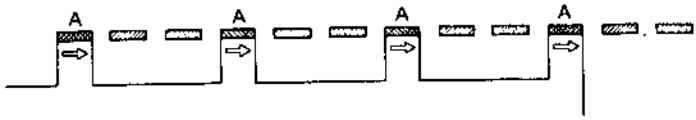


Fig. 4-87. Groups connected so that eight poles with be formed instead of four. All the arrows point in the same direction.

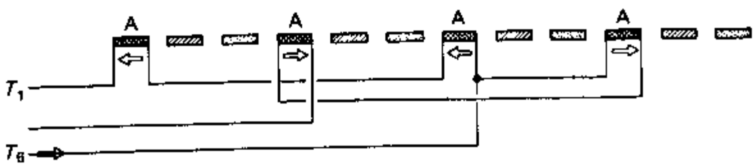


Fig. 4-88. The *A* phase connected in parallel for four-pole operation. The current flows through the groups in the direction of the arrows. Long jumpers are necessary in two-speed motors. This is one phase of a 2 speed constant torque motor.

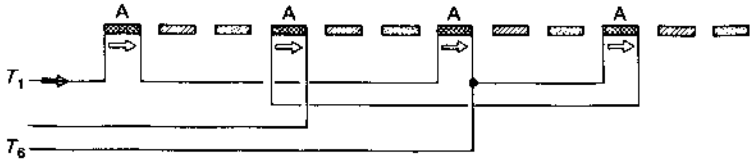


Fig. 4-89. The *A* phase connected series delta for eight-pole operation. The current flows through the groups in the direction of the arrows. This type of motor is used for constant torque at both speeds.

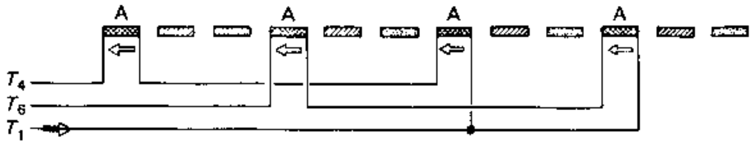


Fig. 4-90. A two-parallel connection for eight pole operation at low speed. This is one phase of a constant H.P. motor.

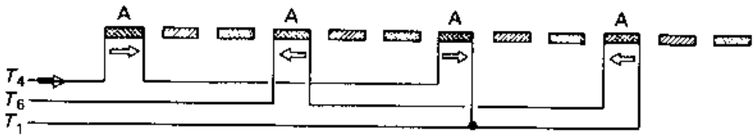
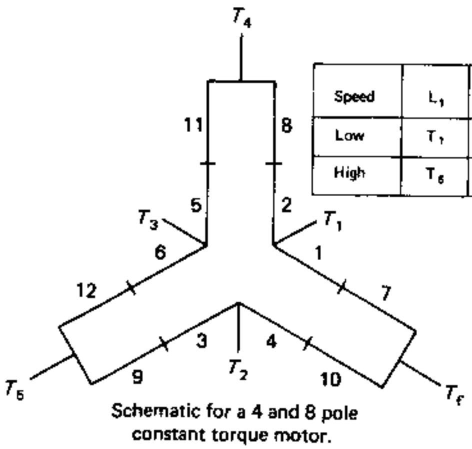


Fig. 4-91. The groups of the *A* phase are connected in series for four-pole operation at high speed. Constant H.P.



Speed	L_1	L_2	L_3	Insulate Separately	Tie Together
Low	T_1	T_2	T_3	$T_4T_5T_6$	
High	T_6	T_4	T_5		$T_1T_2T_3$

Fig. 4-92. A four-pole, constant-torque two-speed motor. The parallel-star (2Y) connection is used for high-speed operation; the series-delta for low-speed operation. T_4, T_5, T_6 to line; T_1, T_2, T_3 connected together, for high speed. T_1, T_2, T_3 to line; T_4, T_5, T_6 not connected, for low speed.

Figures 4-89; 4-90; 4-91; 4-92

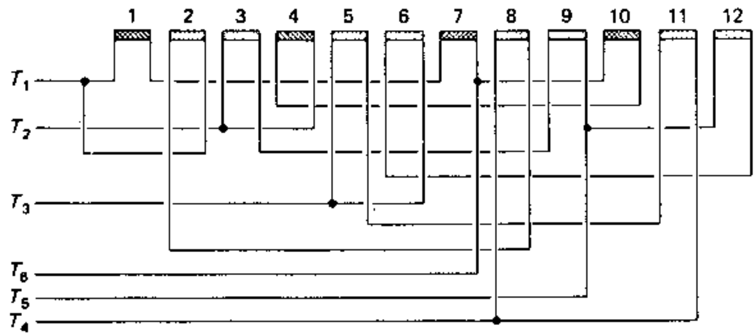
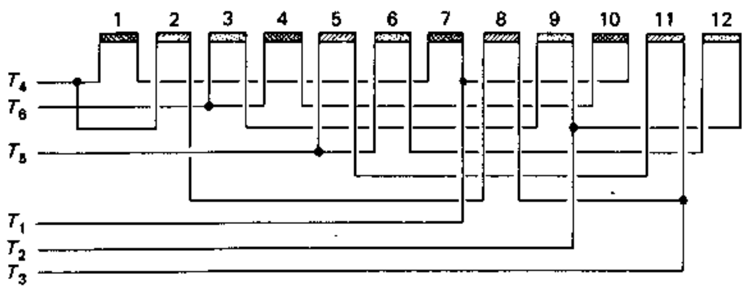


Fig. 4-92. *(continued)*



Speed	L_1	L_2	L_3	Insulate Separately	Tie Together
Low	T_1	T_2	T_3		$T_4T_5T_6$
High	T_6	T_4	T_5	$T_1T_2T_3$	

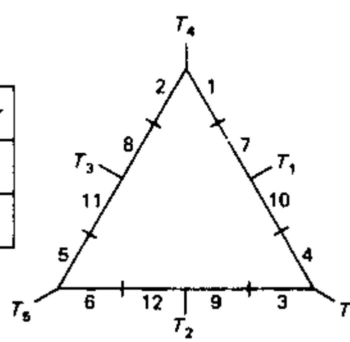


Fig. 4-93A. A two-speed constant horsepower motor. The series-delta connection is used for high-speed operation; two-parallel star for low speed. T_1 T_2 T_3 to line; T_4 T_5 T_6 connected together for low speed. T_6 T_4 T_5 to line; T_1 T_2 T_3 not connected for high speed.

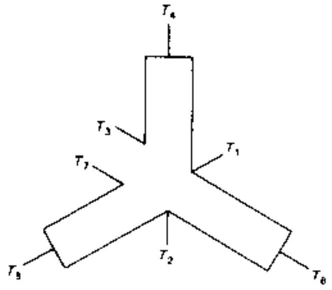
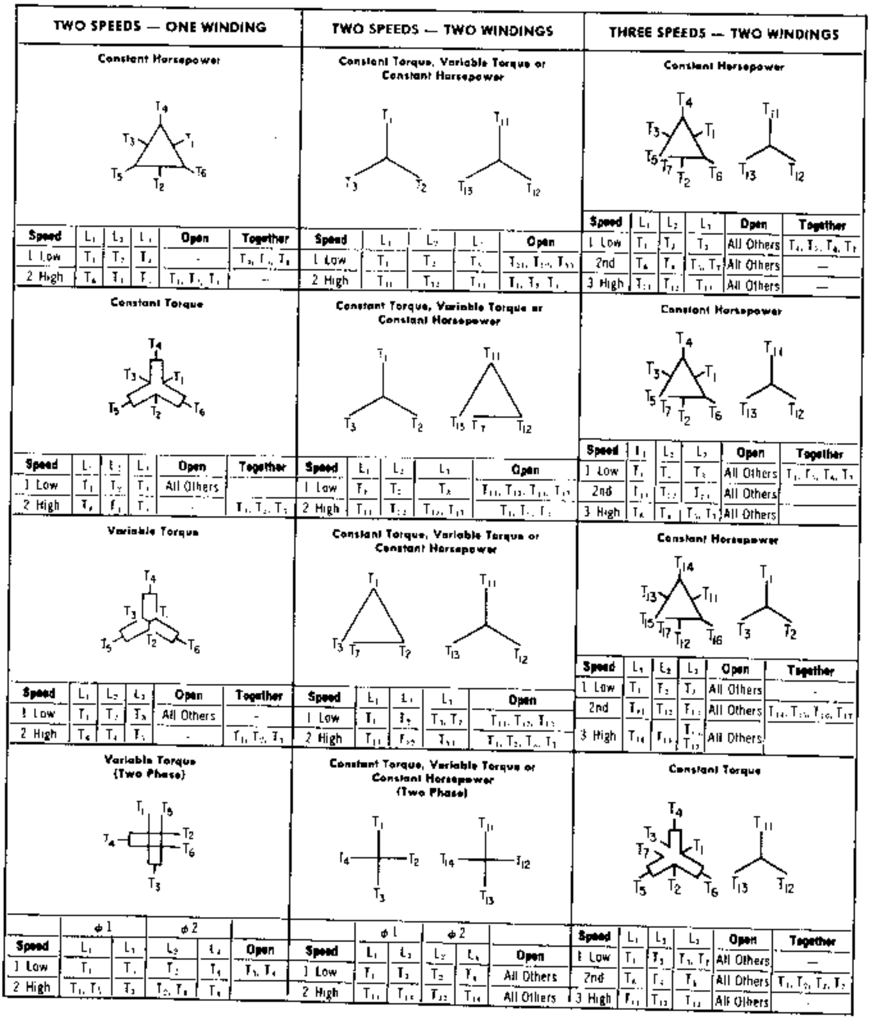


Fig. 4-93B. Two-speed 7-lead motor. Constant torque.



Two Speeds — One Winding: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	-	T_4, T_5, T_6
2 High	T_6	T_4	T_5	T_1, T_2, T_3	—

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3	T_{11}, T_{12}, T_{13}
2 High	T_{11}	T_{12}	T_{13}	T_1, T_2, T_3

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	T_4, T_5, T_6, T_7
2nd	T_6	T_4	T_5, T_7	All Others	—
3 High	T_{11}	T_{12}	T_{13}	All Others	—

Two Speeds — One Winding: Constant Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	
2 High	T_6	T_4	T_5	-	T_1, T_2, T_3

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3	$T_{11}, T_{12}, T_{13}, T_{17}$
2 High	T_{11}	T_{12}	T_{13}, T_{17}	T_1, T_2, T_3

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	T_4, T_5, T_6, T_7
2nd	T_{11}	T_{12}	T_{13}	All Others	
3 High	T_6	T_4	T_5, T_7	All Others	

Two Speeds — One Winding: Variable Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	-
2 High	T_6	T_4	T_5	-	T_1, T_2, T_3

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower

Speed	L_1	L_2	L_3	Open
1 Low	T_1	T_2	T_3, T_7	T_{11}, T_{12}, T_{13}
2 High	T_{11}	T_{12}	T_{13}	T_1, T_2, T_3, T_7

Three Speeds — Two Windings: Constant Horsepower

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3	All Others	-
2nd	T_{11}	T_{12}	T_{13}	All Others	$T_{14}, T_{15}, T_{16}, T_{17}$
3 High	T_{16}	T_{14}	T_{15}, T_{17}	All Others	

Two Speeds — One Winding: Variable Torque (Two Phase)

Speed	$\phi 1$ L_1	$\phi 1$ L_3	$\phi 2$ L_2	$\phi 2$ L_4	Open
1 Low	T_1	T_3	T_2	T_4	T_5, T_6
2 High	T_1, T_3	T_5	T_2, T_4	T_6	

Two Speeds — Two Windings: Constant Torque, Variable Torque or Constant Horsepower (Two Phase)

Speed	$\phi 1$ L_1	$\phi 1$ L_3	$\phi 2$ L_2	$\phi 2$ L_4	Open
1 Low	T_1	T_3	T_2	T_4	All Others
2 High	T_{11}	T_{13}	T_{12}	T_{14}	All Others

Three Speeds — Two Windings: Constant Torque

Speed	L_1	L_2	L_3	Open	Together
1 Low	T_1	T_2	T_3, T_7	All Others	—
2nd	T_6	T_4	T_5	All Others	T_1, T_2, T_3, T_7
3 High	T_{11}	T_{12}	T_{13}	All Others	-

Fig. 4-94. Connections for Multispeed Squirrel Cage Motors.

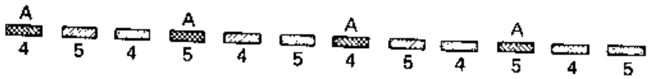


Fig. 4-95. A method of arranging groups in drawing.

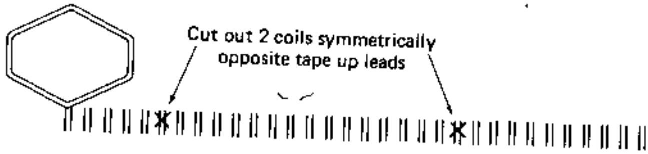


Fig. 4-96. A four-pole, 32-coil motor, but two coils are not in circuit.

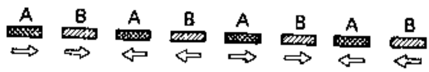


Fig. 4-97. A two-phase, four-pole, 48-coil motor. Note direction of arrows.

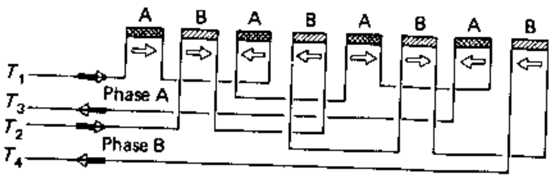


Fig. 4-98. A two-phase, four-pole motor. Note that the two phases are connected alike.

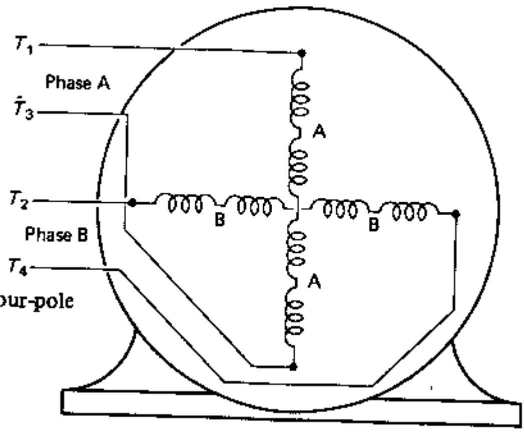


Fig. 4-99. A two-phase, four-pole series connection.

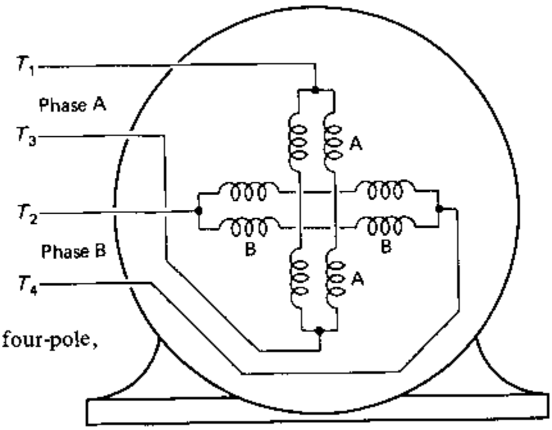


Fig. 4-100. A two-phase, four-pole, two-parallel connection.

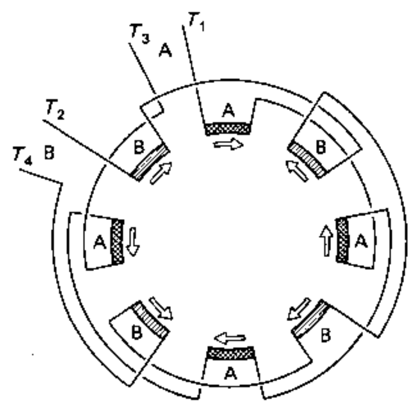


Fig. 4-101. A two-phase, four-pole, series connection with eight groups.

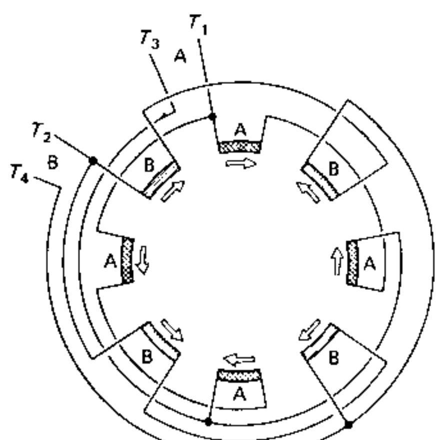


Fig. 4-102. A two-phase, four-pole, two-parallel connection.

Figures 4-100; 4-101; 4-102

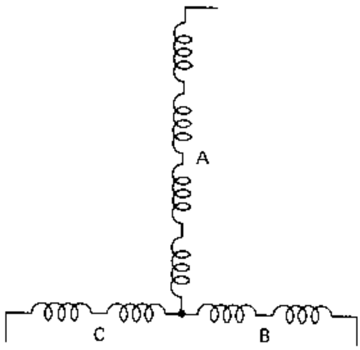


Fig. 4-103. The end of the *A* phase is connected to the center of the *B* phase to form a T, or Scott, connection. One half of the *B* phase becomes the *C* phase, and the other half remains the *B* phase.

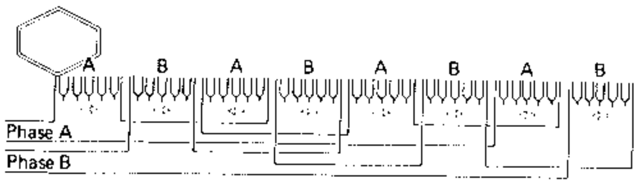


Fig. 4-104. A two-phase, 48-coil series motor to be connected Scott for three-phase operation.

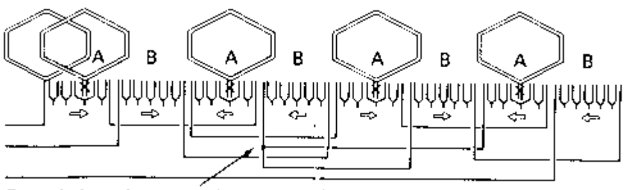


Fig. 4-105. The circuit of a three-phase motor formed by Scott connection.

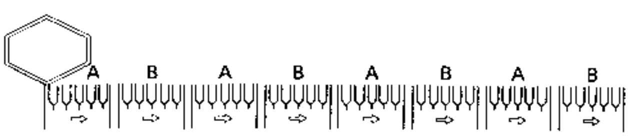


Fig. 4-106. A two-phase, four-pole motor with jumpers removed.

Fig. 4-107. Laying out groups for a three-phase, four-pole, 42-coil, series star (1Y) connection.

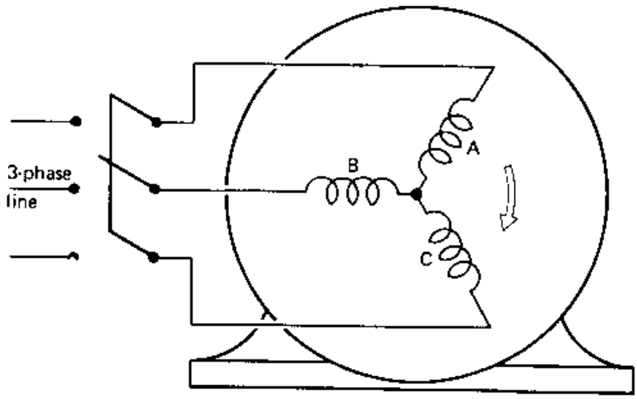


Fig. 4-108. A three-phase motor connected to a three-phase line.

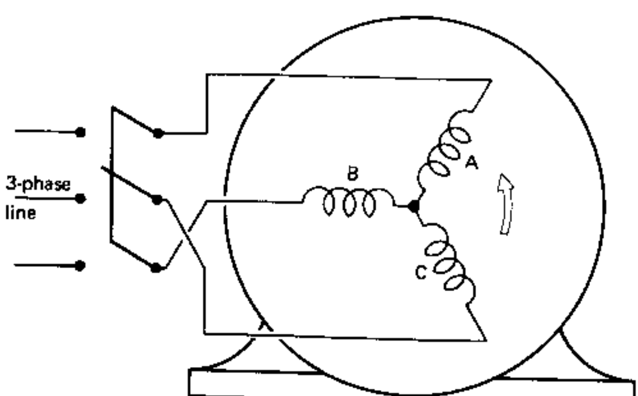


Fig. 4-109. To reverse the direction of rotation, interchange any two motor leads.

Figures 4-107; 4-108; 4-109

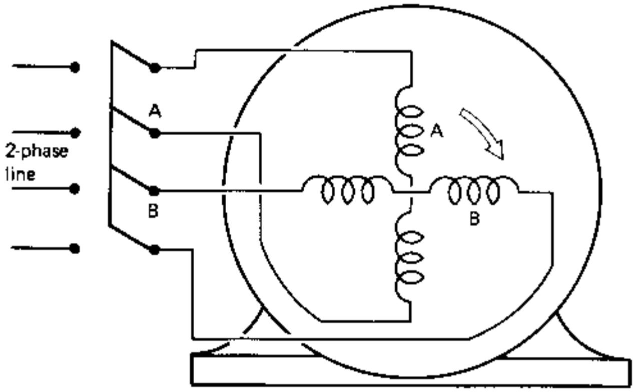


Fig. 4-110. A two-phase motor connected to a two-phase line.

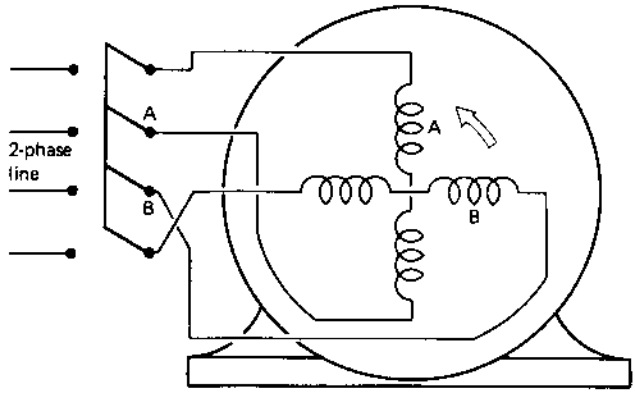


Fig. 4-111. To reverse the direction of rotation, interchange the leads of one phase.

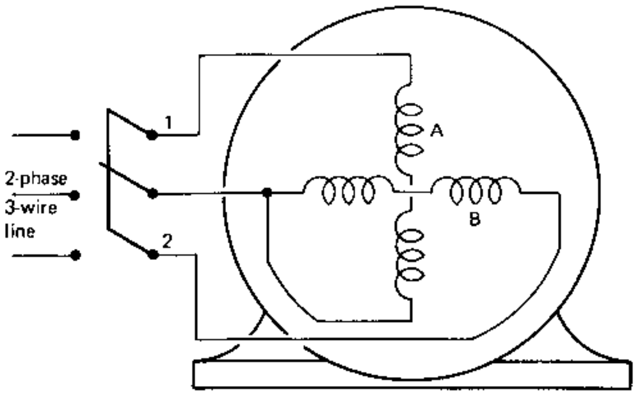


Fig. 4-112. To reverse the direction of a three-wire, two-phase motor interchange the outer two motor leads, *1* and *2*.

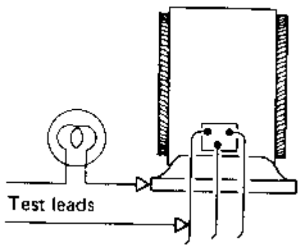
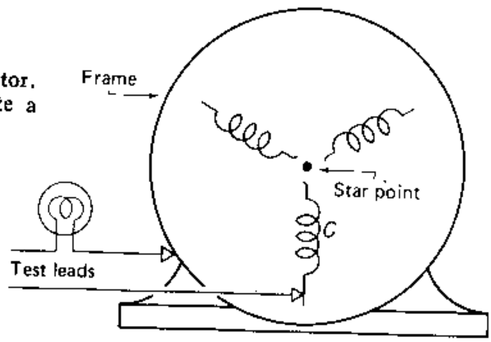


Fig. 4-113. Testing a polyphase motor for grounds.

Fig. 4-114. A star-connected motor. Disconnect the star point to locate a grounded phase.



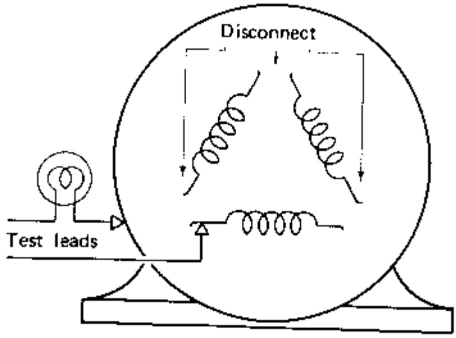


Fig. 4-115. In a delta-connected motor disconnect phases to locate a grounded phase.

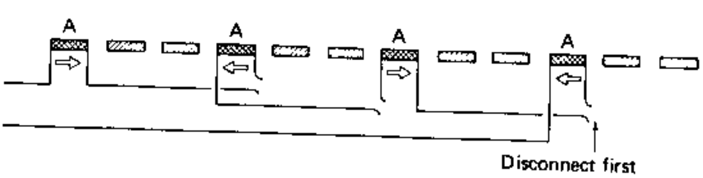


Fig. 4-116. To locate the grounded group, disconnect jumpers between groups of that phase.

Figures 4-113; 4-114; 4-115; 4-116

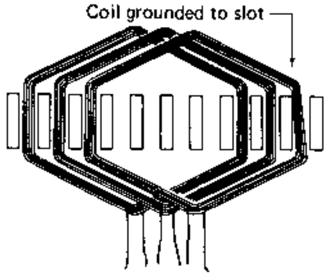


Fig. 4-117. To find a grounded coil, disconnect splices and test each coil separately.

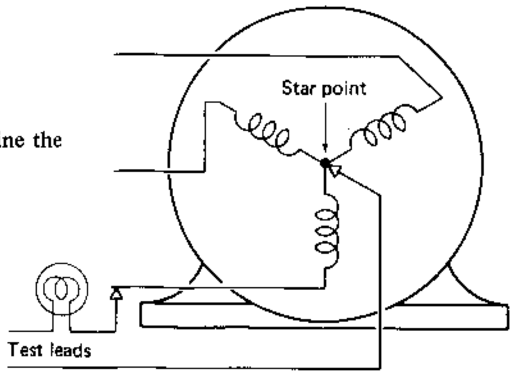


Fig. 4-118. A test to determine the open phase in a star motor.

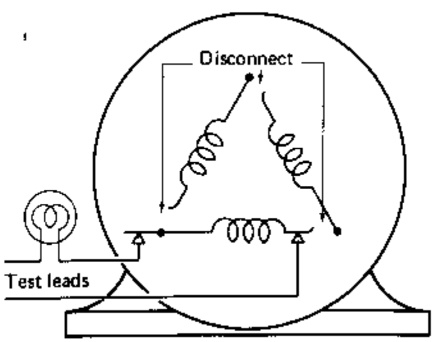


Fig. 4-119. Determining the open phase in a delta motor.

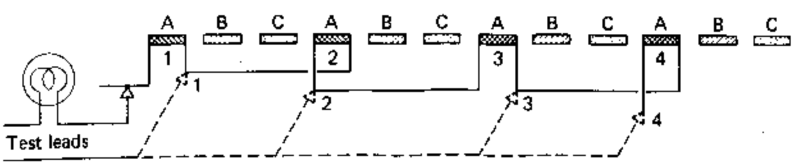


Fig. 4-120. Consecutive tests for locating an open group.

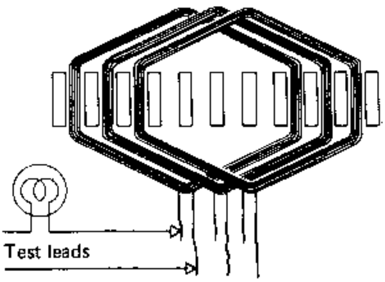


Fig. 4-121. A group with splices disconnected to locate an open coil.

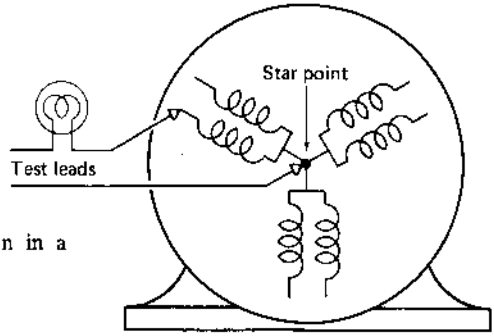


Fig. 4-122. Locating an open in a two-parallel star motor.

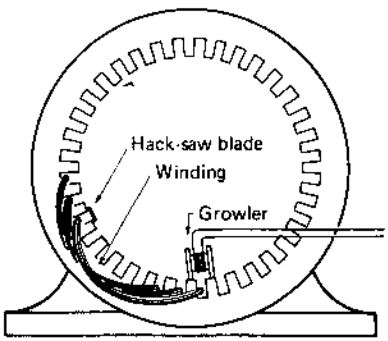


Fig. 4-123. The use of an internal growler to locate a shorted coil.

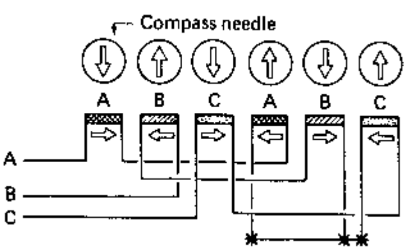


Fig. 4-124. The correct method of con necting a three-phase, two-pole star (WYE) motor is indicated by the compass needle.

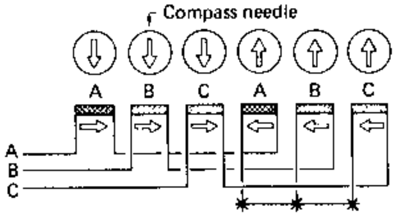


Fig. 4-125. An incorrect connection of phase *B*. Reverse this phase.

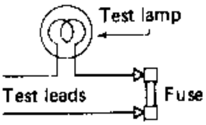


Fig. 4-126. Testing a fuse with a test lamp.

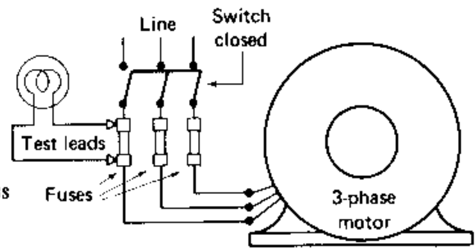


Fig. 4-127. A test lamp placed across a burned-out fuse will light.

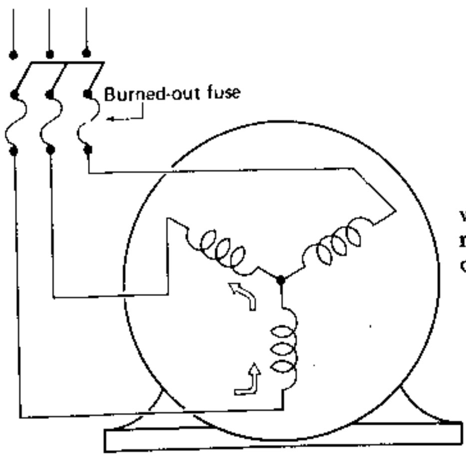


Fig. 4-128. A star-connected motor with burned-out fuse in one phase. Current through the other two phases will overload the coils and burn them out.

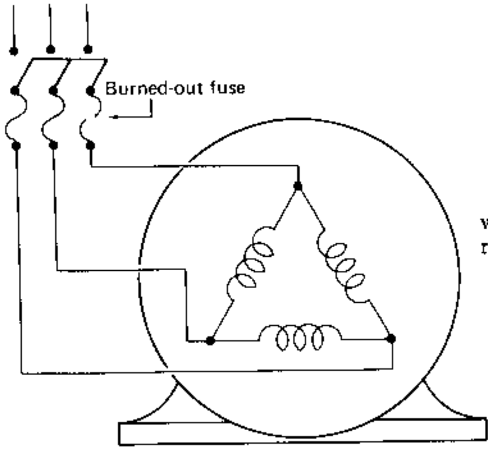


Fig. 4-129. A delta-connected motor with burned-out fuse in one phase. Current will flow in one of the phases.

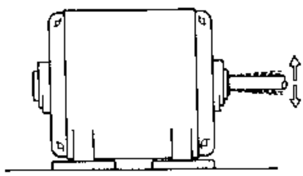


Fig. 4-130. Lift the shaft up and down. Movement indicates worn bearing of shaft.

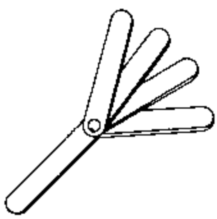


Fig. 4-131. A feeler gauge, which has thin metal strips of different thickness.

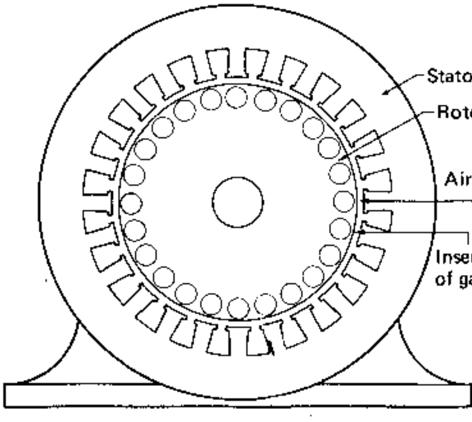


Fig. 4-132. The air gap should be the same around the entire motor. This is checked with a feeler gauge.

Figures 4-129; 4-130; 4-131; 4-132

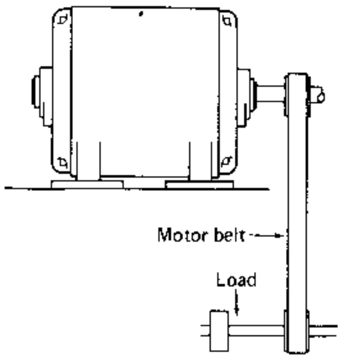


Fig. 4-133. Disconnect belt and try to move load in order to see if load is free to turn.

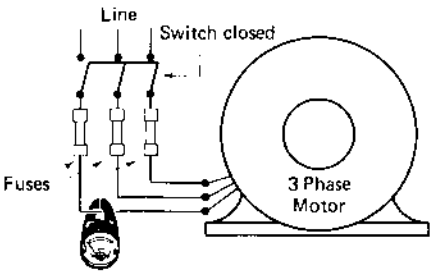


Fig. 4-134. Snap around ammeter used to determine current in each line.

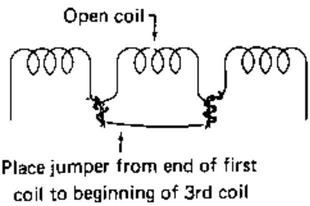


Fig. 4-135. The method of jumping out one coil of a group of three coils.

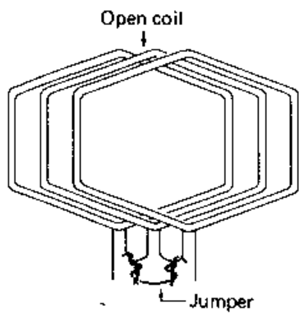


Fig. 4-136. The method of jumping out one coil of a diamond-shaped group.

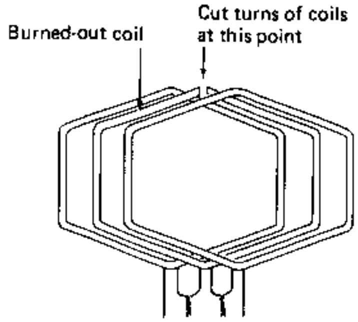
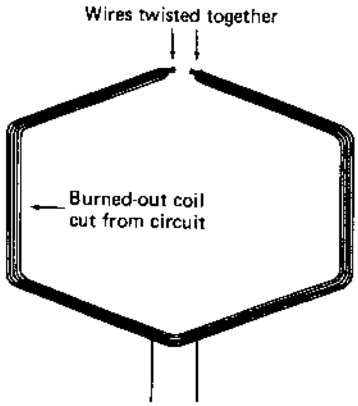


Fig. 4-137. Cutting turns of a burned-out coil.

Fig. 4-138. A coil cut and wires twisted together on both sides.



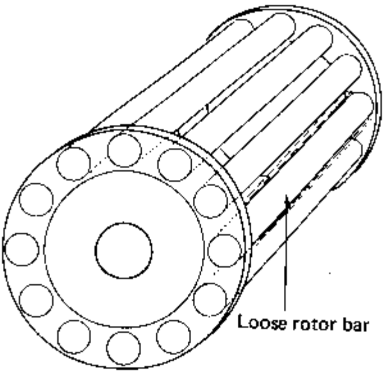


Fig. 4-139. Rotor bars are welded or cast on end rings. One or more bars may loosen, thus causing poor operation of motor.

Figures 4-137; 4-138; 4-139

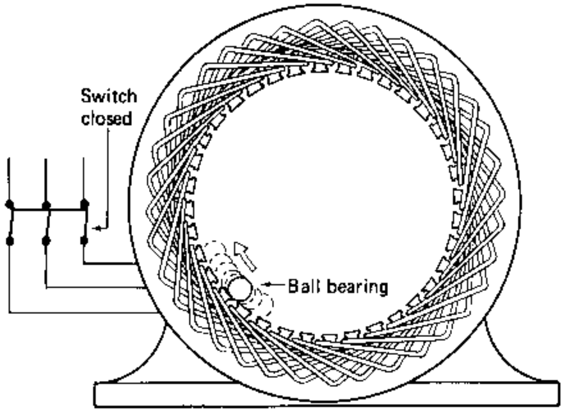


Fig. 4-140. The ball bearing should rotate around the core of the stator if internal connections are correct.

CHAPTER 5

Alternating-current Motor Control

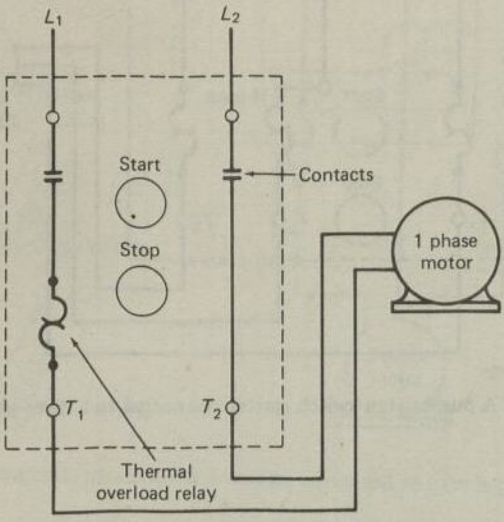


Fig. 5-1. A pushbutton switch starter connected to a single-phase motor.

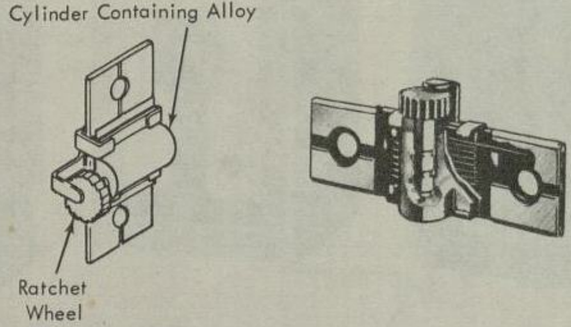


Fig. 5-2. A thermal relay of the melting-alloy type.

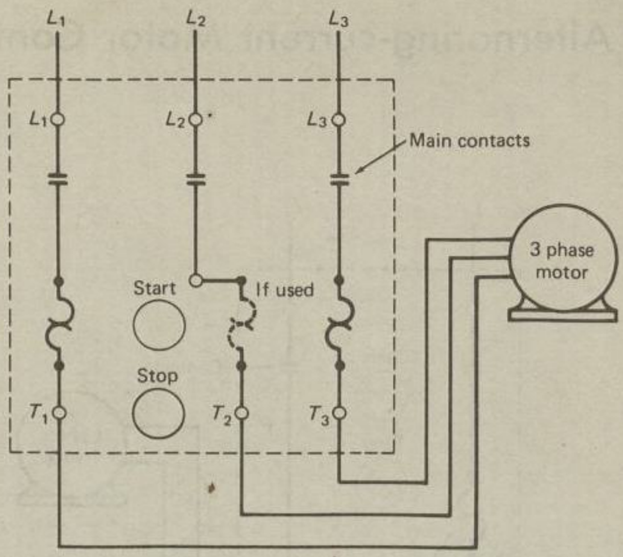


Fig. 5-3. A pushbutton switch starter connected to a three-phase motor.

Fig. 5-4. Types of manual starters. *(Furnas Electric Company)*

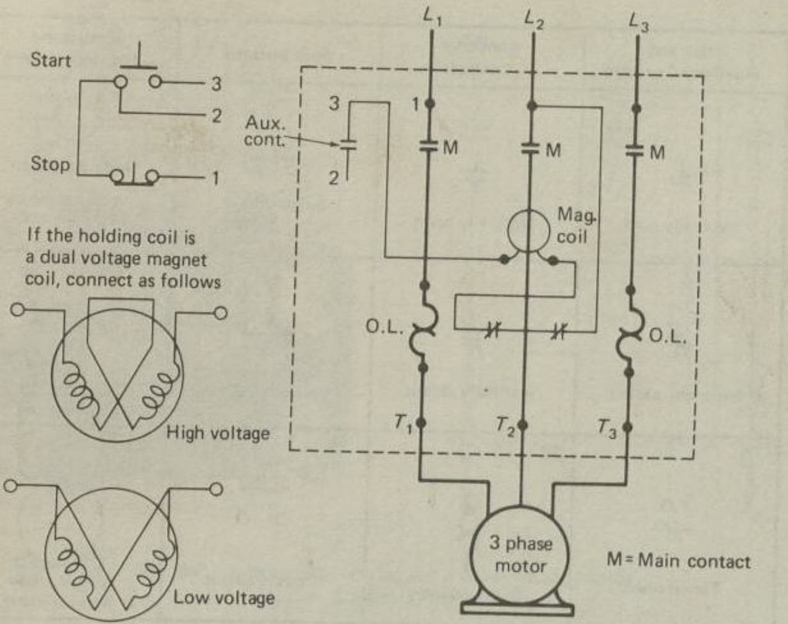


Fig. 5-5. A magnetic across-the-line starter connected to a three-phase motor.

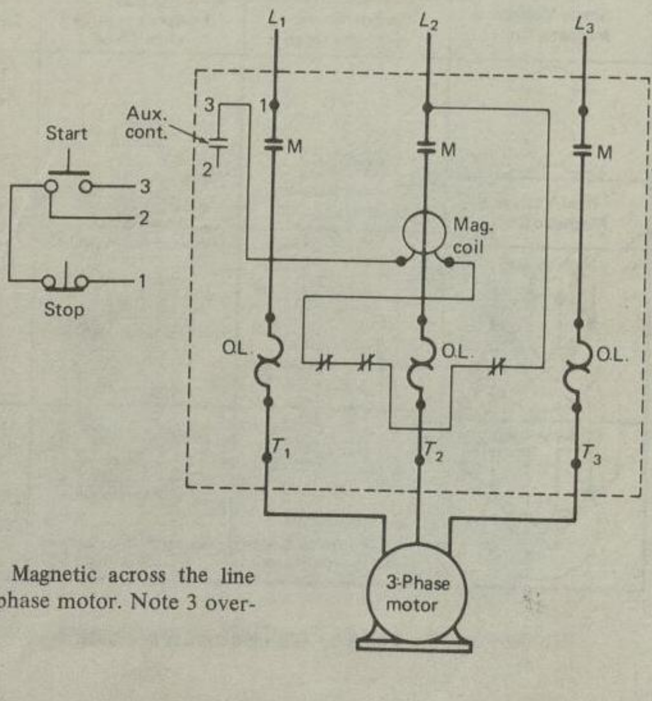


Fig. 5-6. Magnetic across the line starter for 3-phase motor. Note 3 overload relays.

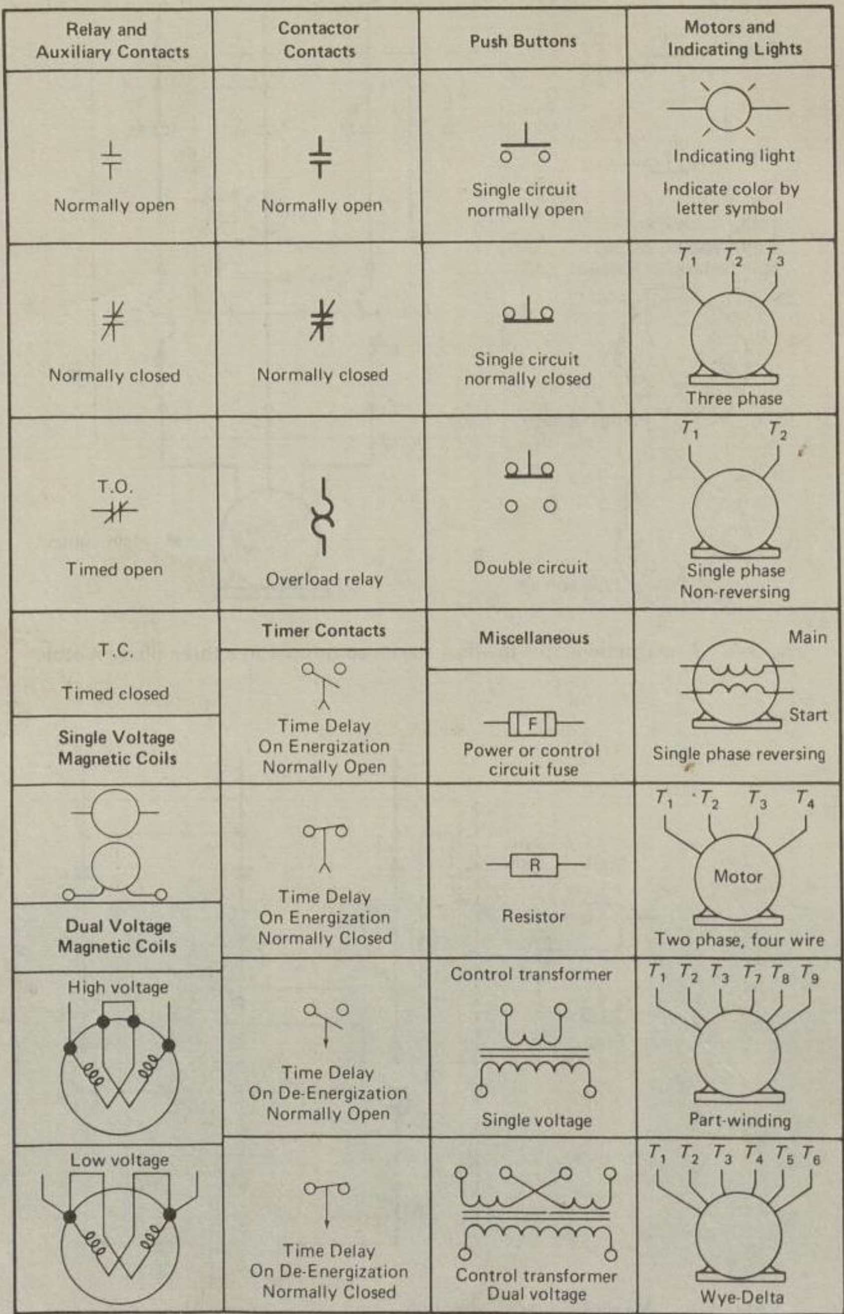


Fig. 5-7. Wiring diagram symbols.

Figure 5-7

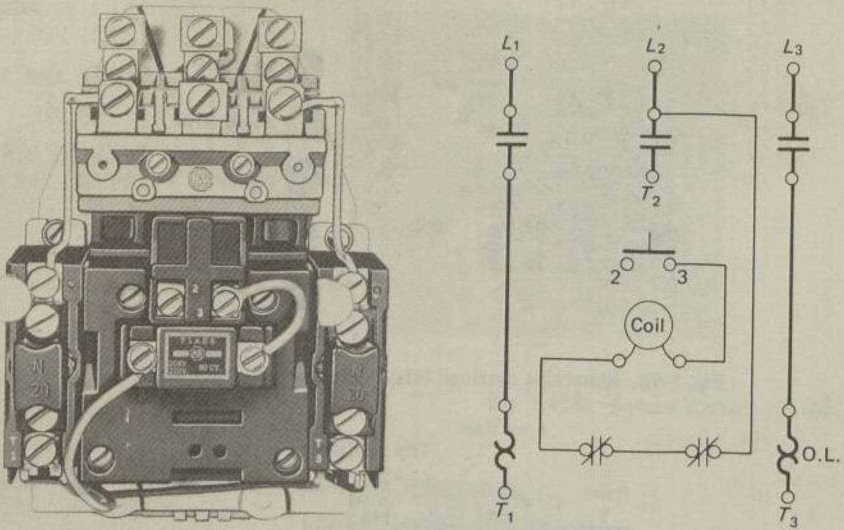


Fig. 5-8. A magnetic starter for a three-phase motor. *(Allen Bradley Company)*

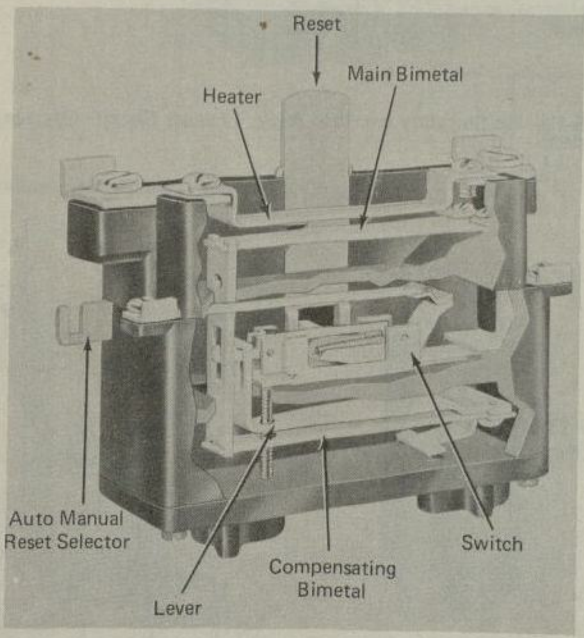


Fig. 5-9A. Bimetallic overload relay. *(Furnas Electric Company)*

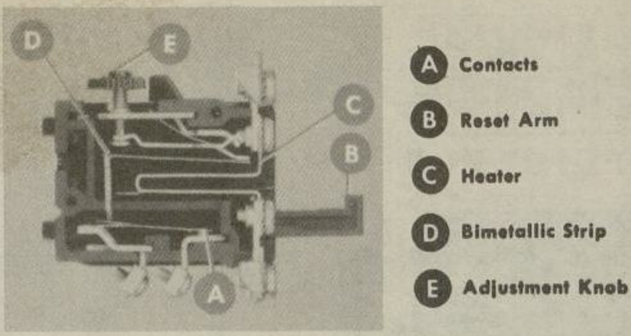


Fig. 5-9B. Bimetallic overload relay. *(General Electric Company)*

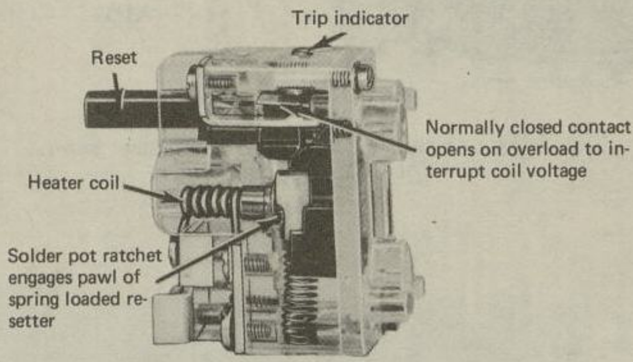


Fig. 5-10. Melting alloy overload relay. *(Furnas Electric Company)*

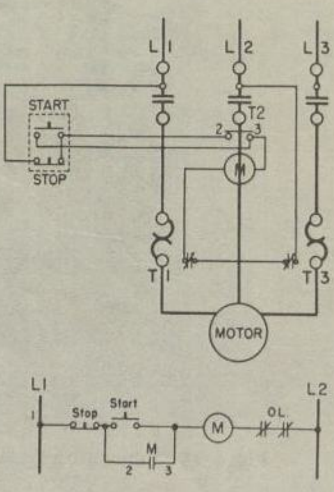


Fig. 5-11A. 3-phase starter. *(Allen-Bradley Company)*

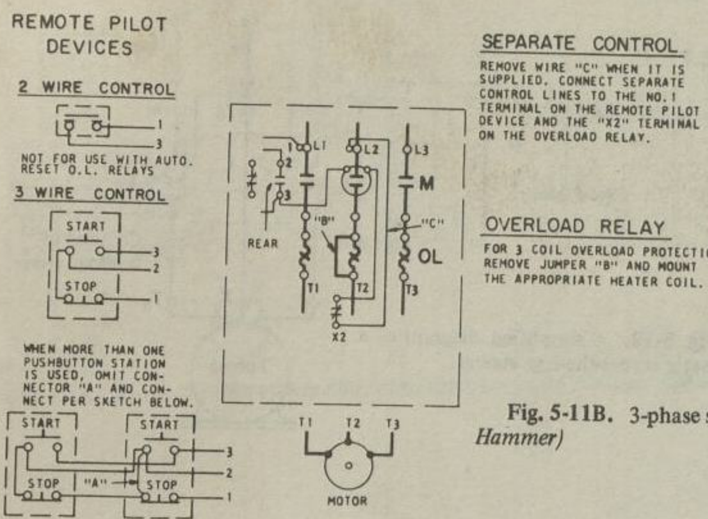


Fig. 5-11B. 3-phase starter. *(Cutler-Hammer)*

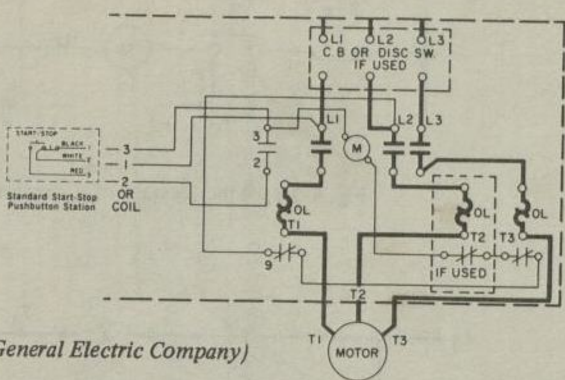


Fig. 5-11C. 3-phase starter. *(General Electric Company)*

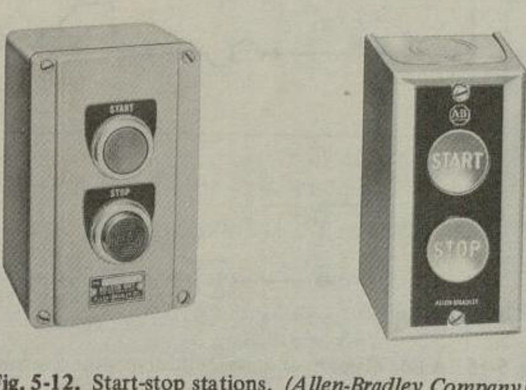


Fig. 5-12. Start-stop stations. *(Allen-Bradley Company)*

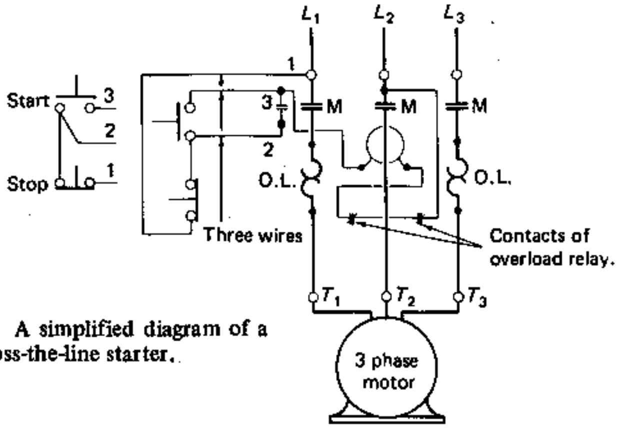


Fig. 5-13. A simplified diagram of a magnetic across-the-line starter.

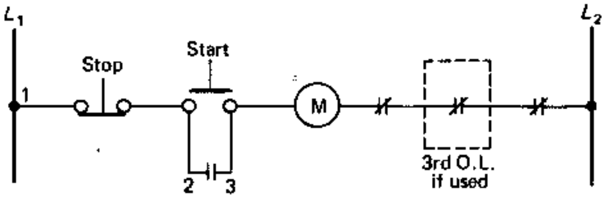


Fig. 5-14. Line diagram of a control circuit.

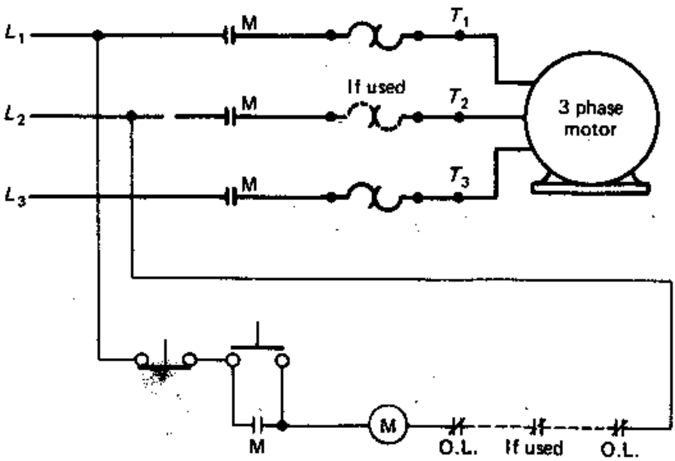


Fig. 5-15. A line diagram of a magnetic across-the-line starter.

Figures 5-13; 5-14; 5-15

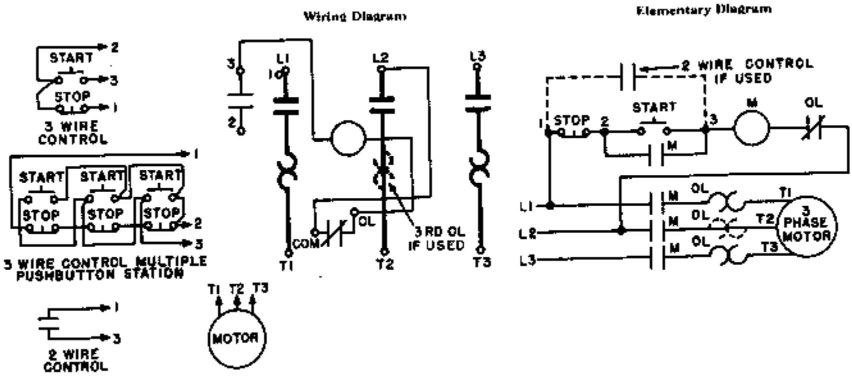


Fig. 5-16. 3-pole, 3-phase starter with external 2 or 3 wire control. *(Square D Company)*

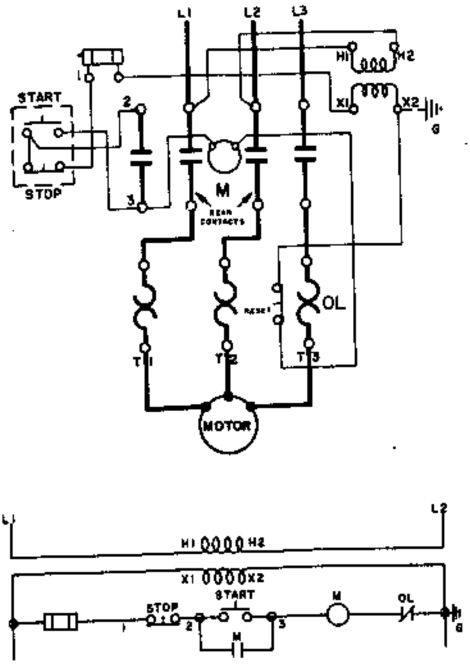


Fig. 5-17. 3-phase starter with 3-coil thermal O.L. relay and step down control transformer in control circuits. *(Cutler-Hammer)*

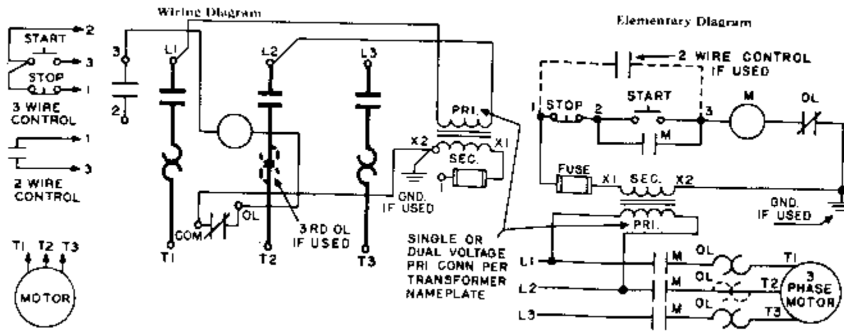


Fig. 5-18. 3-phase starter with control-circuit transformer and secondary fuse. *(Square D Company)*

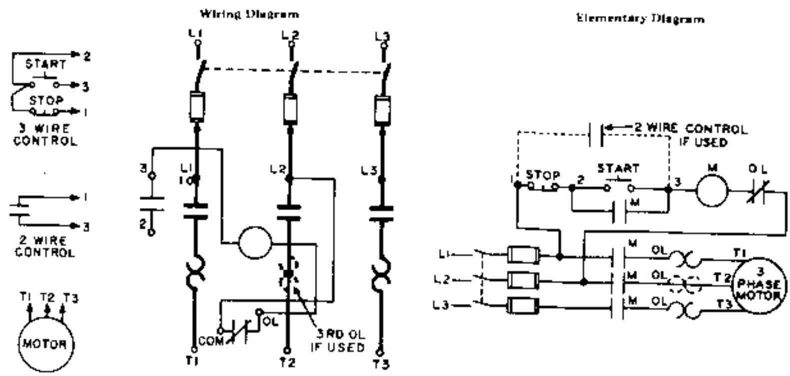


Fig. 5-19. Combination starters with fusible disconnect switch. *(Square D Company)*

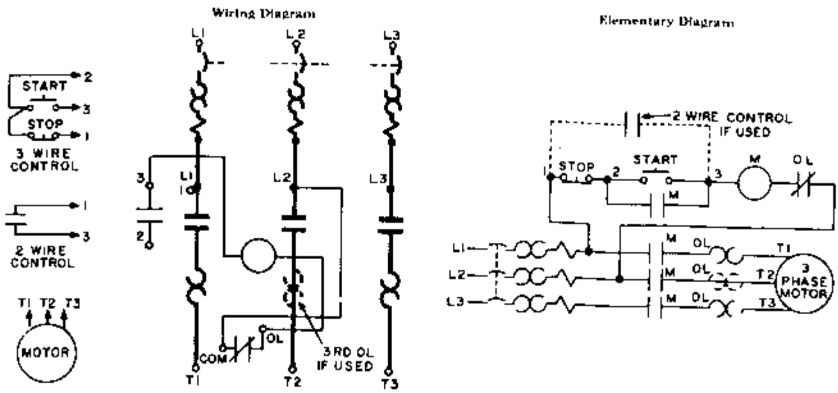


Fig. 5-20. Combination starters with thermal magnetic circuit breaker. *(Square D Company)*

Figures 5-18; 5-19; 5-20

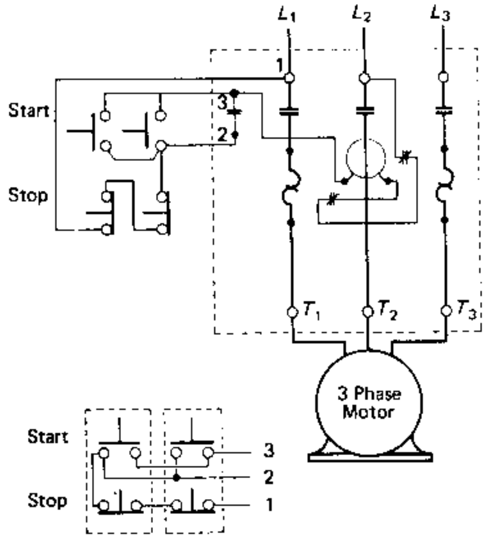


Fig. 5-21. A magnetic switch controlled by two START-STOP stations.

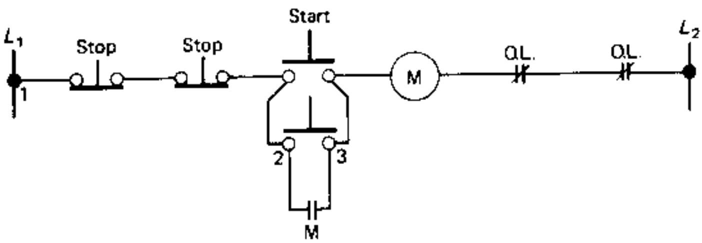


Fig. 5-22. A control circuit for two START-STOP stations.

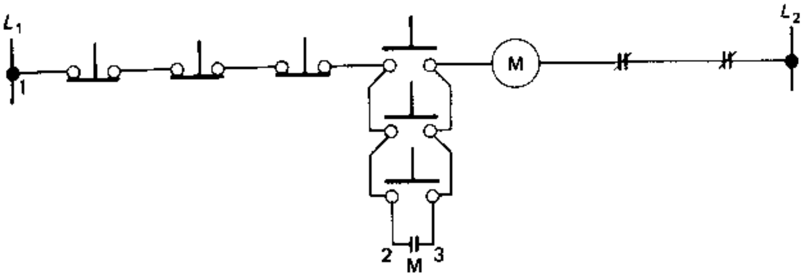


Fig. 5-23. A control circuit for three START-STOP stations.

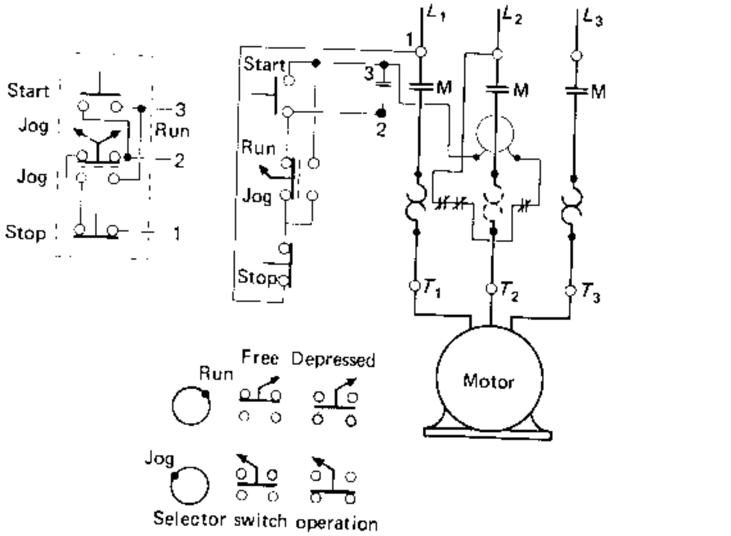


Fig. 5-24. A START-JOG-STOP station with selector push button, connected to a magnetic switch.

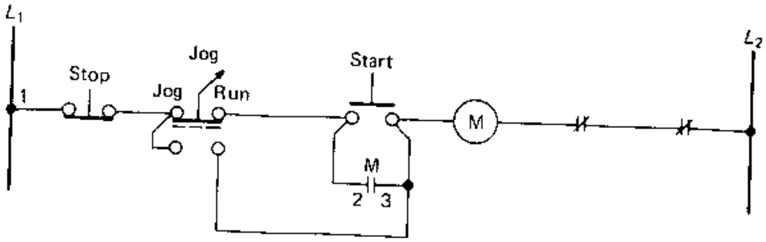


Fig. 5-25. START–JOG–STOP station with selector push button.

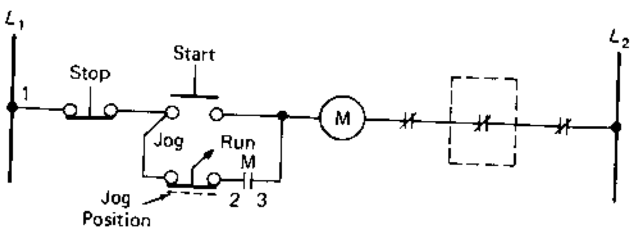


Fig. 5-26. Jogging with push-turn selector switch.

Figures 5-24; 5-25; 5-26

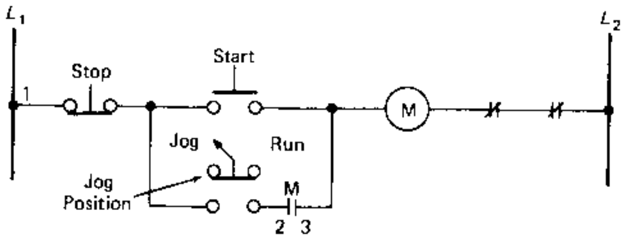


Fig. 5-27. Jogging with a selector switch.

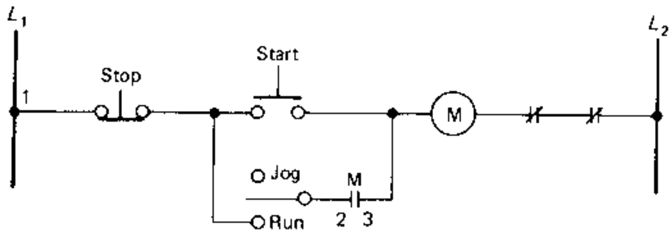
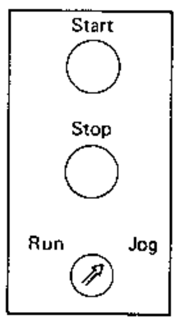


Fig. 5-28. Control circuit with JOG-RUN selector switch.

Fig. 5-29. A panel of a station in which the START button can be used for inching or jogging.



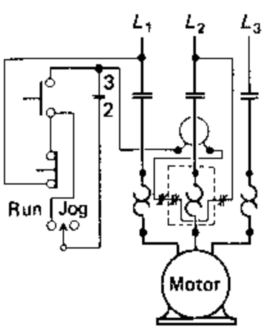


Fig. 5-30. Magnetic switch with JOG-RUN selector switch.

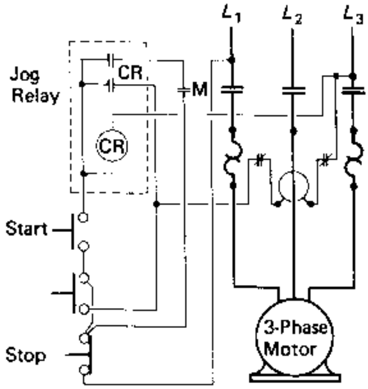


Fig. 5-31. A magnetic switch operated by a START-JOG-STOP station with a jog-relay attachment.

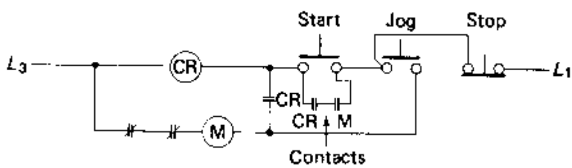


Fig. 5-32. An elementary diagram of **Fig. 5-31.**

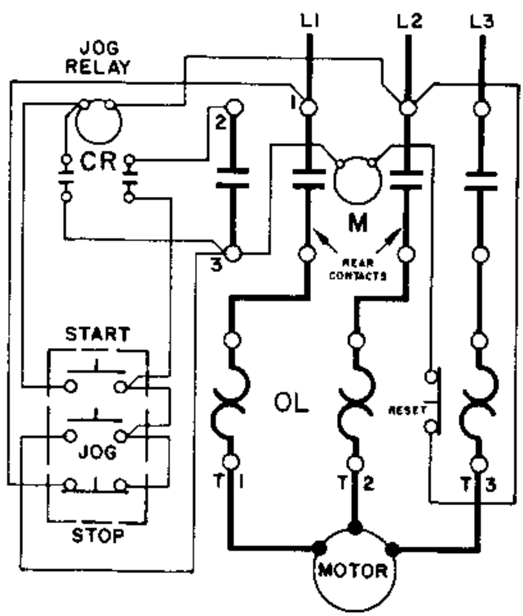


Fig. 5-33. A jog relay connected to a magnetic switch.

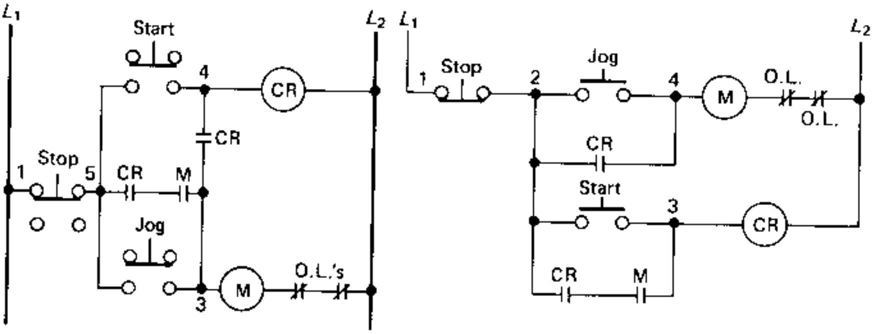


Fig. 5-34. Control circuits of START-JOG-STOP button connected to a jog relay.

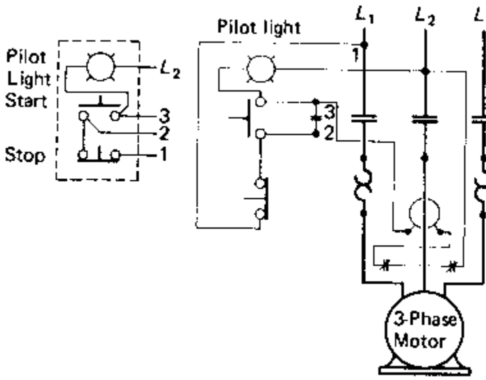


Fig. 5-35. Push button station with pilot light connected to a 3-phase magnetic starter.

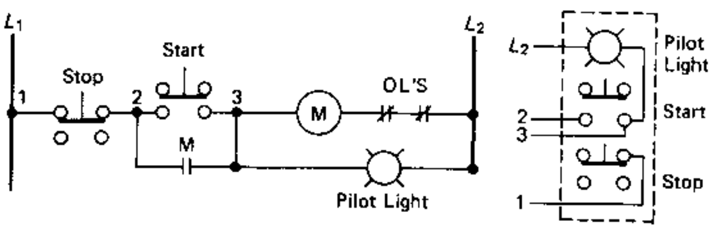


Fig. 5-36. A simple control circuit of a START-STOP station sith a pilot light.

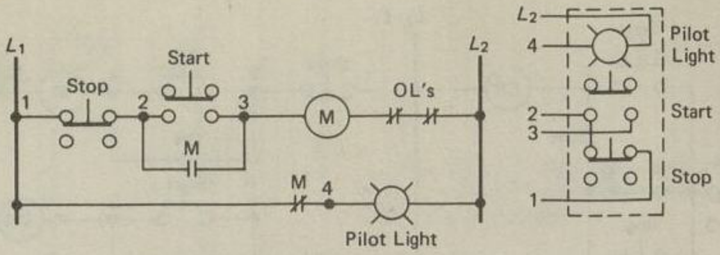


Fig. 5-37. Pilot light indicates when motor is not running. Normally closed contact M must be added to the starter.

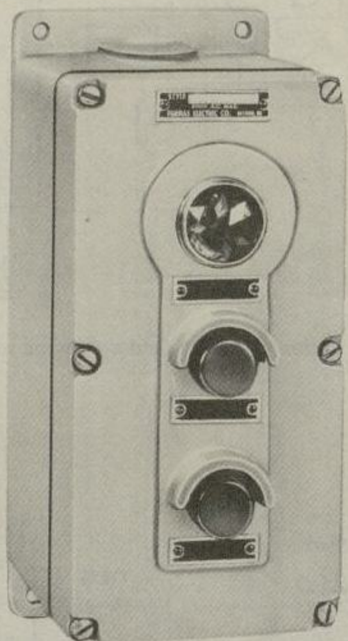


Fig. 5-38. Station with pilot light. *(Furnas Electric Company)*

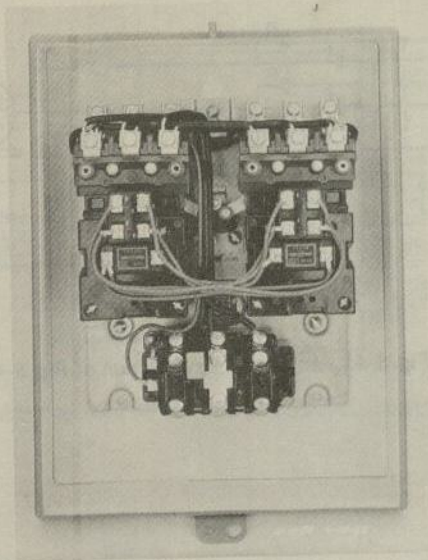


Fig. 5-39. An A.C. full-voltage magnetic reversing controller. *(Allen Bradley Company)*

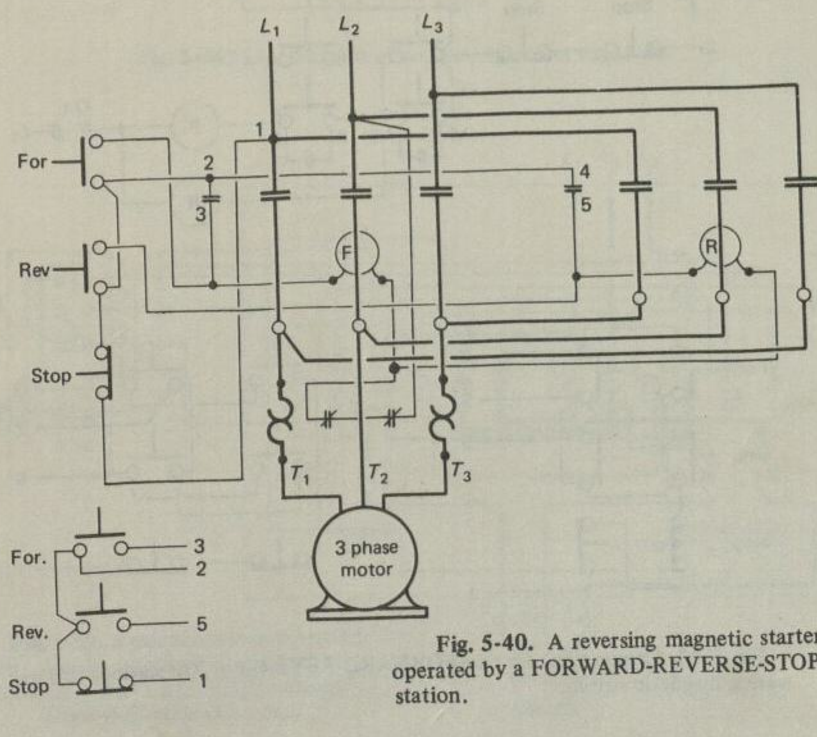


Fig. 5-40. A reversing magnetic starter operated by a FORWARD-REVERSE-STOP station.

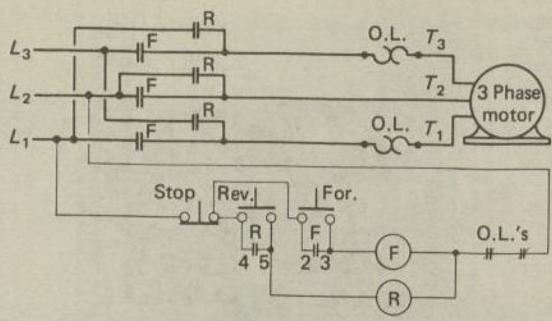


Fig. 5-41. An elementary diagram of **Fig. 5-40.**

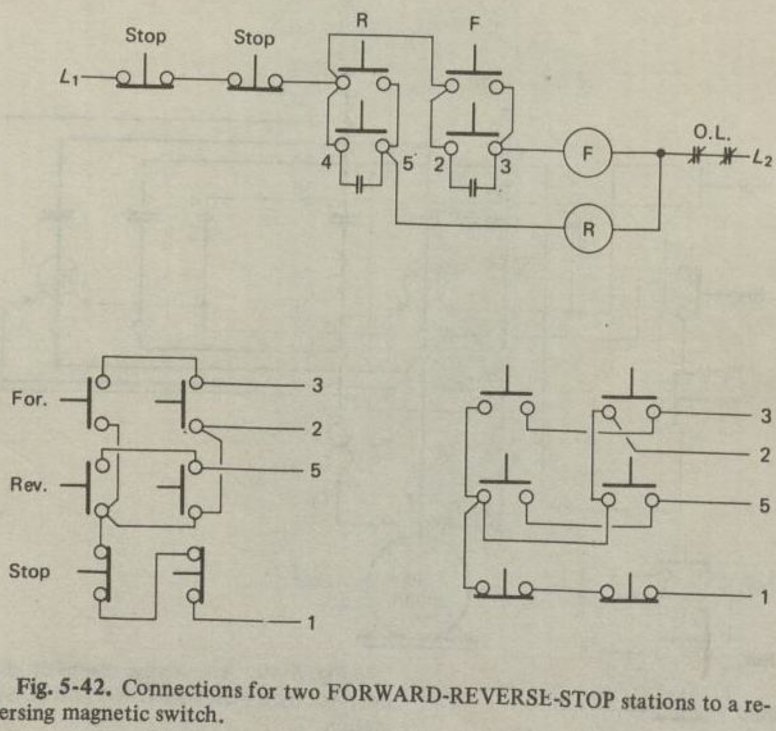


Fig. 5-42. Connections for two FORWARD-REVERSE-STOP stations to a reversing magnetic switch.

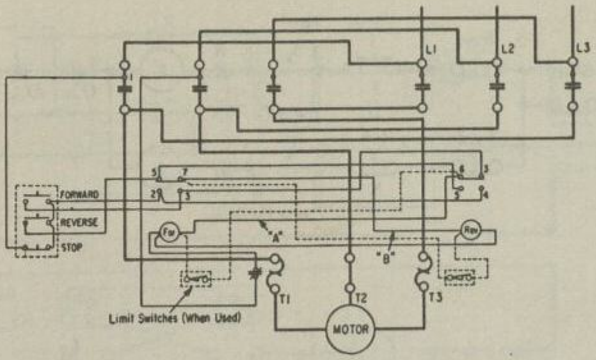


Fig. 5-43. Reversing magnetic starter with electrical interlock. *(Allen-Bradley)*

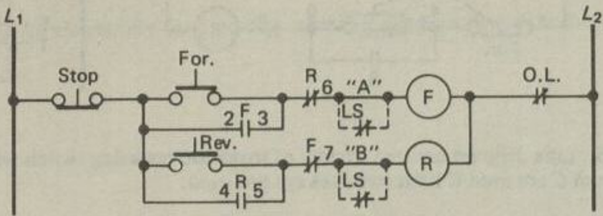


Fig. 5-44. Line diagram of control circuits of **Fig. 5-43.**

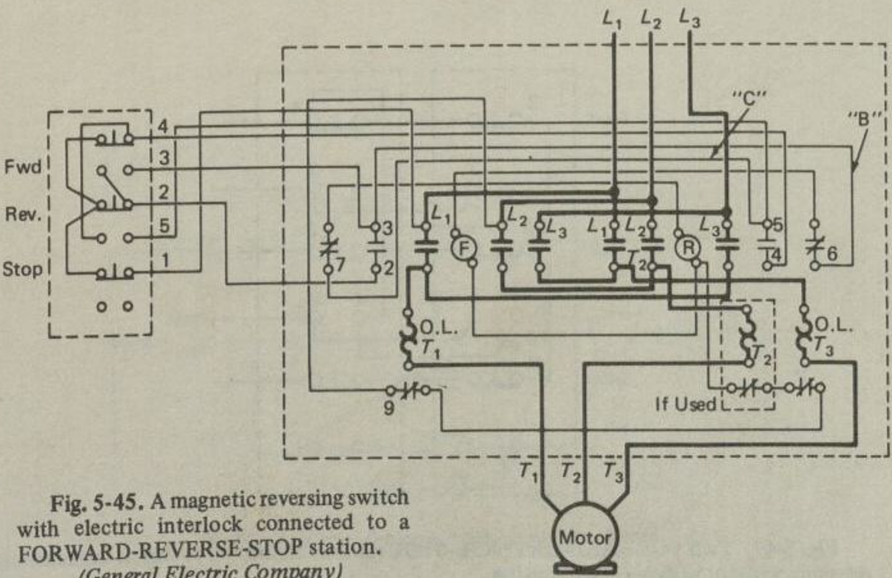
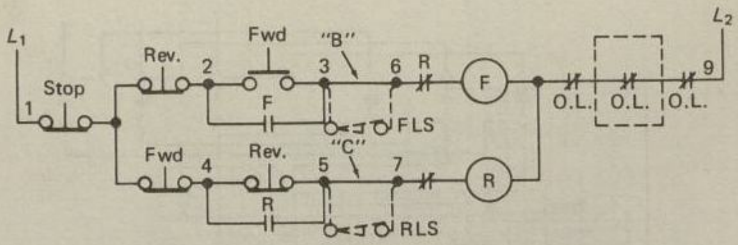


Fig. 5-45. A magnetic reversing switch with electric interlock connected to a FORWARD-REVERSE-STOP station. *(General Electric Company)*



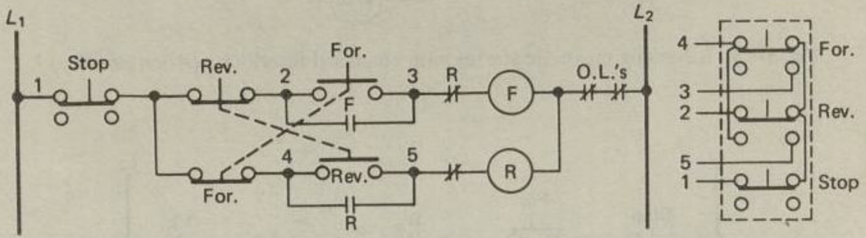


Fig. 5-46. Line diagram control circuits of magnetic reversing switch with electric interlock. *B* and *C* are used if limit switches are not used.

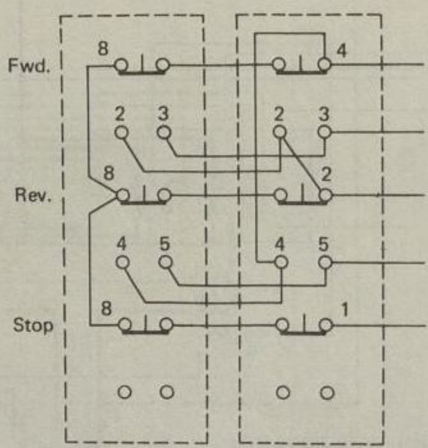


Fig. 5-47. Two FORWARD-REVERSE-STOP stations connected to fermis immediately resersing without pressing STOP button.

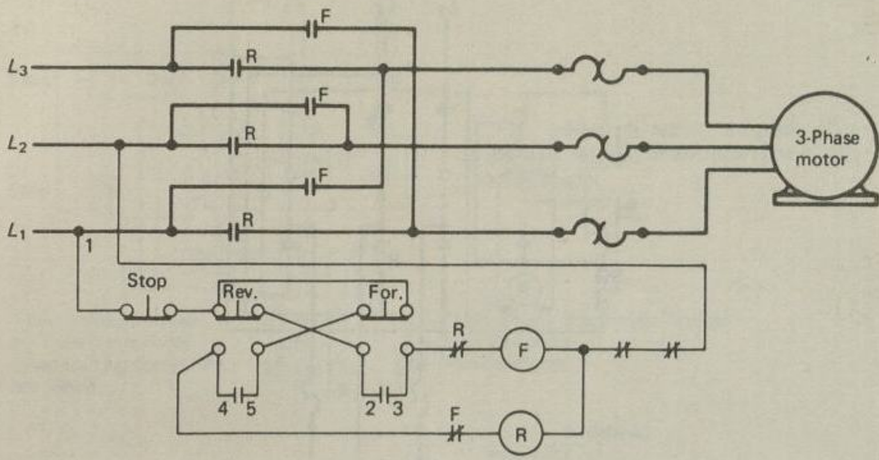


Fig. 5-48. An elementary diagram of a reversing magnetic starter with electrical interlocks.

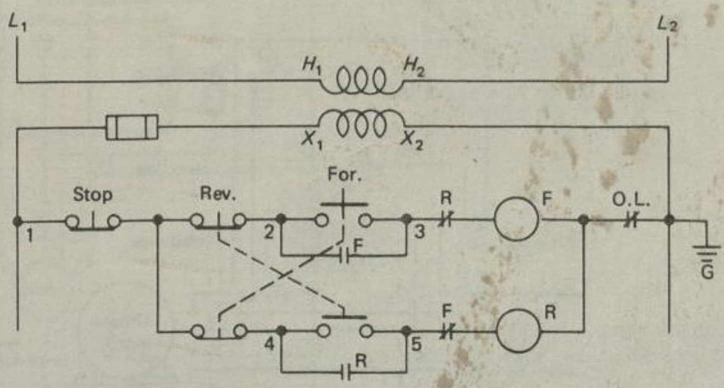


Fig. 5-49. Control circuit with step down transformer.

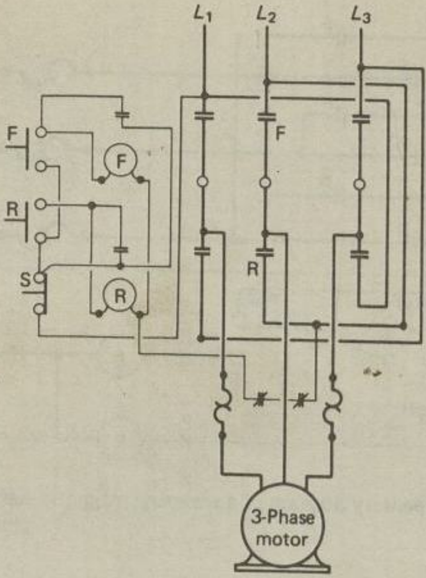


Fig. 5-50. A magnetic reversing switch in a vertical, instead of a horizontal, position.

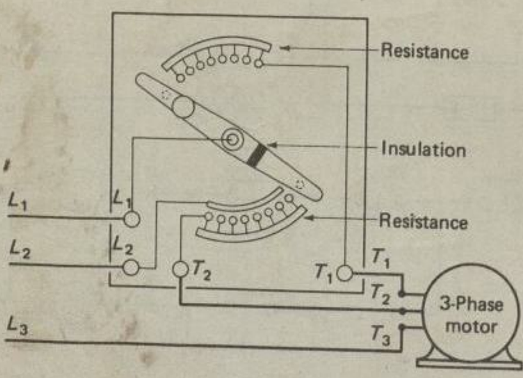


Fig. 5-51. A manual resistance starter of the rheostat type.

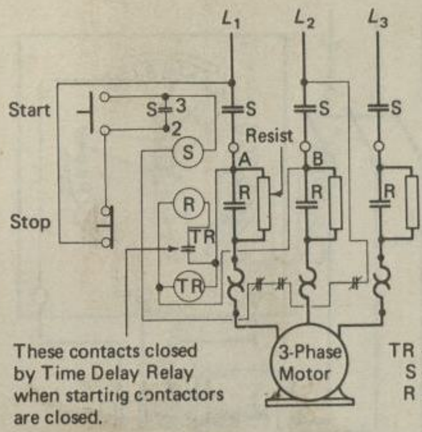


Fig. 5-52. A wiring diagram of a single-step, primary-resistance type of automatic starter.

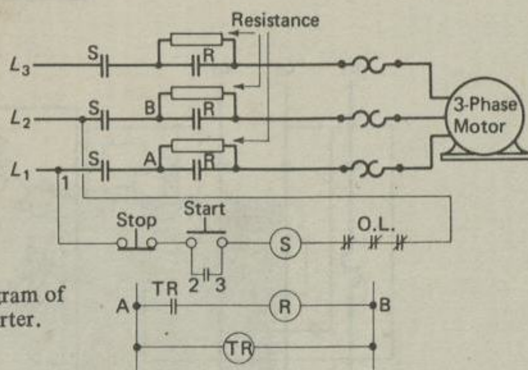


Fig. 5-53. An elementary diagram of a primary-resistance automatic starter.

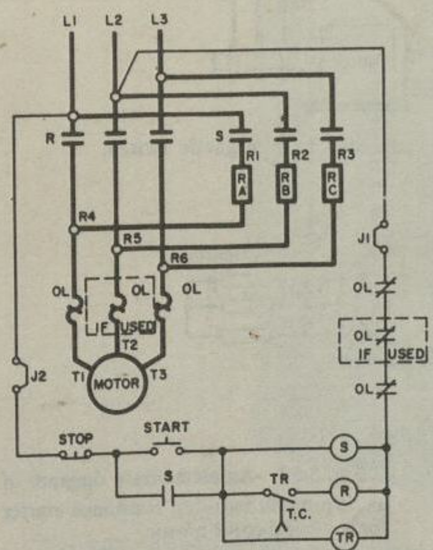


Fig. 5-54. A primary-resistor stator with pneumatic timer. *(General Electric Company)*

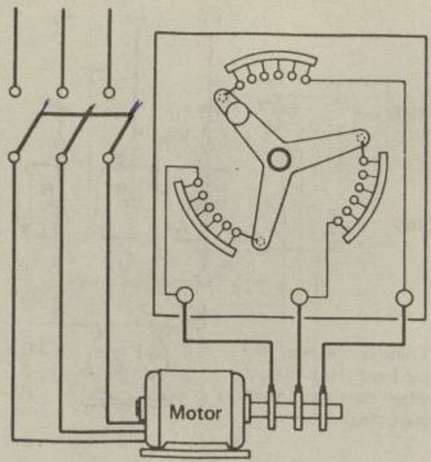


Fig. 5-55. A secondary-resistance starter connected to a wound motor. A 3-pole manual switch is used for the stator.

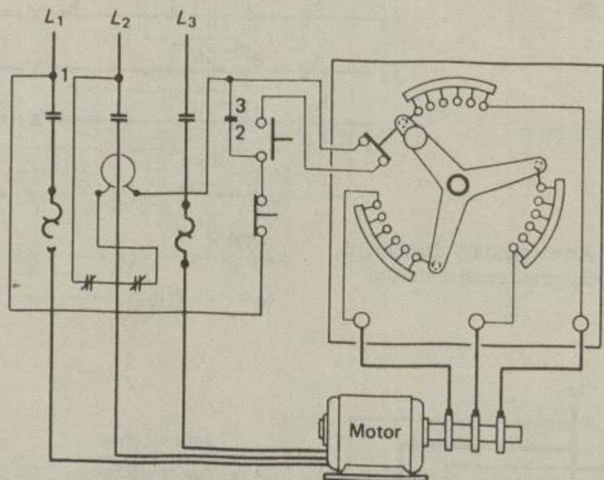


Fig. 5-56. A resistance starter connected to a magnetic switch.

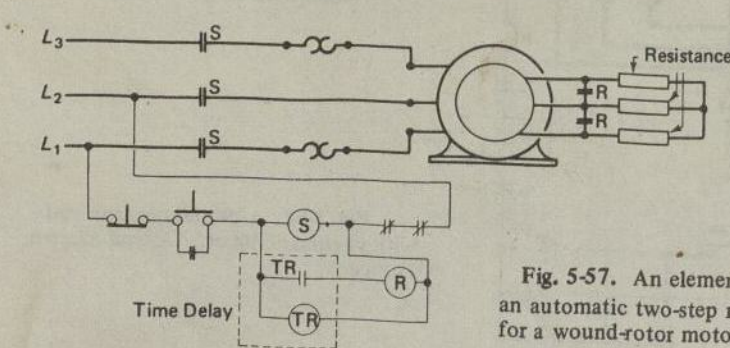


Fig. 5-57. An elementary diagram of an automatic two-step resistance starter for a wound-rotor motor.

Figures 5-55; 5-56; 5-57

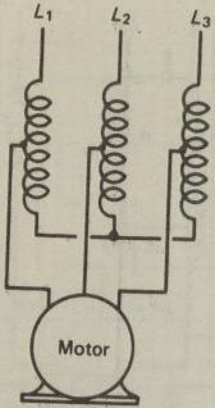


Fig. 5-58. The connection of a start position of a compensator.

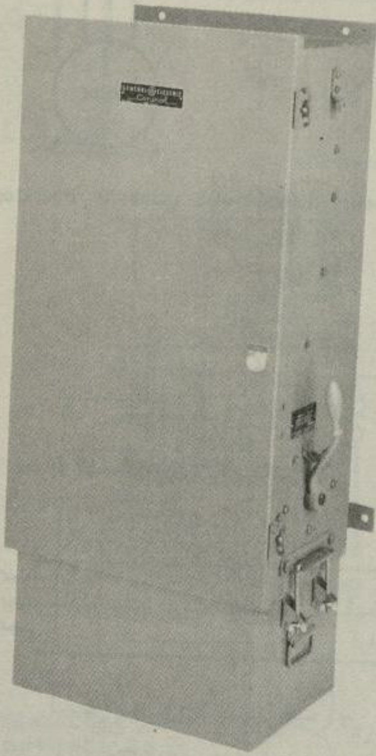


Fig. 5-59. Autotransformer type manual starter. *(General Electric Company)*

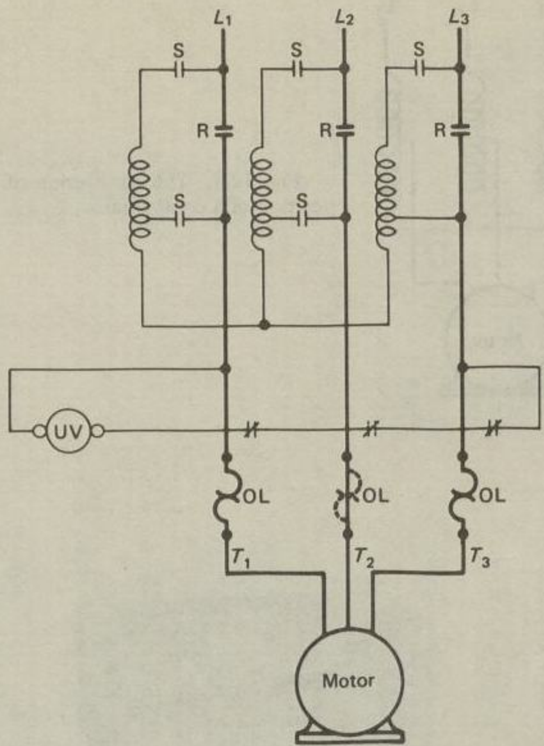


Fig. 5-60. Schematic diagram of a manually operated 3-phase autotransformer starter.

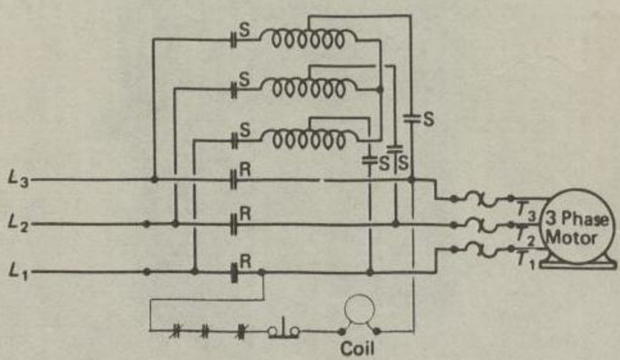


Fig. 5-61. An elementary diagram of a three-phase compensator.

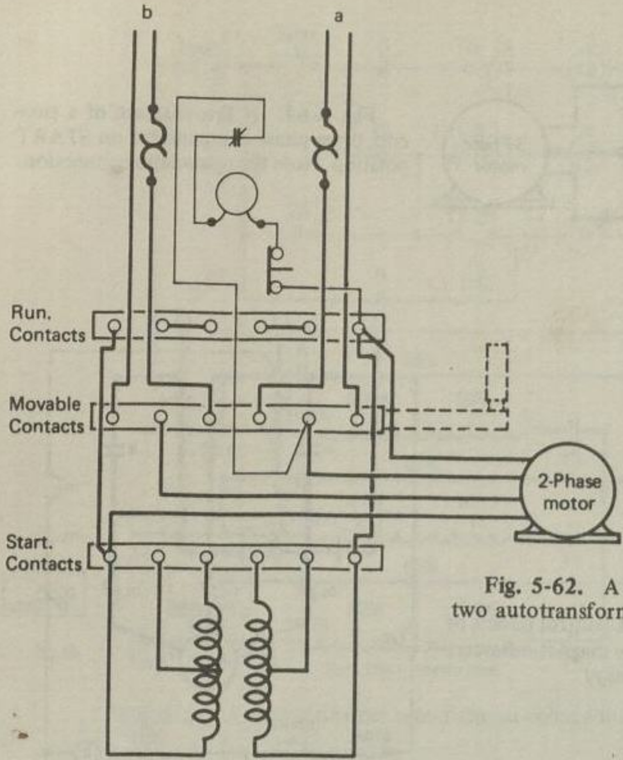


Fig. 5-62. A two-phase starter with two autotransformers.

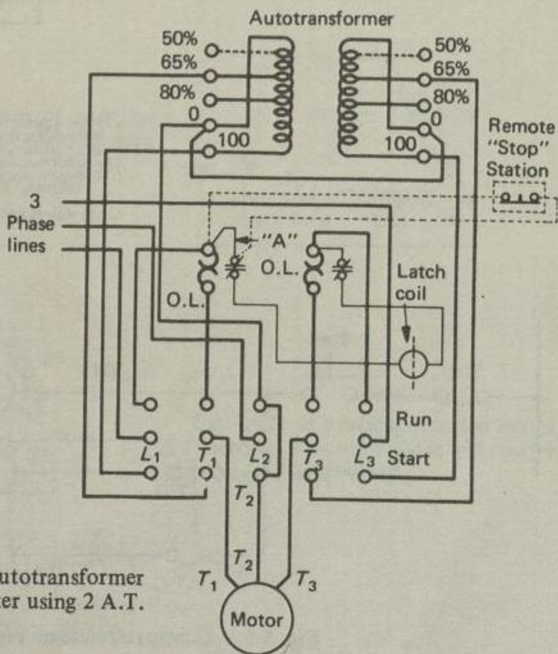


Fig. 5-63. A manual autotransformer type reduced-voltage starter using 2 A.T. coils.

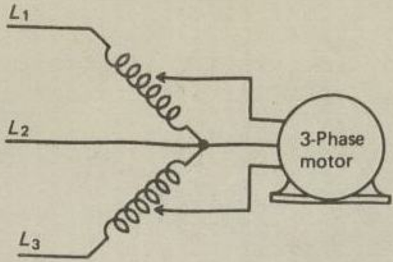


Fig. 5-64. A line diagram of a two-coil, three-phase compensator on START position. Note the open-delta connection.

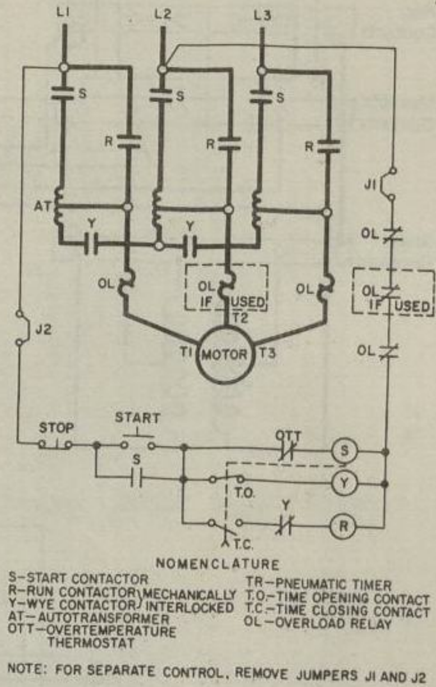


Fig. 5-65. Motor and control circuit of an autotransformer type magnetic starter. *(General Electric Company)*

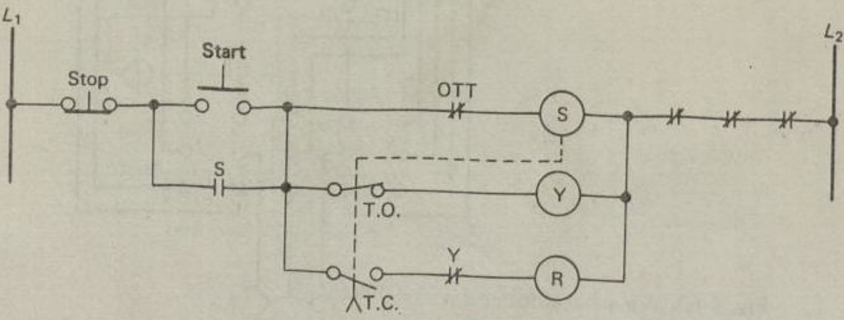


Fig. 5-66. Control circuits of Fig. 5-65.

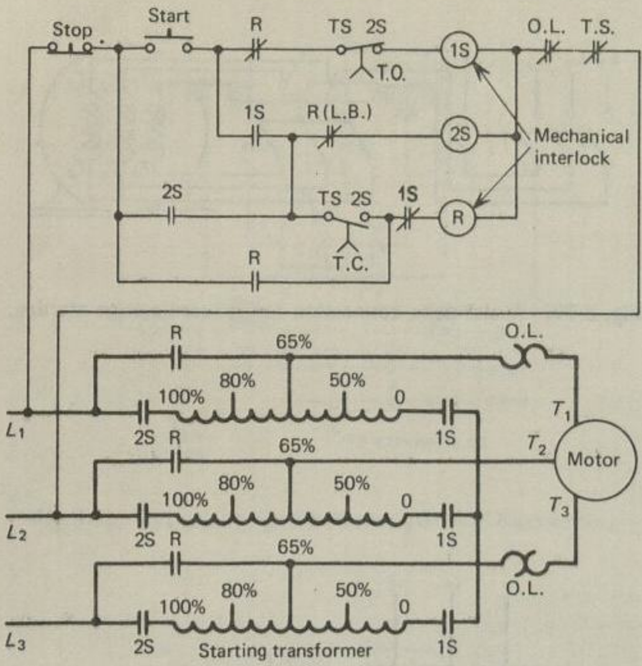


Fig. 5-67. Autotransformer type reduced-voltage magnetic starter.

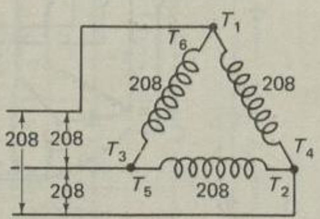


Fig. 5-68. Each phase of a delta-connected motor receives the full line voltage.

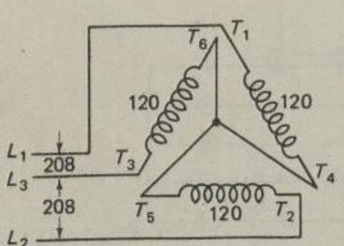


Fig. 5-69. If a delta-connected motor is connected wye, each phase will receive 58 percent of line voltage.

	L_1	L_2	L_3	Together
Start	T_1	T_2	T_3	$(T_4\ T_5\ T_6)$
Run	$T_1 T_6$	$T_2 T_4$	$T_3 T_5$	-------

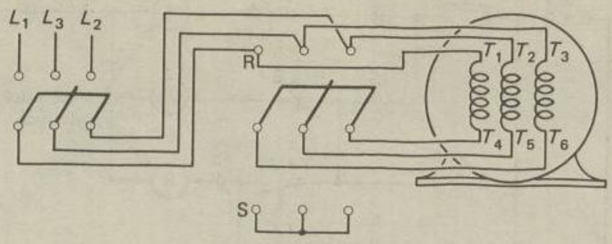


Fig. 5-70. A star-delta connection for reduced-voltage starting.

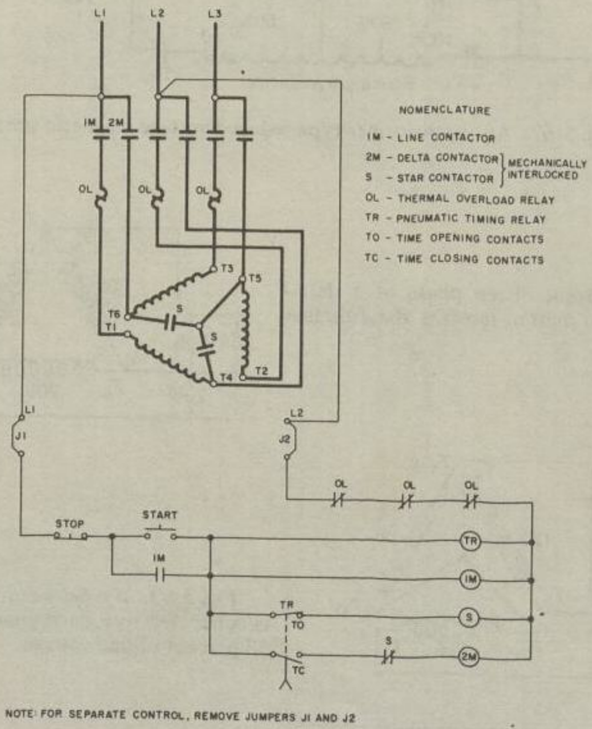


Fig. 5-71. Wye delta starter of the open transition type. *(General Electric Co.)*

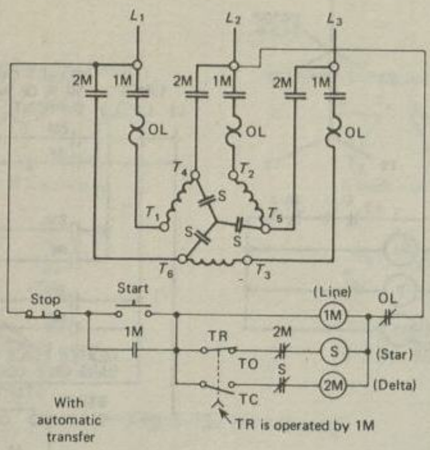


Fig. 5-72. Wye delta magnetic starter. *(General Electric Co.)*

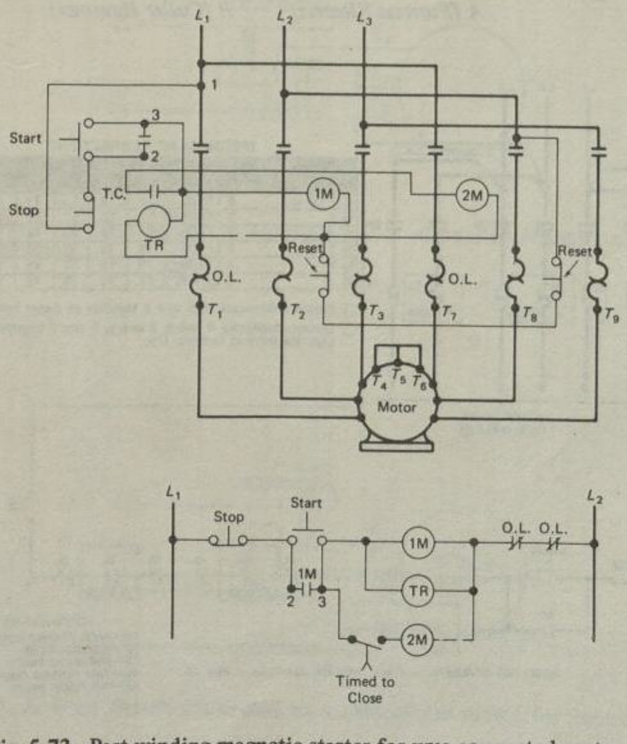


Fig. 5-73. Part-winding magnetic starter for wye-connected motor.

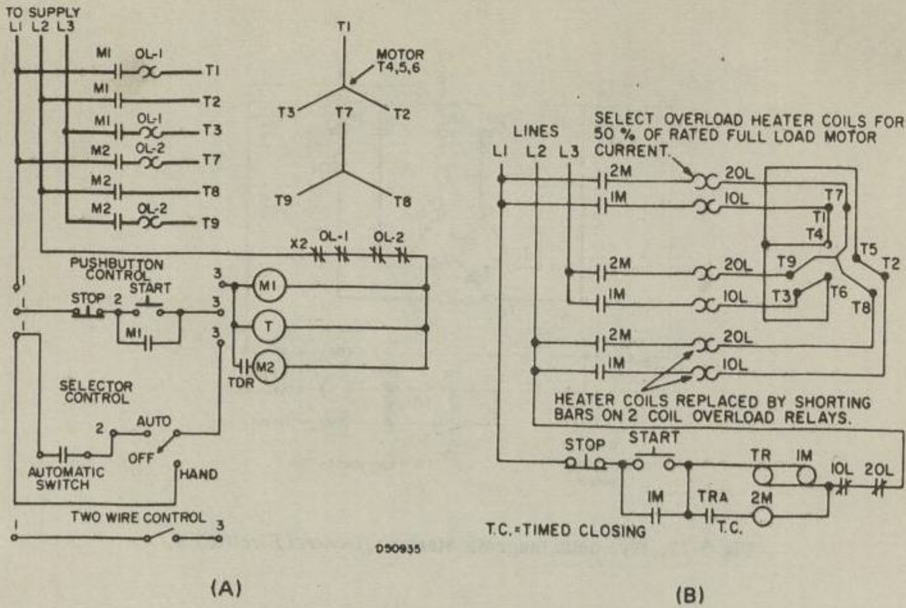
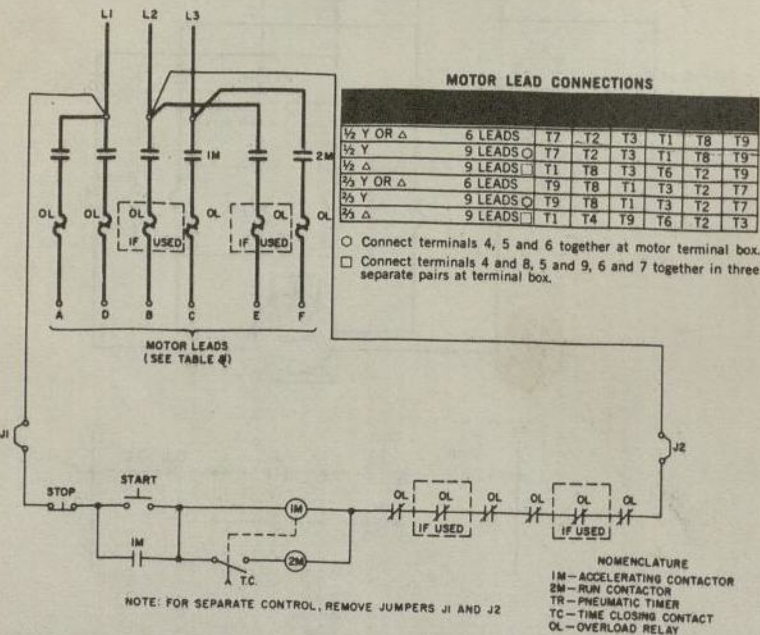


Fig. 5-74. Typical wiring diagrams of two step increment starting.
A (Furness Electric) *B (Cutler Hammer)*



MOTOR LEAD CONNECTIONS

½ Y OR Δ	6 LEADS	T7	T2	T3	T1	T8	T9
½ Y	9 LEADS ○	T7	T2	T3	T1	T8	T9
½ Δ	9 LEADS □	T1	T8	T3	T6	T2	T9
⅔ Y OR Δ	6 LEADS	T9	T8	T1	T3	T2	T7
⅔ Y	9 LEADS ○	T9	T8	T1	T3	T2	T7
⅔ Δ	9 LEADS □	T1	T4	T9	T6	T2	T3

○ Connect terminals 4, 5 and 6 together at motor terminal box.
□ Connect terminals 4 and 8, 5 and 9, 6 and 7 together in three separate pairs at terminal box.

Fig. 5-75. Connections for G.E. part-winding starters.

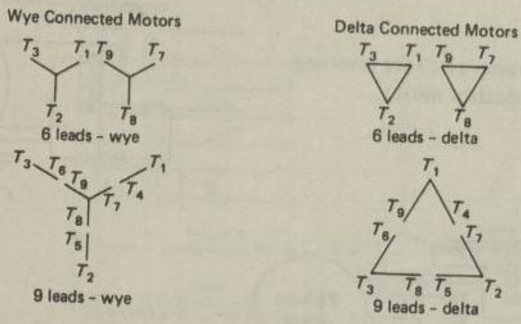


Fig. 5-75. *(continued)*

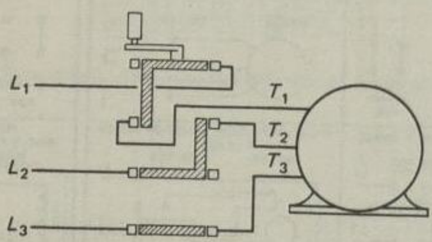


Fig. 5-76. A three-phase motor connected to a manual reversing-drum switch for clockwise rotation.

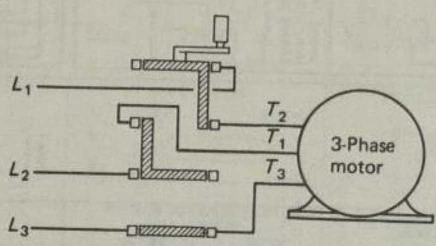


Fig. 5-77. A drum switch connected to a three-phase motor for counterclockwise rotation.

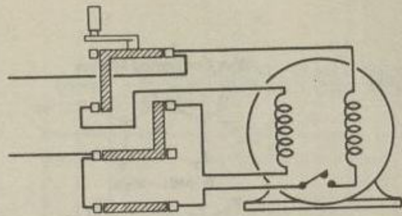


Fig. 5-78. A drum switch for reversing a split-phase or capacitor motor.

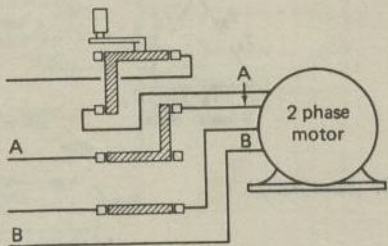


Fig. 5-79. A drum switch for reversing a two-phase motor.

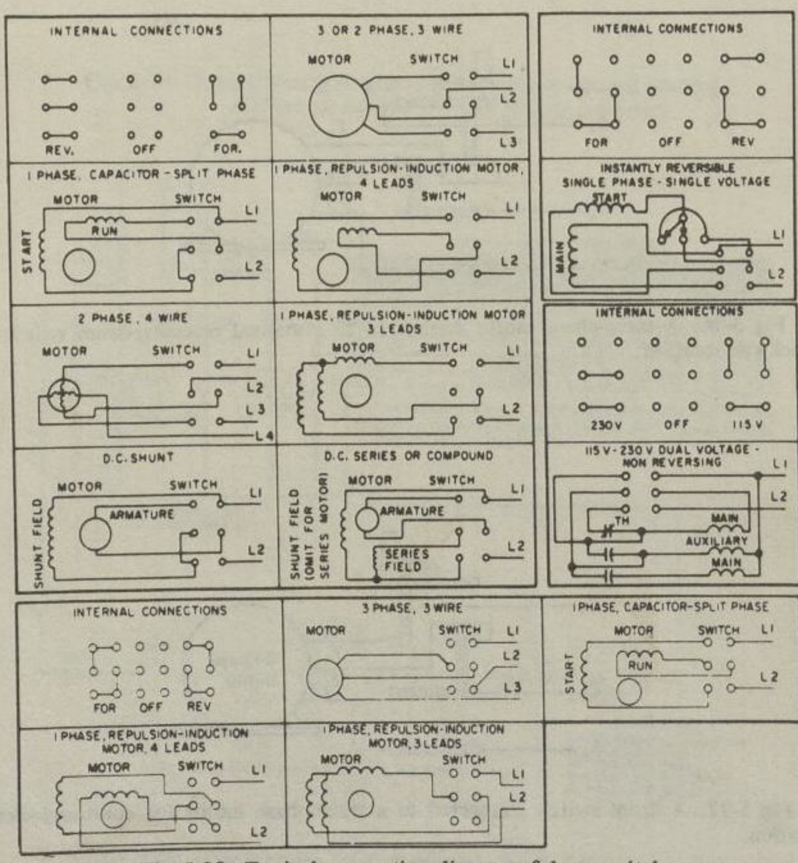
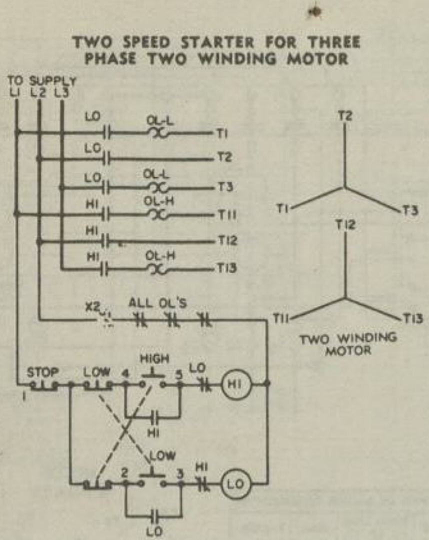


Fig. 5-80. Typical connection diagram of drum switches.



POSITION	L1	L2	L3	OPEN
LOW SPEED	T1	T2	T3	T11, T12, T13
HIGH SPEED	T11	T12	T13	T1, T2, T3

Fig. 5-81. A two-speed controller for two sets of three-phase windings.

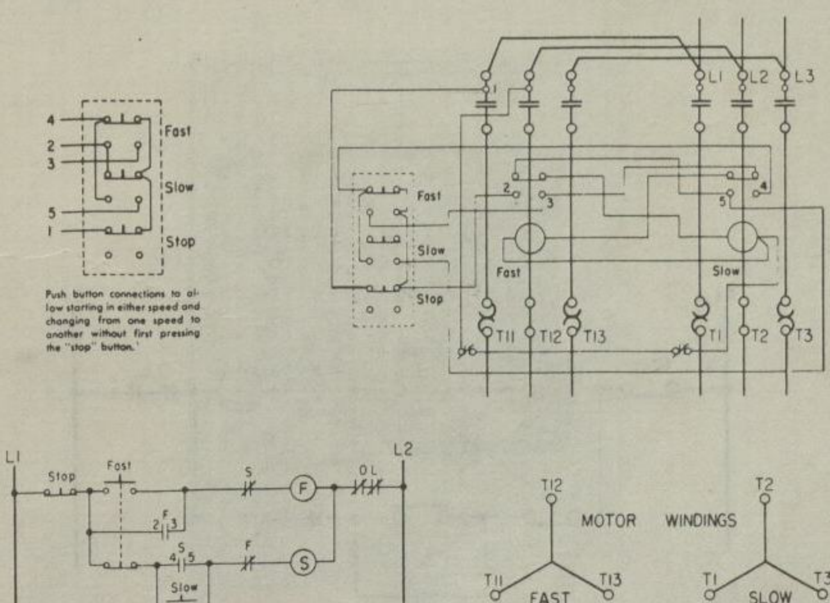
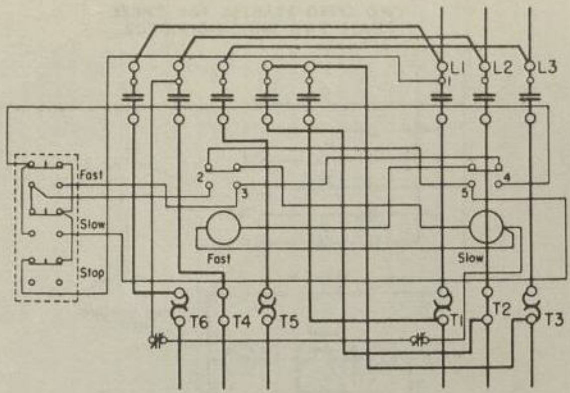


Fig. 5-82. Two-speed, two-winding full-voltage starter. *(Allen Bradley Co.)*



SYNOPSIS OF MOTOR CONNECTIONS			
Speed	Supply Lines L1 L2 L3	Open	Together
Slow	T1 T2 T3	T4, 5, 6	None
Fast	T6 T4 T5	None	T1, 2, 3

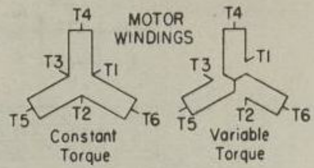


Fig. 5-83. A connection diagram of a two-speed, single-winding, three-phase, squirrel-cage motor controller for constant or variable torque. *(Allen Bradley Company)*

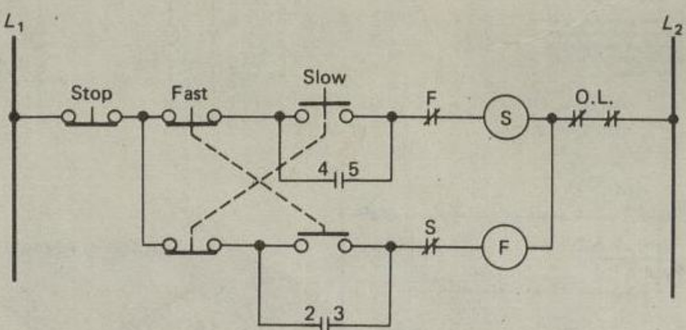
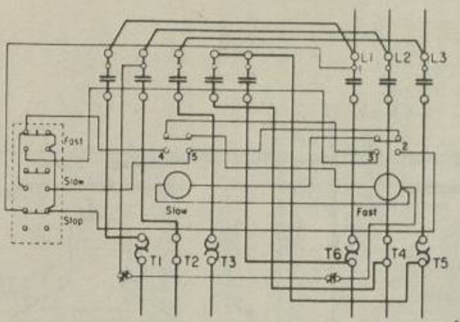
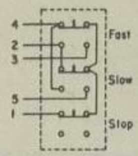


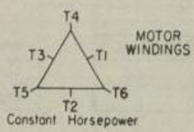
Fig. 5-84. Control circuits of starter of **Fig. 5-83.**





Push button connections to allow starting in either speed and changing from one speed to another without first pressing the "stop" button.

SYNOPSIS OF MOTOR CONNECTIONS					
Speed	Supply Lines L1	L2	L3	Open	Together
Slow	T1	T2	T3	None	T4, 5, 6
Fast	T6	T4	T5	T1, 2, 3	None



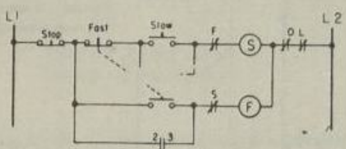


Fig. 5-85. Wiring diagram of a two-speed constant horsepower consequent pole motor starter. *(Allen Bradley Company)*

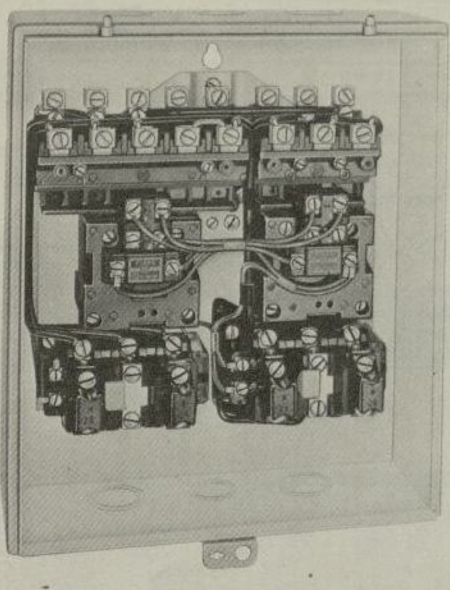
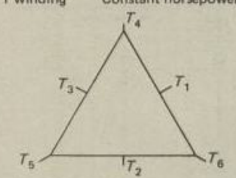


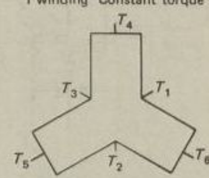
Fig. 5-86. A multispeed starter for consequent pole motors. *(Allen Bradley Company)*

3 phase 2 speed
1 winding Constant horsepower



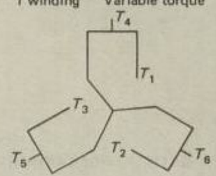
Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3		$T_{4,5,6}$
High	T_6	T_4	T_5	All others	

3 phase 2 speed
1 winding Constant torque



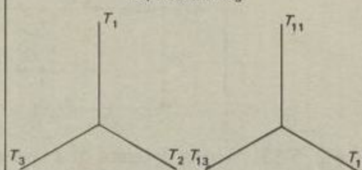
Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	All others	
High	T_6	T_4	T_5		$T_{1,2,3}$

3 phase 2 speed
1 winding Variable torque



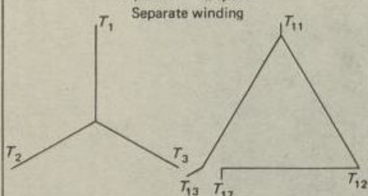
Speed	L_1	L_2	L_3	Open	Together
Low	T_1	T_2	T_3	All others	
High	T_6	T_4	T_5		$T_{1,2,3}$

3 phase 2 speed
Separate winding



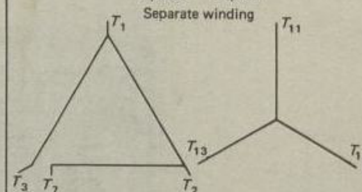
Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3	All others
High	T_{11}	T_{12}	T_{13}	All others

3 phase 2 speed
Separate winding



Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3	All others
High	T_{11}	T_{12}	T_{13}, T_{17}	All others

3 phase 2 speed
Separate winding



Speed	L_1	L_2	L_3	Open
Low	T_1	T_2	T_3, T_7	All others
High	T_{11}	T_{12}	T_{13}	All others

Fig. 5-87. Two-speed motor connections.

Figure 5-87

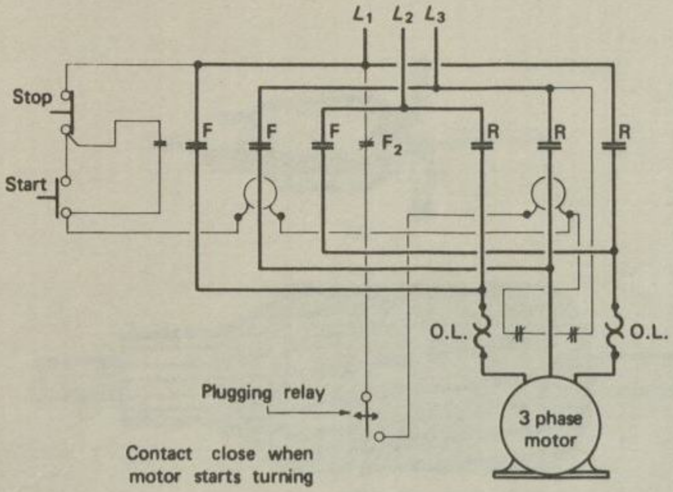


Fig. 5-88. A controller using a plugging relay for braking.

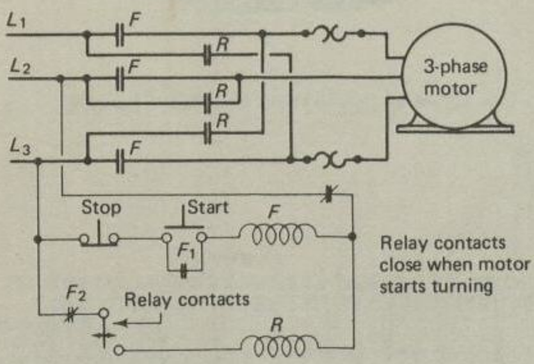


Fig. 5-89. A line diagram of a controller with a plugging relay.

CHAPTER 6

Direct-current Armature Winding

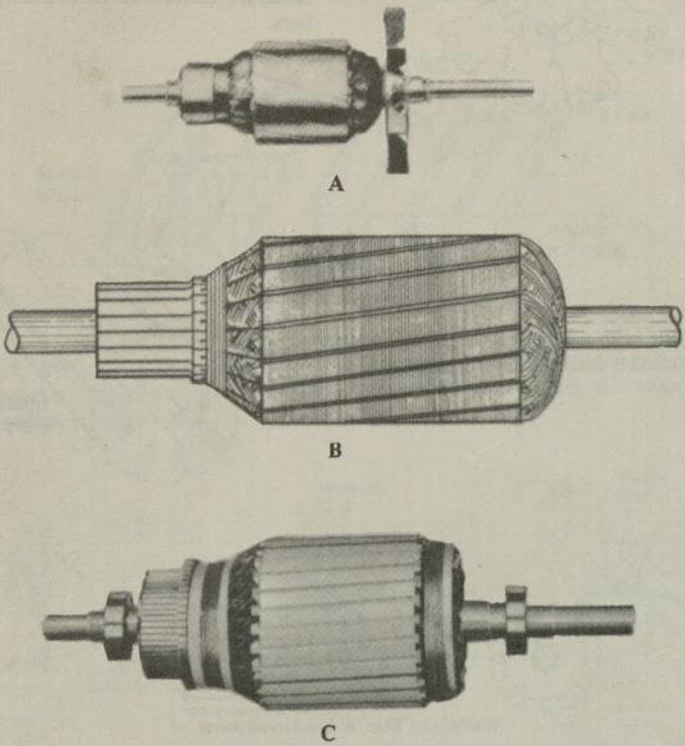


Fig. 6-1. Different types of d-c armatures.

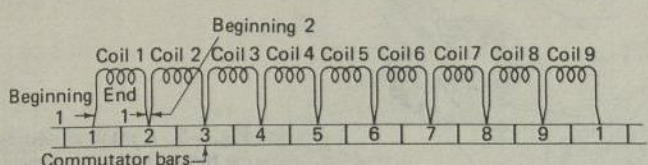


Fig. 6-2A. A schematic diagram of a simple loop winding that consists of nine coils and nine commutator bars. The end lead of each coil and the beginning lead of the next coil are placed in the same commutator bar. The end lead of the last coil is placed in the same bar as the beginning lead of the first coil.

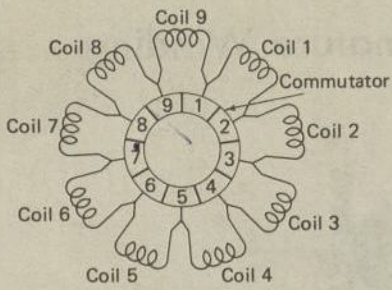


Fig. 6-2B. A circular schematic diagram showing all the coils of a nine-coil armature connected to the commutator bars.

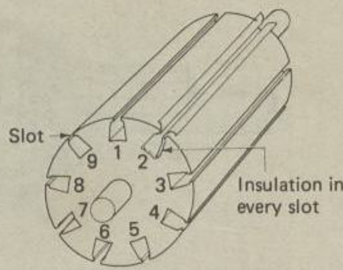


Fig. 6-3. Slots in the armature into which the coils are wound.

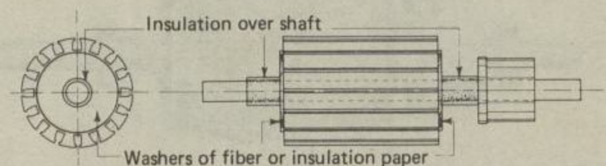


Fig. 6-4. In addition to the slot insulation, the insulation shown above is necessary to protect the winding from grounding.

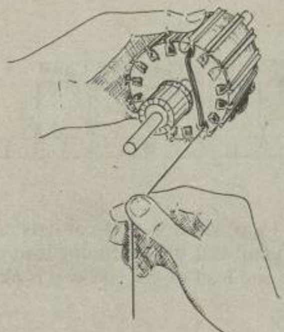
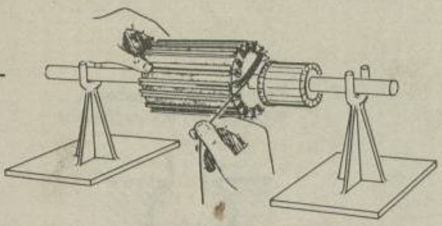


Fig. 6-5. A small armature can be held in one hand during winding.

Fig. 6-6. Large armatures are supported by horses during winding.



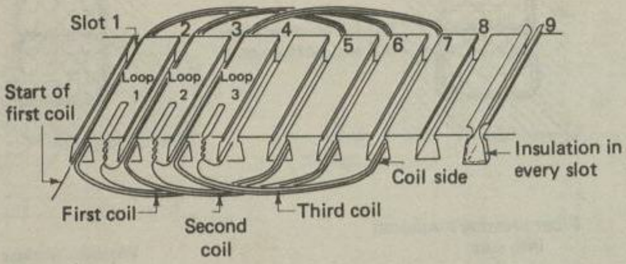


Fig. 6-7. The start of a loop winding. The entire armature is wound before the loops are connected to the commutator. Note that the first coil is wound into slots *1* and *5*. This is the pitch or span of the coil.

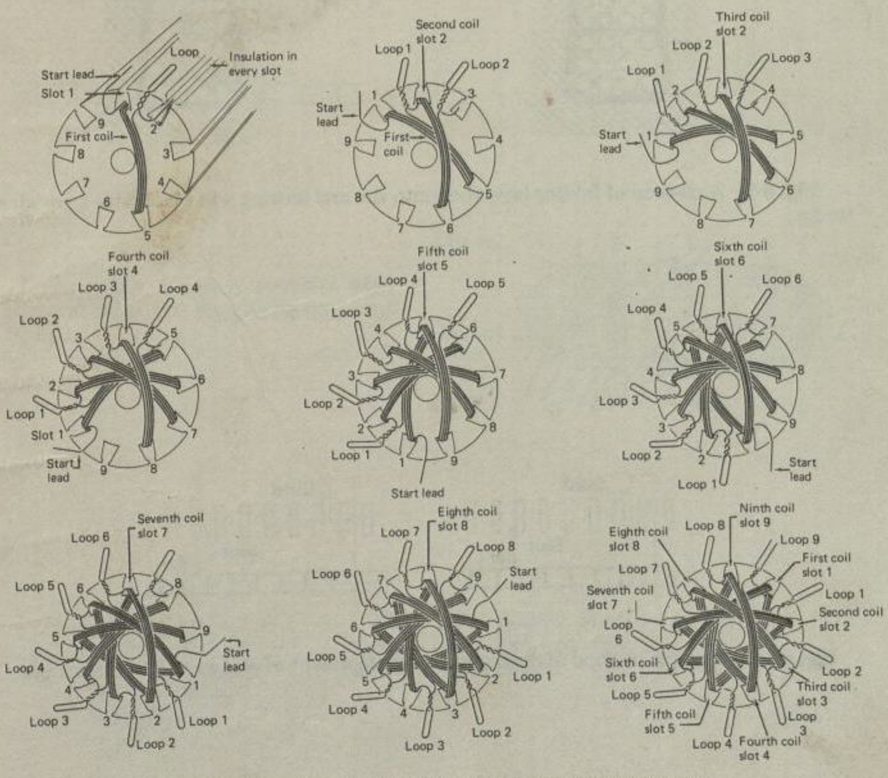


Fig. 6-8. Steps in winding the coils of a nine-slot armature.

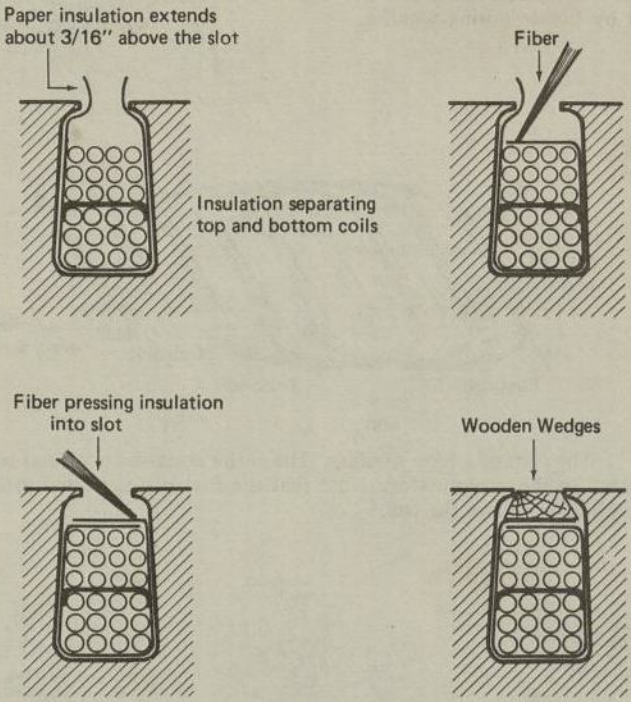


Fig. 6-9. A method of folding insulation into slot and locking it in place with a wooden wedge.

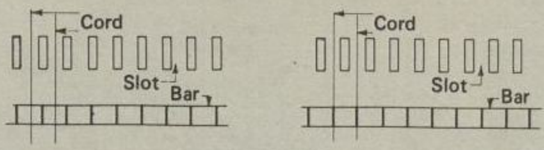


Fig. 6-10. A simple method of determining the alignment of slot and commutator bar.

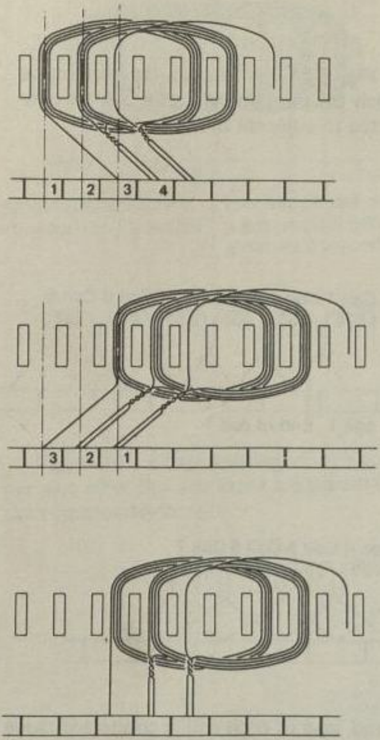
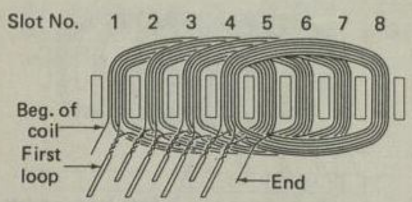


Fig. 6-11. Three conditions of lead swing.

Fig. 6-12. A two-coil-per-slot winding with short and long loops for identification.



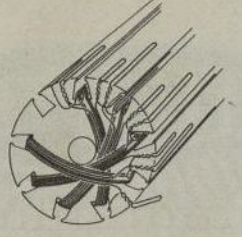


Fig. 6-13. A loop armature having twice as many loops as slots after four coils have been wound.

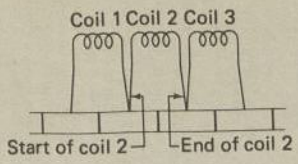
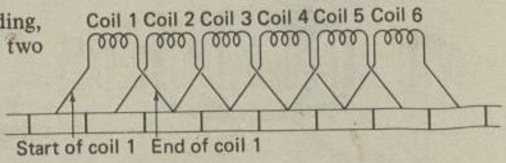


Fig. 6-14. A simplex lap winding in which the start and end of a coil are connected to adjacent bars.

Fig. 6-15. In a duplex lap winding, the end lead of each coil is connected two bars away from the beginning lead.



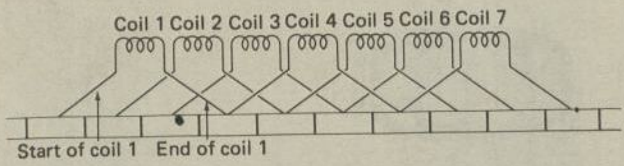


Fig. 6-16. In a triplex lap winding, the end lead of each coil is connected three bars away from the beginning lead.

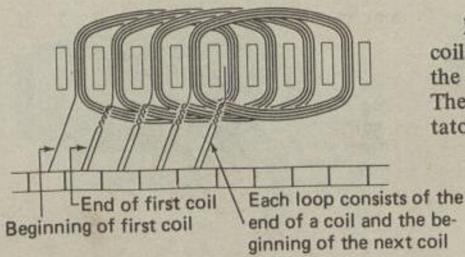
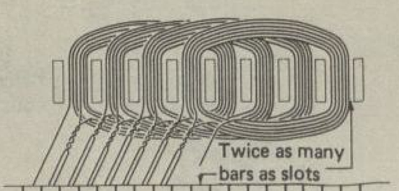


Fig. 6-17. A lap winding with one coil per slot has the beginning and end of the same coil connected to adjoining bars. The loops are connected to the commutator bars in succession.

Fig. 6-18. A lap winding with two coils per slot. The beginning and end of each coil is connected to adjoining bars.



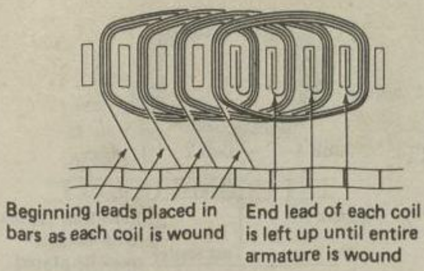


Fig. 6-19. A lap winding of one coil per slot with beginning leads in place.

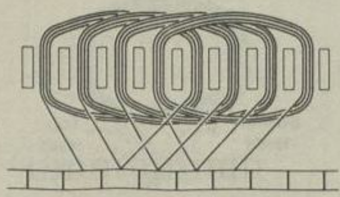


Fig. 6-20. A lap winding of one coil per slot after the end leads are placed in the commutator bars.

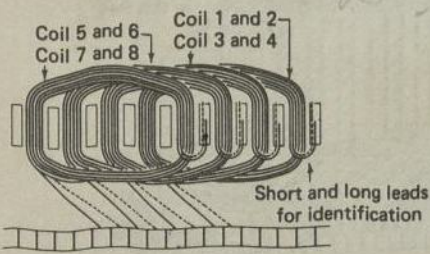


Fig. 6-21. A method of winding an armature having two coils per slot. The bottom or beginning leads are placed in the commutator bars as each coil is wound. The top leads are placed in the bars after the armature in wound.

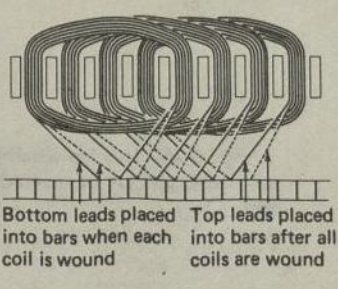


Fig. 6-22. The connections after the top leads are placed in the bars to produce a simplex lap winding with two coils in each slot.

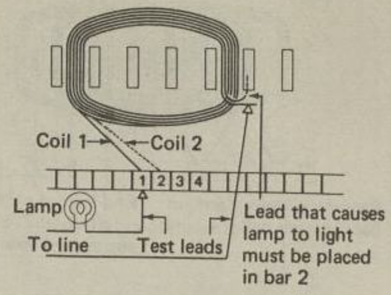


Fig. 6-23. Lamp method of determining in which bars top leads must be placed to produce a simplex lap winding.

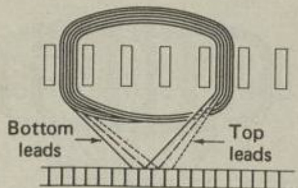


Fig. 6-24. A lap winding with three coils per slot.

3coils/1slot

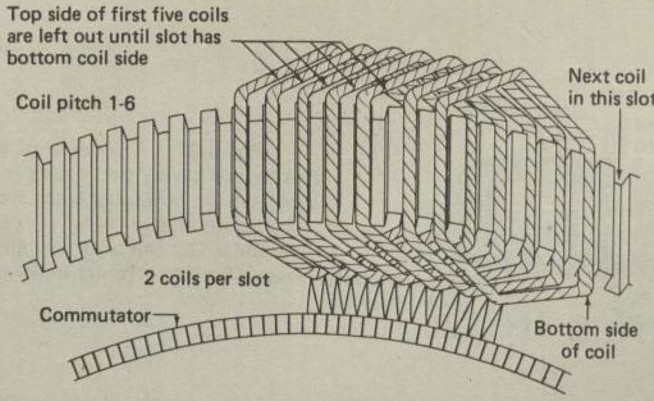
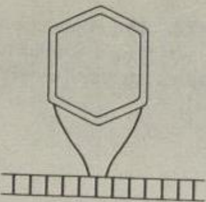


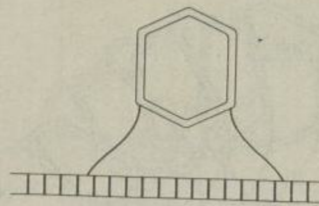
Fig. 6-25. A lap winding with two coils per slot.

Fig. 6-26. In a lap winding leads face each other and are connected to adjacent bars.



Figures 6-23; 6-24; 6-25; 6-26

Fig. 6-27. In a wave winding, leads face away from one another and must be a definite number of commutator bars apart.



Khi nào áp dụng xếp tiến, xếp lùi

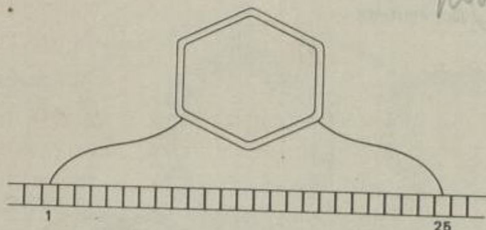


Fig. 6-28. Lead connections for a four-pole, 49-bar armature. According to the formular, the leads should be 24 bars apart; hence, they are placed in bars *1* and *25*.

progressive (adj) [prəgresiv] tiến tới, tả(?) dần lên

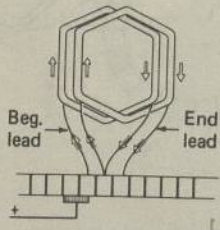
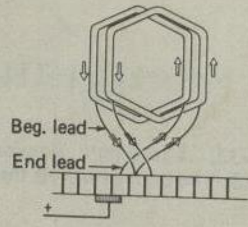


Fig. 6-29. A simplex progressive lap winding. The current flows in a clockwise direction.

retrogressive adj giật lùi, thoái hóa

Fig. 6-30. A retrogressive lap winding. The leads cross one another even though they are connected to adjacent bars. The current flows in a counterclockwise direction.



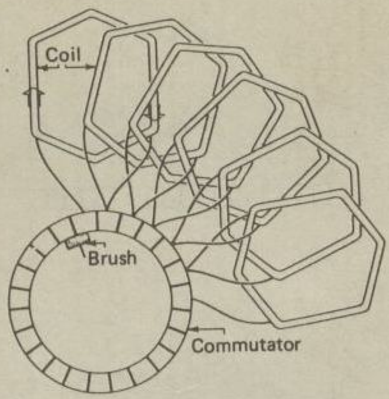


Fig. 6-31. A simplex, progressive lap winding.

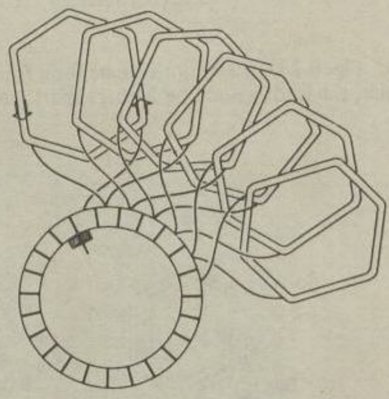


Fig. 6-32. A simplex, retrogressive lap winding.

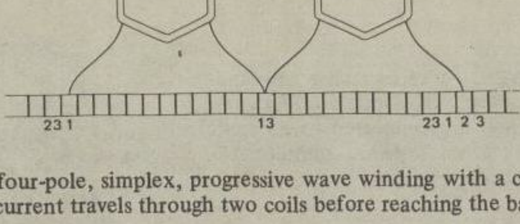


Fig. 6-33. A four-pole, simplex, progressive wave winding with a commutator pitch of 1 and 13. The current travels through two coils before reaching the bar adjacent to the start.

Figures 6-31; 6-32; 6-33

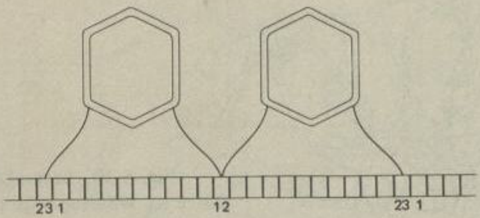


Fig. 6-34. A four-pole, simplex, retrogressive wave winding with a commutator pitch of 1 and 12.

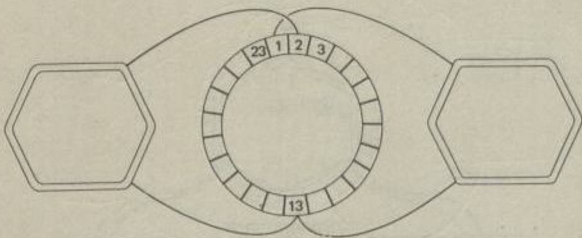


Fig. 6-35. A four-pole, simplex, progressive wave winding with a commutator pitch of 1 and 13.

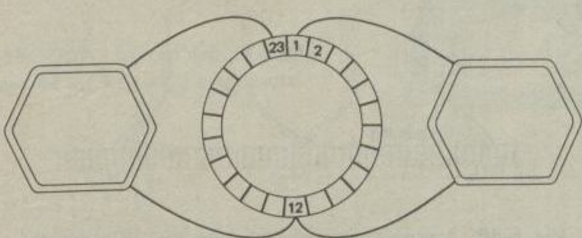


Fig. 6-36. A four-pole, simplex, retrogressive wave winding with a commutator pitch of 1 and 12.

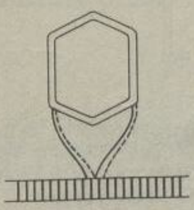


Fig. 6-37. Two coils of a progressive lap winding.

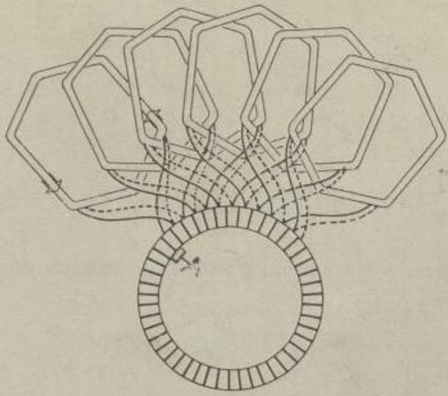


Fig. 6-38. Several coils of a retrogressive lap winding with two coils per slot.

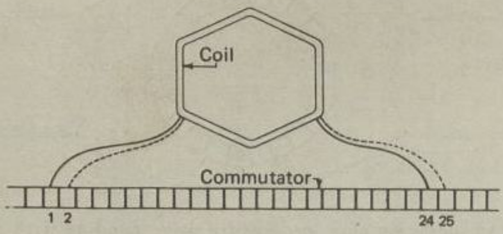


Fig. 6-39. Wave-wound coils.

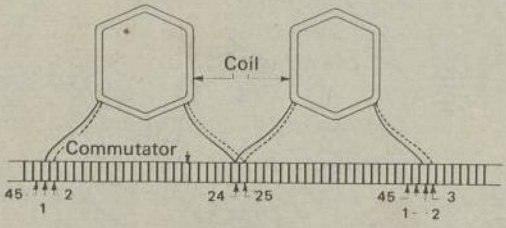


Fig. 6-40. A progressive wave winding, two coils per slot.

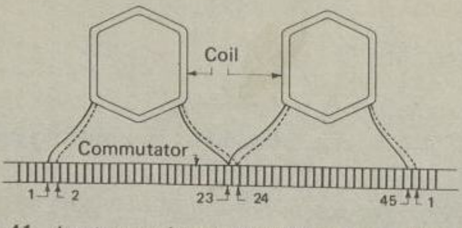


Fig. 6-41. A retrogressive wave winding, two coils per slot.

Figures 6-38; 6-39; 6-40; 6-41

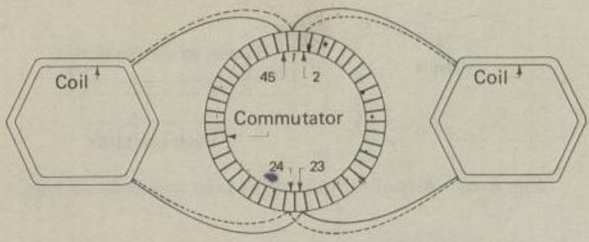


Fig. 6-42. A retrogressive wave winding.

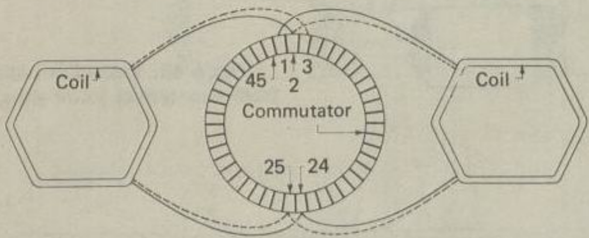
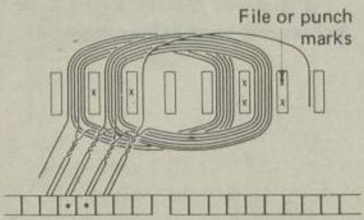


Fig. 6-43. A progressive wave winding.

Fig. 6-44. Pitch and lead data of a lap winding may be marked on the armature.



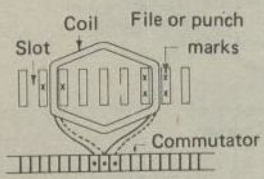
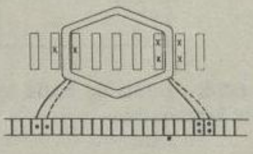


Fig. 6-45. Pitch and lead data of a lap winding marked at the slots and bars of one particular coil.

Fig. 6-46. Pitch and lead data of a wave winding marked at the slots and bars of a particular coil.



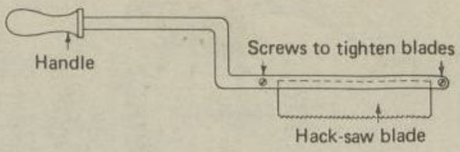


Fig. 6-47. A tool for cutting slots in commutator bars.

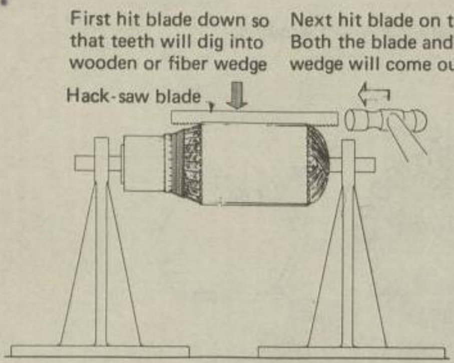
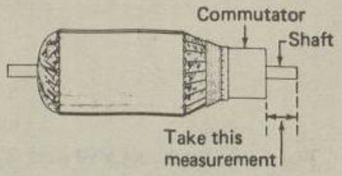


Fig. 6-48. Method of removing wedges from armature or stator slots.

Fig. 6-49. Measurements to be taken before removing commutator.



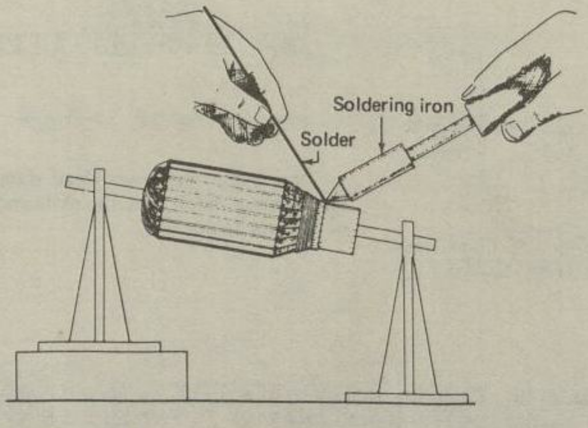


Fig. 6-50. Soldering leads to the commutator. The soldering iron is held slightly above the horizontal.

Figures 6-47; 6-48; 6-49; 6-50

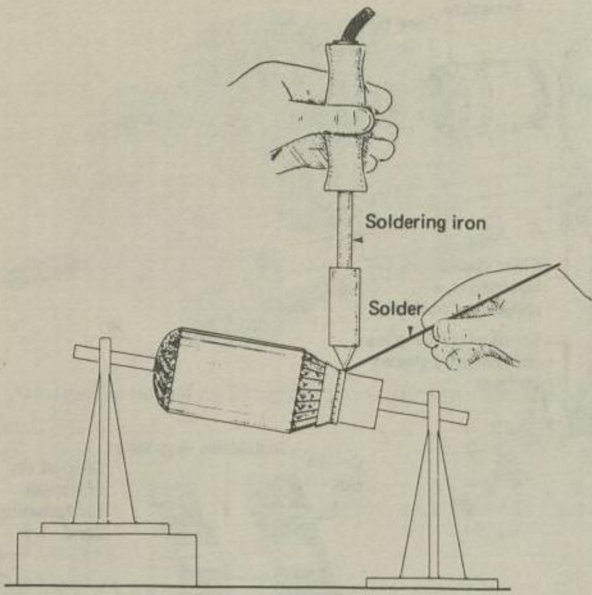


Fig. 6-51. Holding the iron vertically prevents the solder from spanning two bars.

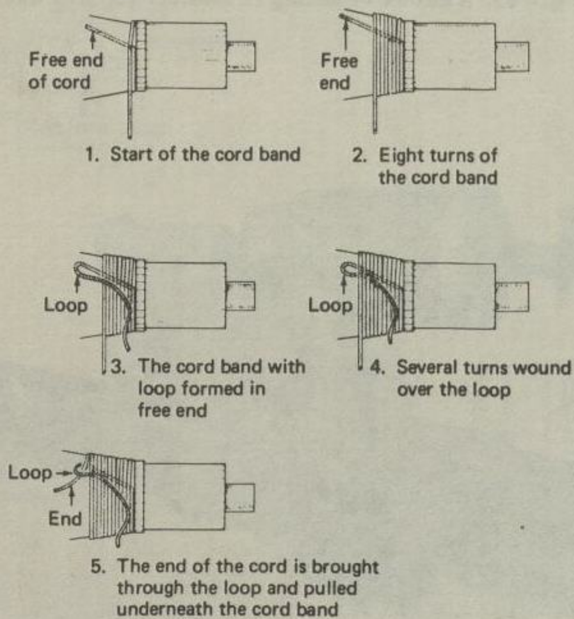


Fig. 6-52. A method of winding a cord band on an armature.

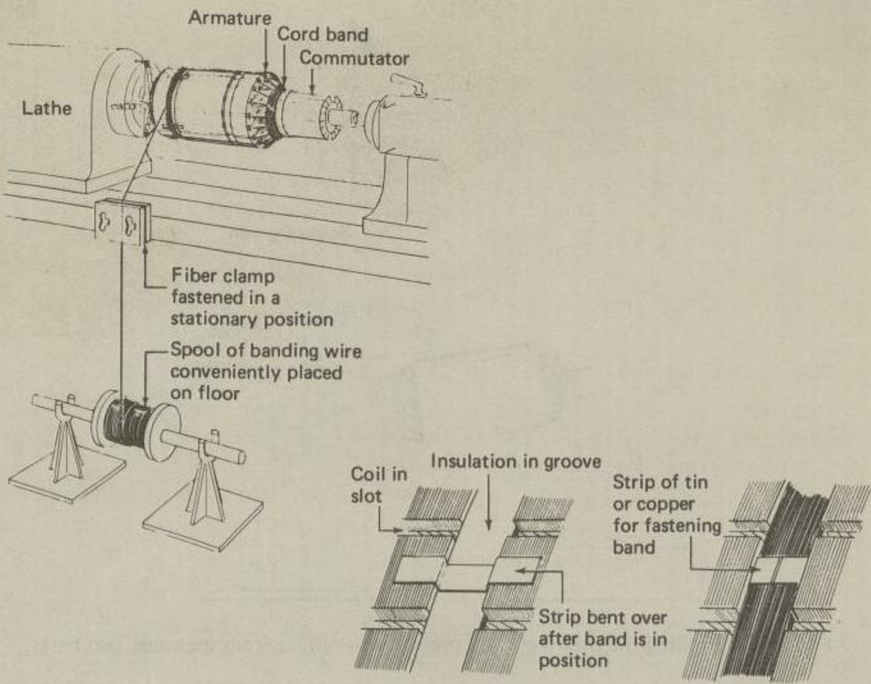


Fig. 6-53. A method of banding an armature with steel wire.

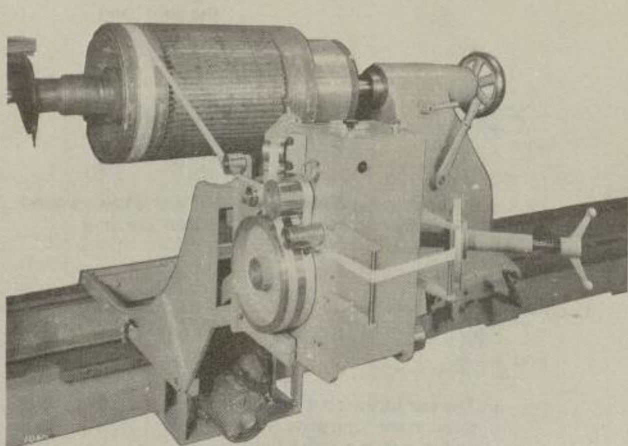


Fig. 6-54. Peerless glass tape tension device. *(Peerless Tool Division Cam Industries Inc.)*

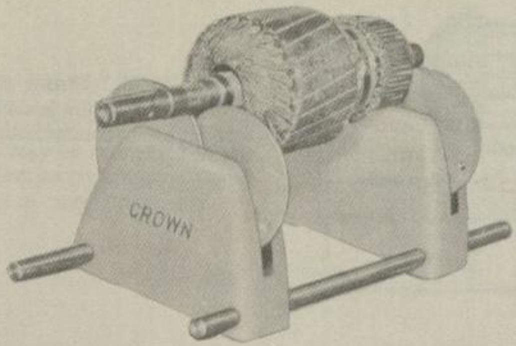


Fig. 6-55. Armature mounted on balancing ways. *(Crown Industrial Products)*

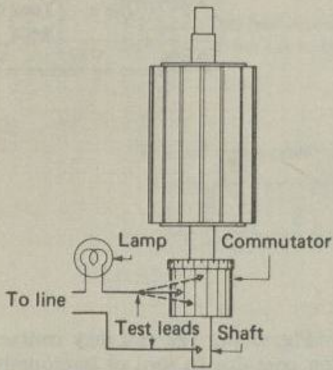
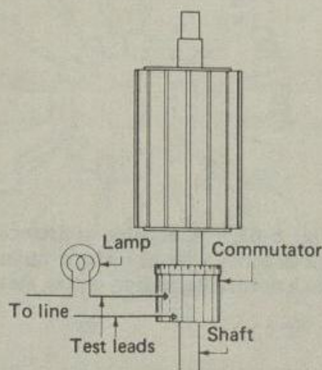


Fig. 6-56. A test for a grounded commutator.

Fig. 6-57. A test circuit for finding shorts between bars.



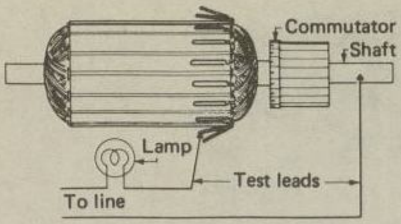
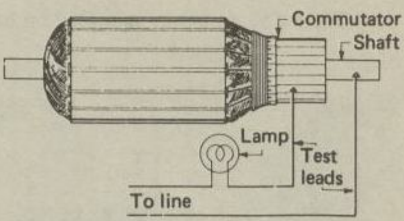


Fig. 6-58. Testing the winding for grounds before the leads have been connected to the commutator.

Fig. 6-59. Testing the completed armature for grounds after the leads have been connected to the commutator.



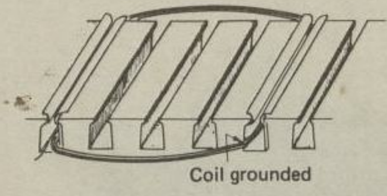
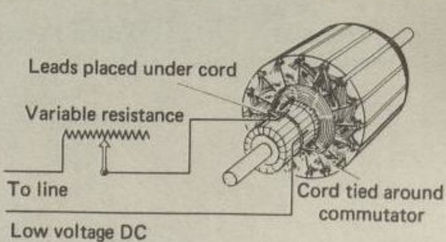


Fig. 6-60. The coil may contact the iron core due to torn or improperly cut slot insulation.

Fig. 6-61. A variable resistance is placed in series with the line in order to obtain a normal deflection on the meter.



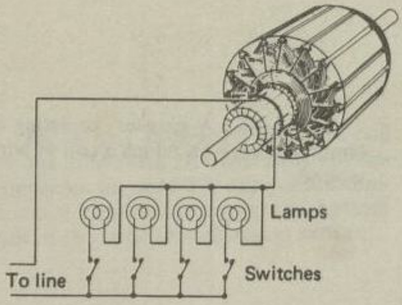


Fig. 6-62. Lamps placed in series with 115 volts of direct current to supply current to the armature for testing. Switches *1, 2, 3,* and *4* may be connected in the circuit, depending on the armature tested and the amount of current necessary.

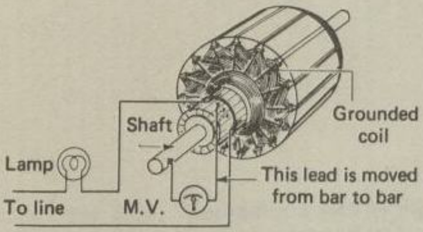


Fig. 6-63. Testing an armature for grounds. One meter lead is moved from bar to bar until the lowest reading is indicated on the meter. The grounded coil is connected to this bar.

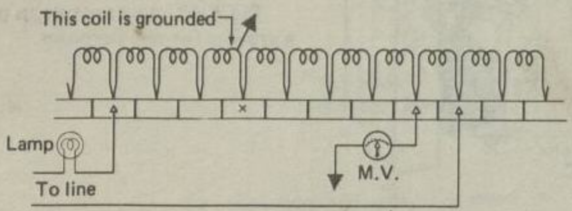


Fig. 6-64. A schematic diagram of the test circuit shown in **Fig. 6-63.**

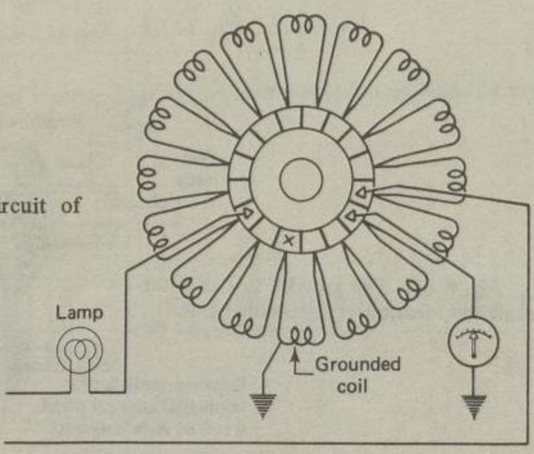


Fig. 6-65. A complete circuit of ground test.

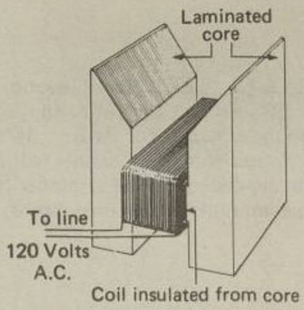


Fig. 6-66. A growler consisting of a laminated core on which a coil of wire is wound.

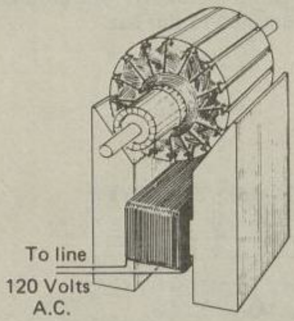


Fig. 6-67. An armature in position on a growler for test purposes.

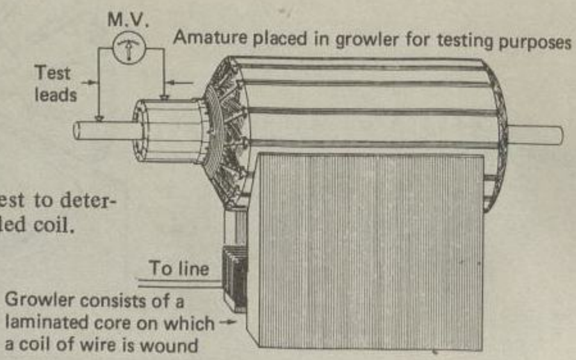


Fig. 6-68. The growler test to determine the location of a grounded coil.

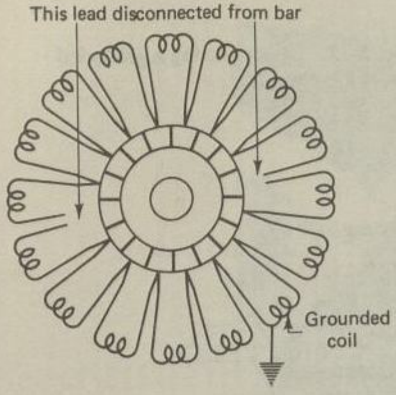


Fig. 6-69. Locating a grounded coil by the trial method. The leads are disconnected on opposite sides of the commutator, and in this case, the bottom half of the armature will test grounded.

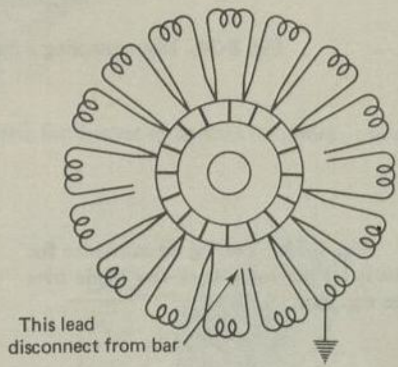


Fig. 6-70. Disconnect a lead in the center of the grounded group and test in which quarter grounded coil is located.

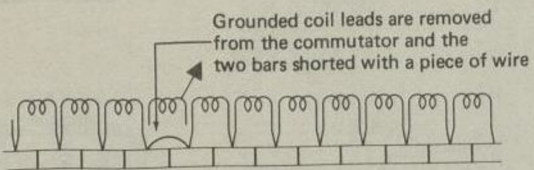


Fig. 6-71. Schematic diagram showing how a grounded coil is disconnected from the commutator.

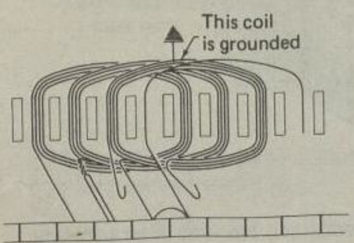


Fig. 6-72. Disconnecting a grounded coil from a loop winding.

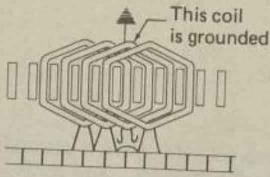


Fig. 6-73. Disconnecting a grounded coil from a lap winding.

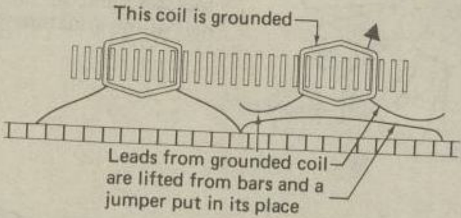
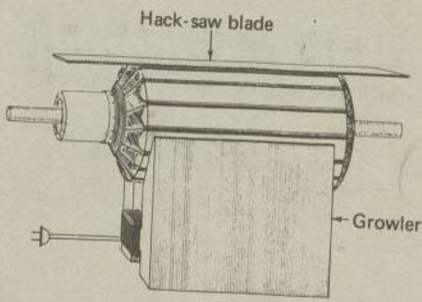


Fig. 6-74. Disconnecting a grounded coil from a wave winding.

Fig. 6-75. Testing an armature for shorts by placing a hack-saw blade over the top slot.



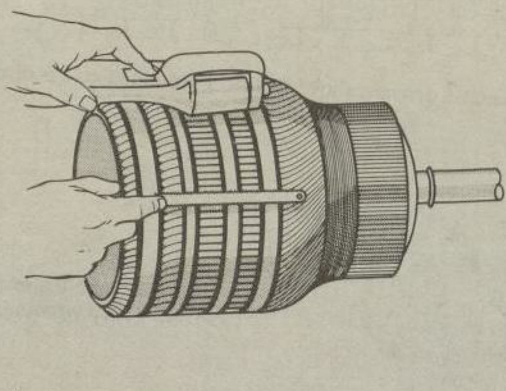
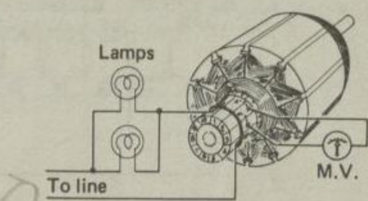


Fig. 6-76. Using an internal growler to locate shorted coils in an armature.

Figures 6-74; 6-75; 6-76

Fig. 6-77. An external growler. This is used for testing armatures for shorts, opens and grounds. *(Crown Industrial Products)*

Fig. 6-78. Testing an armature for shorted coils by using the bar-to-bar test. A shorted coil will be indicated by a low or zero reading on the meter.



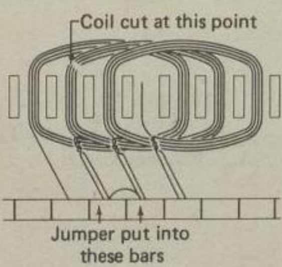
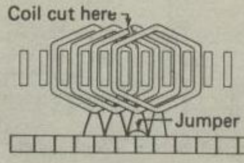


Fig. 6-79. Cutting the shorted coil and connecting a jumper between the two bars connected to the coil.

Fig. 6-80. Cutting out a shorted coil on a form-wound armature.



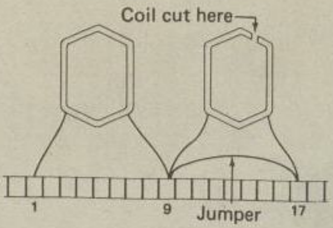


Fig. 6-81. Cutting out a shorted coil on a four-pole wave winding.

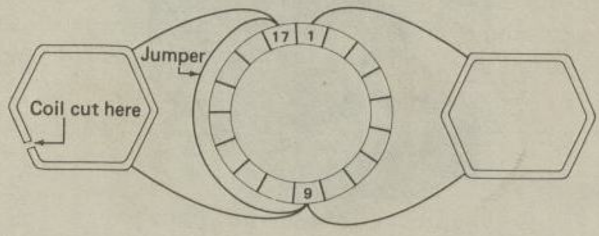


Fig. 6-82. Cutting out a shorted coil on a wave winding.

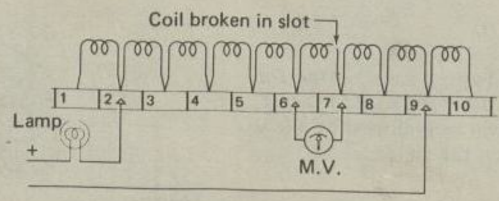
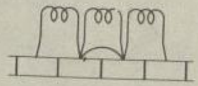


Fig. 6-83. A method of locating an open coil. The meter will not show a reading until it bridges bars 6 and 7. The meter completes the circuit from positive to negative.

Fig. 6-84. A method of jumping out an open coil on a lap winding.



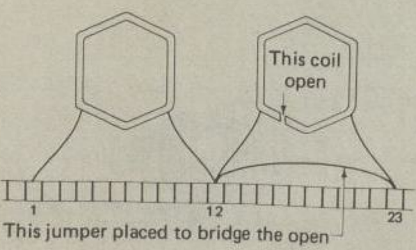


Fig. 6-85. A method of repairing a wave-wound armature having an open coil.

Figures 6-81; 6-82; 6-83; 6-84; 6-85

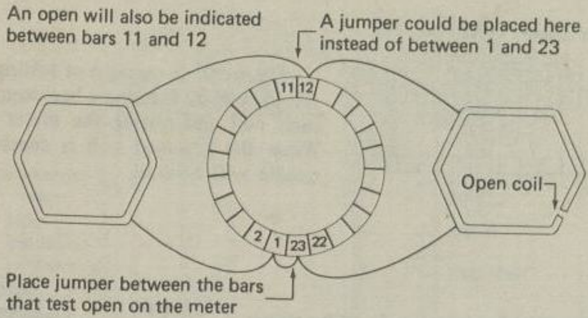


Fig. 6-86. A quick method of closing an open on a four-pole wave winding.

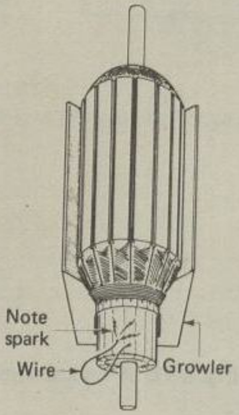
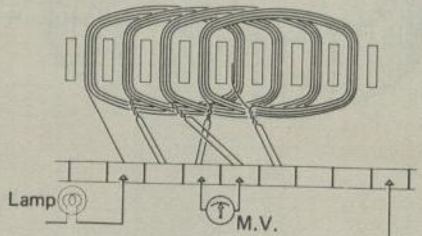


Fig. 6-87. If two bars are shorted with a piece of wire, a small spark indicates a complete circuit through the coil.

Fig. 6-88. Loops placed in wrong bars.



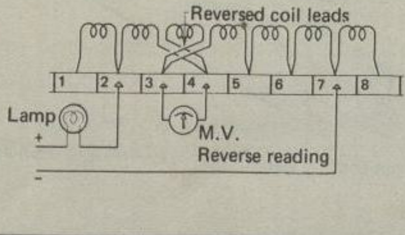


Fig. 6-89. A test of a loop winding for reversed coils. Between bars 3 and 4 the meter will indicate reversed reading; between bars 2 and 3 a double reading; between bars 4 and 5 a double reading. All others will be normal.

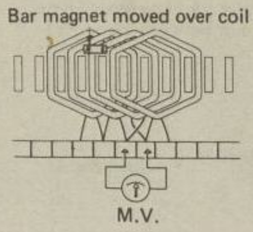
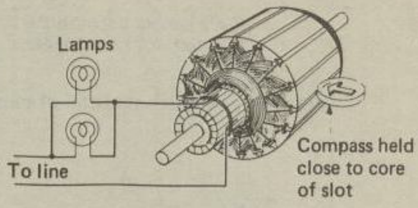


Fig. 6-90. A method of testing for reversed coils by running a bar magnet over each coil and noting the meter needle. When the reversed coil is reached, the needle will reverse.

Fig. 6-91. Test for a reversed coil by using a compass. The armature is turned slowly until the reversed coil is alongside the compass. The needle will reverse at this point.



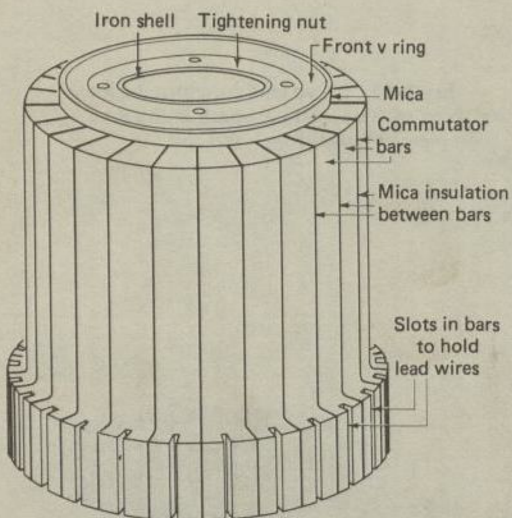
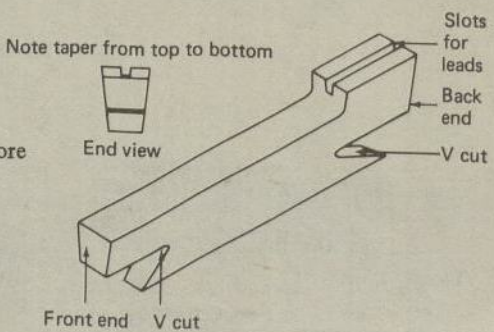


Fig. 6-92. A typical commutator.

Fig. 6-93. A commutator bar before it is mounted.



Figures 6-90; 6-91; 6-92; 6-93

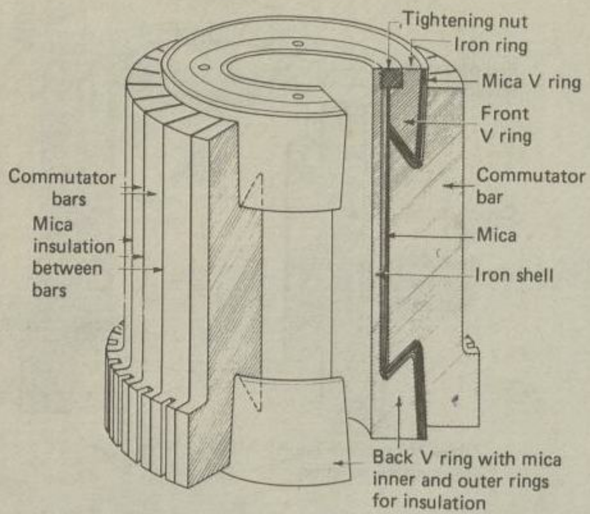


Fig. 6-94. A commutator with a portion removed to show section and assembly

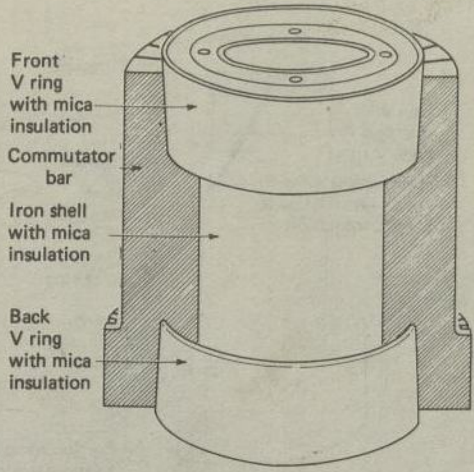


Fig. 6-95. A commutator with half the bars removed and the front and back V ring in place.

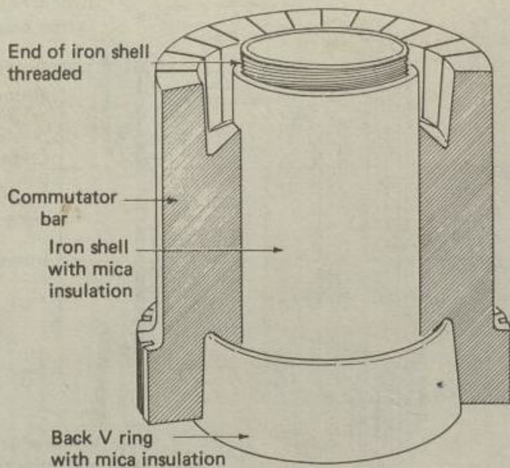


Fig. 6-96. A commutator with the front V ring and half the bars removed.

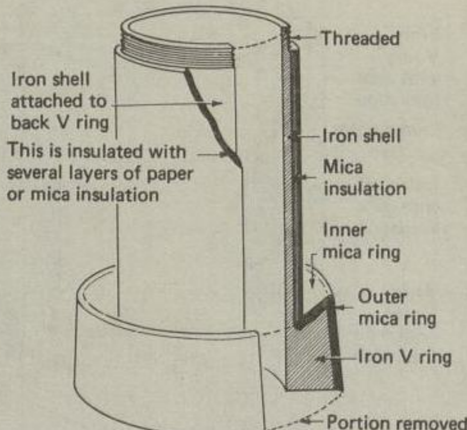


Fig. 6-97. A back V ring with shell attached to iron core.

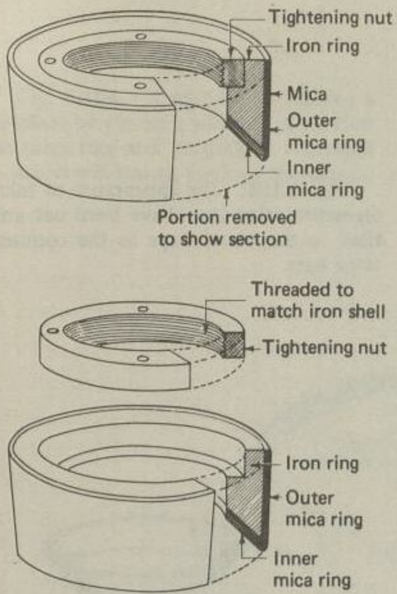
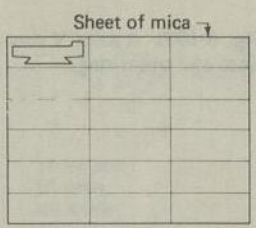


Fig. 6-98. A front V ring and tightening nut.

Fig. 6-99. The mica sheet marked off into small strips of mica.



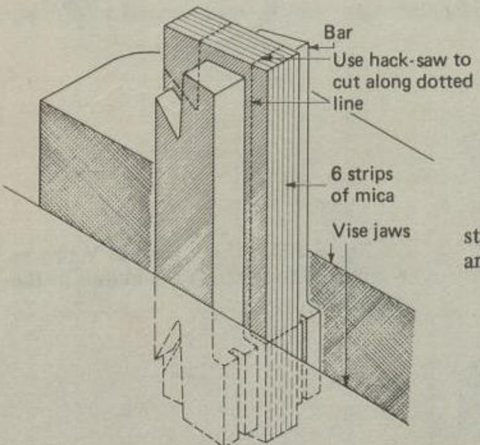


Fig. 6-100. Rectangular strips of mica stacked between two commutator bars and placed in a vise before being cut.

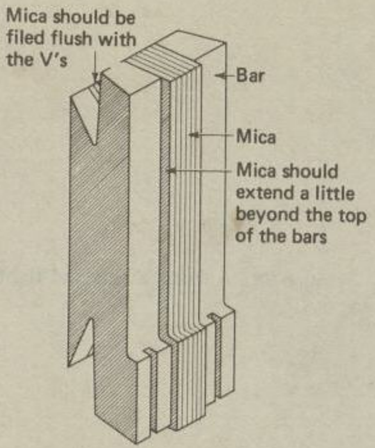


Fig. 6-101. The appearance of mica segments after they have been cut and filed to the same shape as the commutator bars.

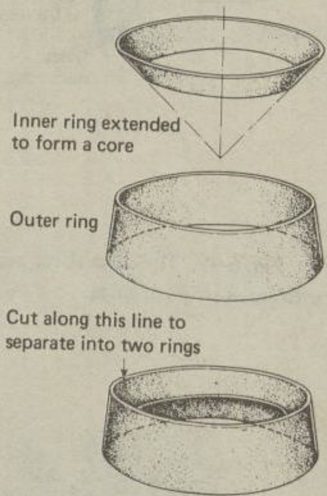


Fig. 6-102. A mica V ring consists of an inner and outer ring.

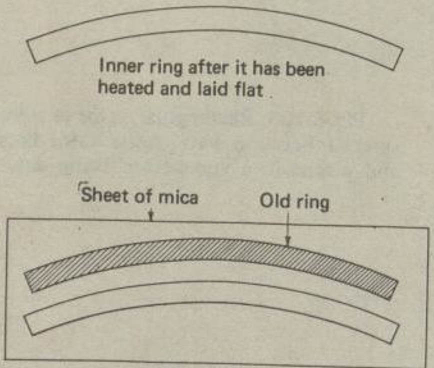


Fig. 6-103. Using the old V ring as a template to mark off the outline of the new ring.

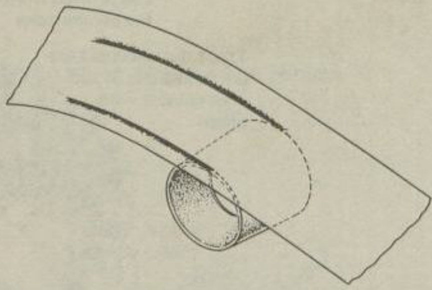


Fig. 6-104. A method of making a template by placing a piece of paper over the mica ring and pressing at the edges so that it will leave a mark on the paper.

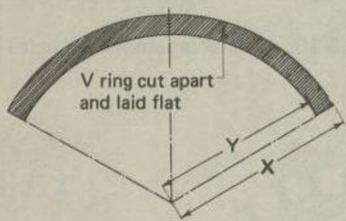


Fig. 6-105. The appearance of a section of a cone cut through and laid flat.

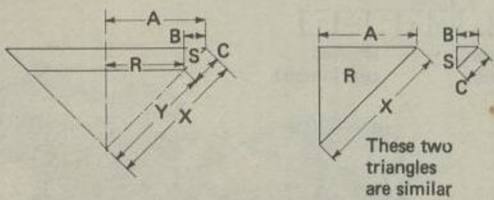
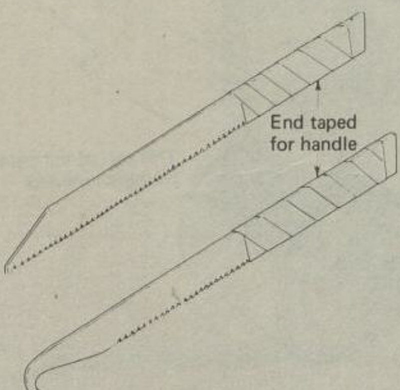


Fig. 6-106. Distances *A*, *B*, and *C* obtained from actual measurement on the iron V ring. These are necessary in order to get the radius *x*.



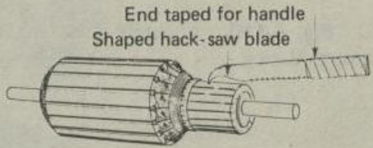


Fig. 6-107. Special tools for removing the defective mica between bars.

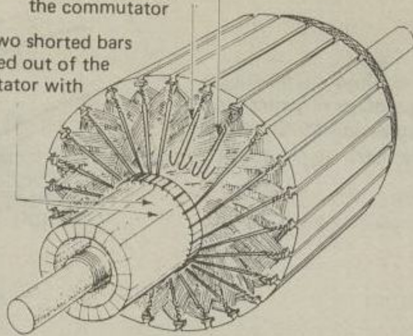


Fig. 6-108. A step in removing shorted bars.

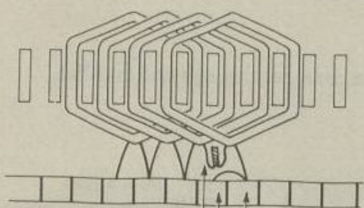


Fig. 6-109. A quick repair that can be made if two bars are shorted.

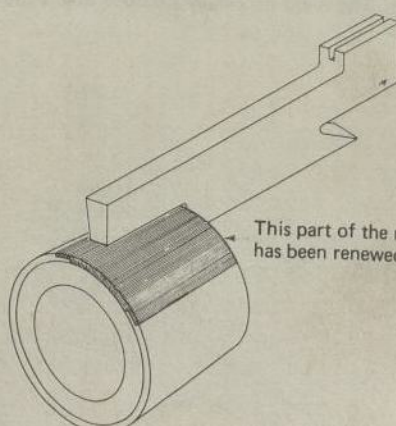


Fig. 6-110. A patch placed on the outer V ring.

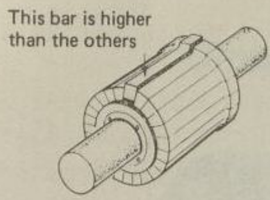


Fig. 6-111. A high bar in a commutator.

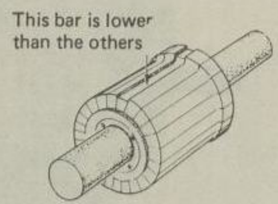


Fig. 6-112. A low bar in a commutator.

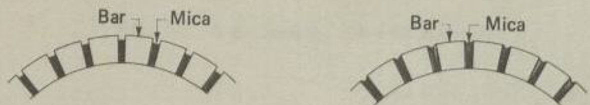


Fig. 6-113. (Left) A commutator correctly undercut. (Right) An improperly undercut commutator.

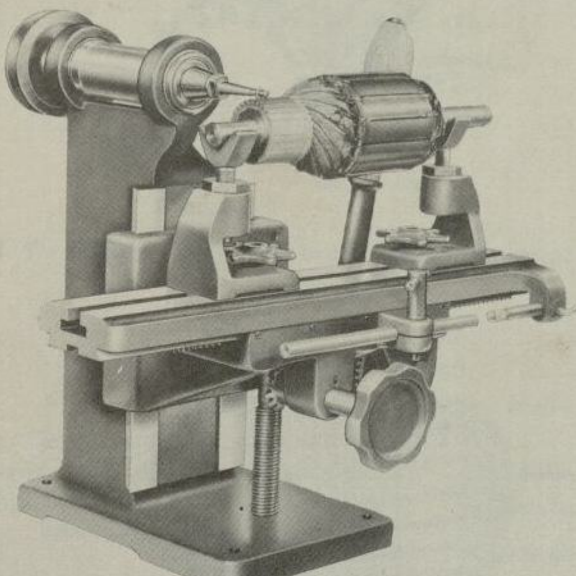


Fig. 6-114. Peerless Mica undercutter. *(Peerless Tool Division Cam Industries Inc.)*

CHAPTER 7

Direct-current Motors

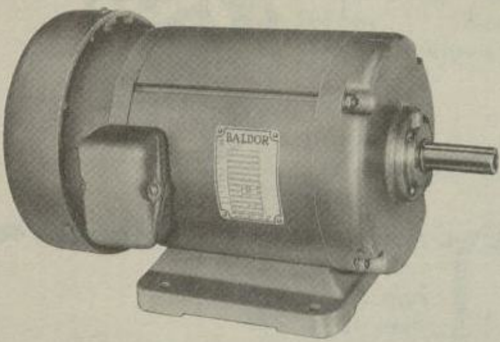


Fig. 7-1. A d-c motor. *(Baldor Electric Co.)*

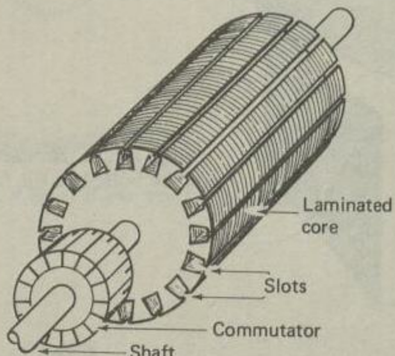


Fig. 7-2. The armature of a d-c motor before windings are inserted in slots.

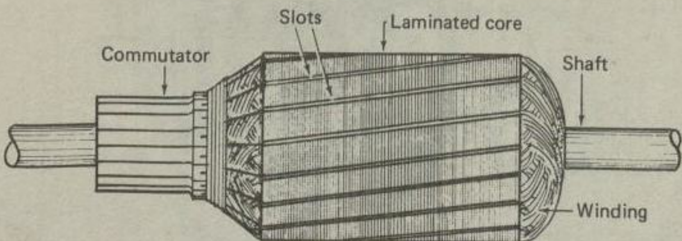


Fig. 7-3. The armature with skewed slots and windings in place.

Figures 7-1; 7-2; 7-3

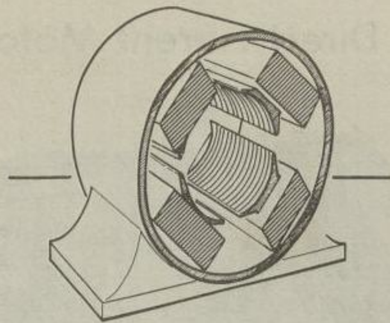


Fig. 7-4. A complete field assembly and frame of a d-c motor.

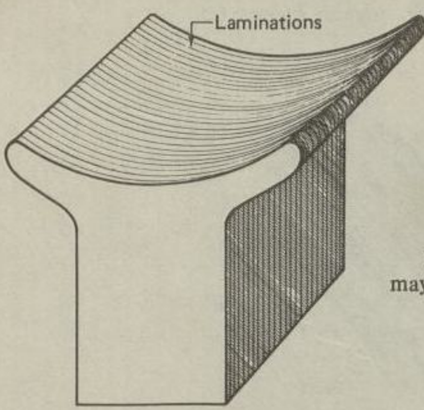


Fig. 7-5. A laminated field core. This may be bolted to the frame.

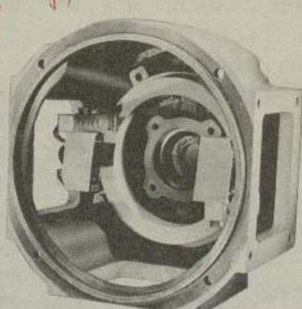


Fig. 7-6. An end plate of a d-c motor showing brush rigging. *(General Electric Co.)*

sleeve bearing
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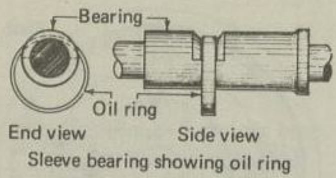
Fig. 7-7. Construction of sleeve bearing and oil ring.



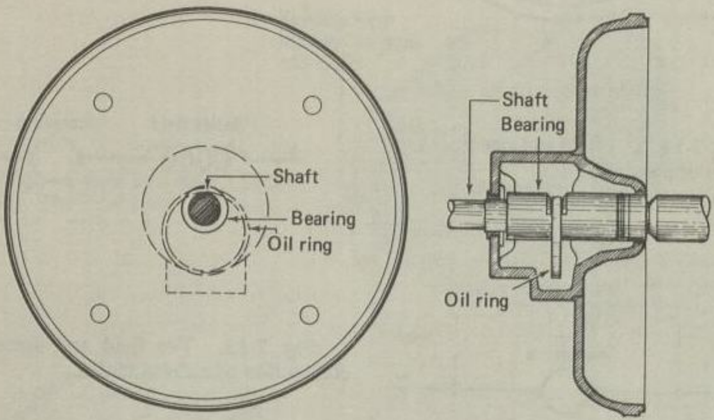


Fig. 7-8. A sleeve bearing assembled on an end plate.

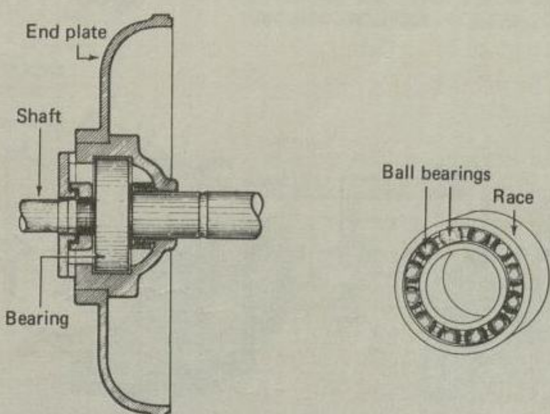


Fig. 7-9. The ball bearing at right mounted in the end plates as shown.

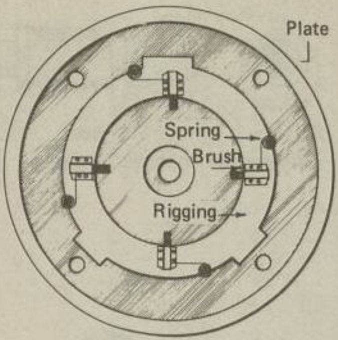
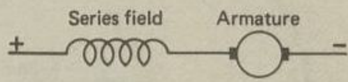


Fig. 7-10. The brush rigging attached to the end plate.

Fig. 7-11. The field and armature connection of a series motor.



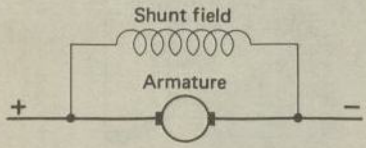
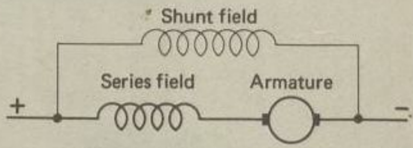


Fig. 7-12. The field and armature connection of a shunt motor.

Fig. 7-13. The field and armature connection of a compound motor.



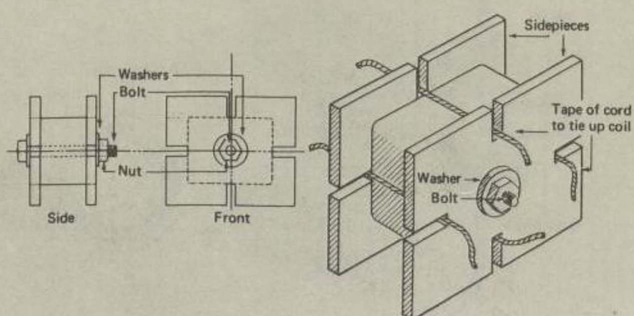


Fig. 7-14A. The construction of a form on which to wind d-c field coils.

Figures 7-10; 7-11; 7-12; 7-13; 7-14 A

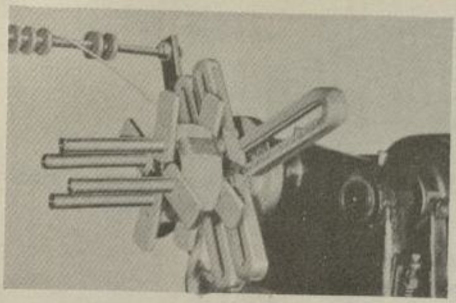


Fig. 7-14B. Coil winder head. *(Crown Industrial Products)*

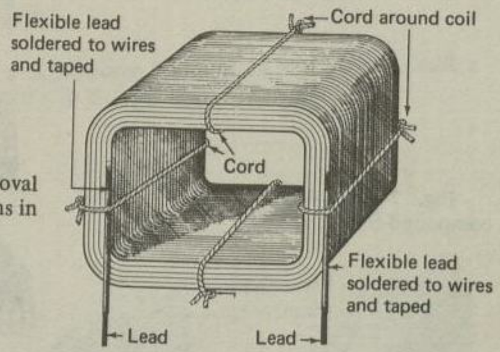


Fig. 7-15. A field coil after removal from form. The cord holds the turns in place.

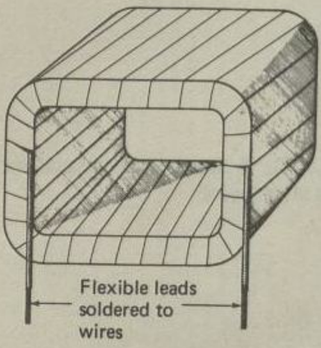


Fig. 7-16. A series-field coil is taped after flexible leads are soldered to the beginning and end of the coil. The coil is usually taped with a layer of varnished cambric and a layer of cotton tape.

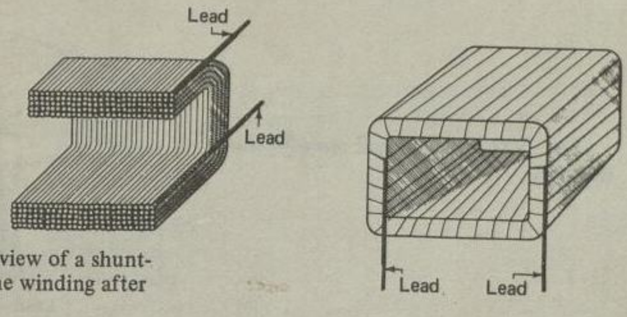


Fig. 7-17. A cutaway view of a shunt-field winding and the same winding after taping.

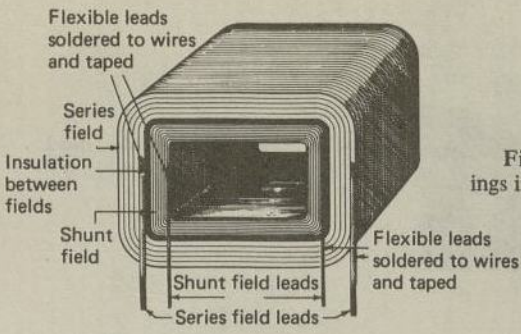


Fig. 7-18. The arrangement of windings in a compound field coil.

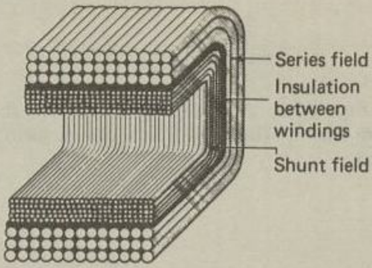


Fig. 7-19. A cutaway view of a compound-field coil.

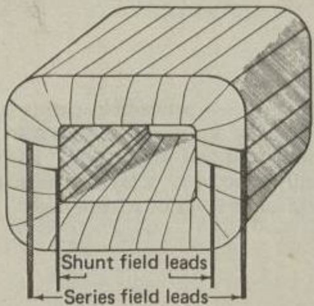


Fig. 7-20. A compound-field coil and its leads after taping.

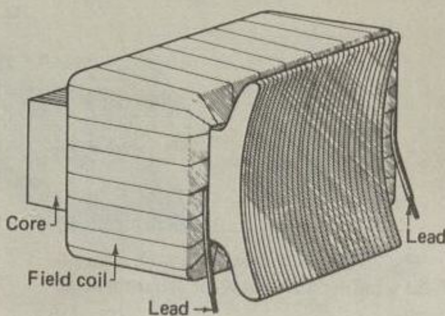


Fig. 7-21. A field coil assembled on its core.

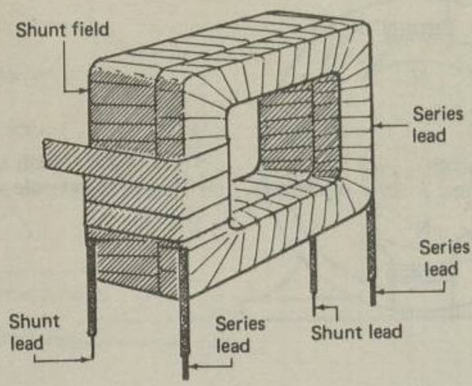
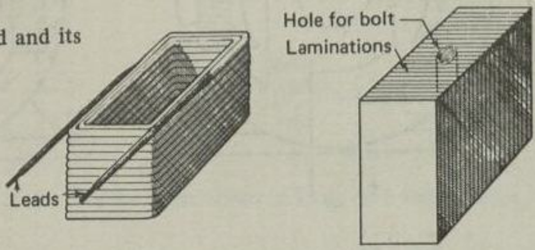


Fig. 7-22. A compound field for a large motor. The shunt and series fields are wound and taped separately, then placed side by side and taped again.

Fig. 7-23. An interpole field and its core.



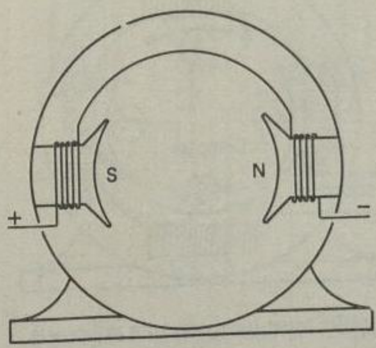


Fig. 7-24. In a two-pole motor, the fields are connected to form a north and south pole.

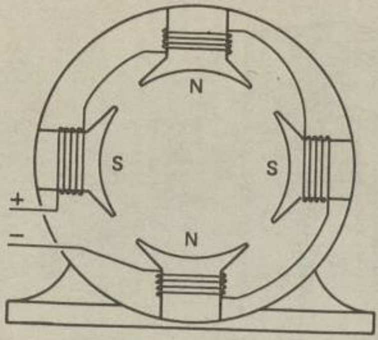


Fig. 7-25. North and south poles alternate in a four-pole motor.

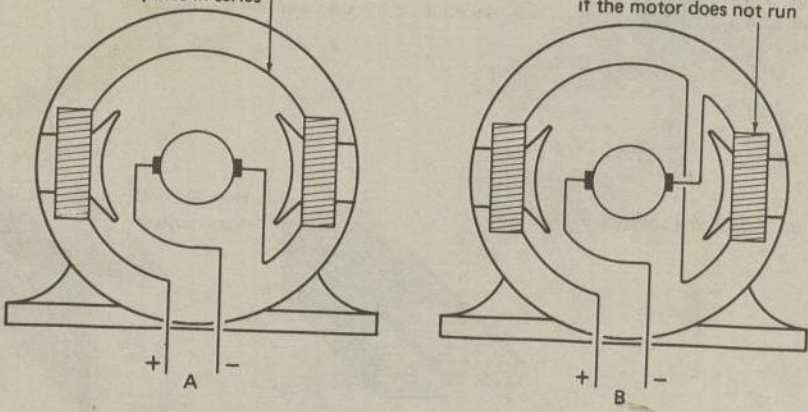


Fig. 7-26. A test for correct field polarity on a small two-pole motor.

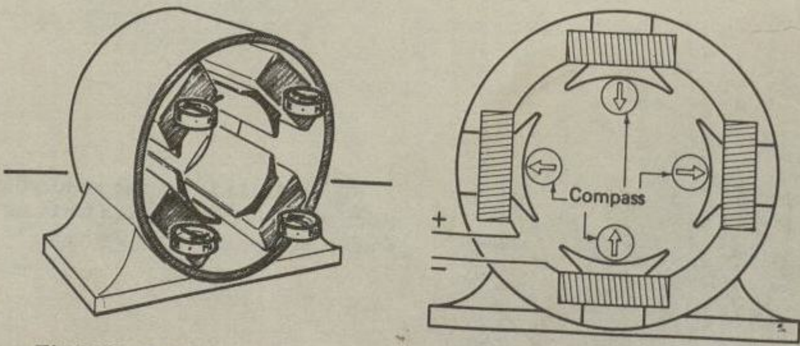


Fig. 7-27. On a four-pole motor, adjacent poles must have opposite polarity.

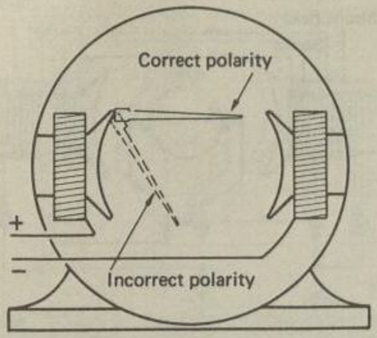


Fig. 7-28. Testing polarity of the field coils with a nail.

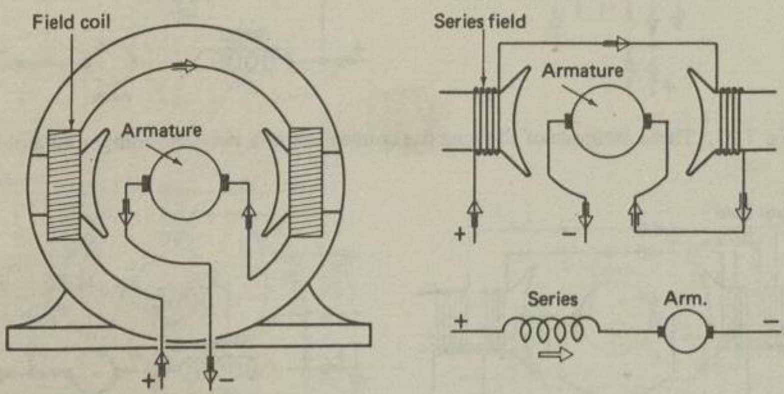


Fig. 7-29. Several methods of showing the connections of a two-pole series motor.

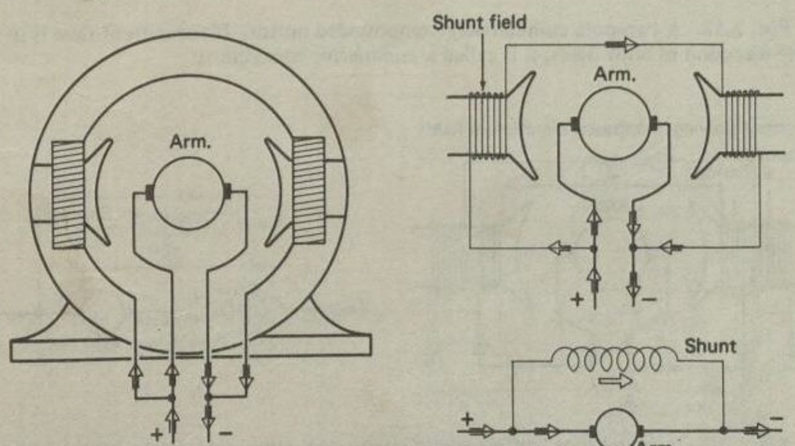


Fig. 7-30. Three methods of showing the connections of a two-pole shunt motor.

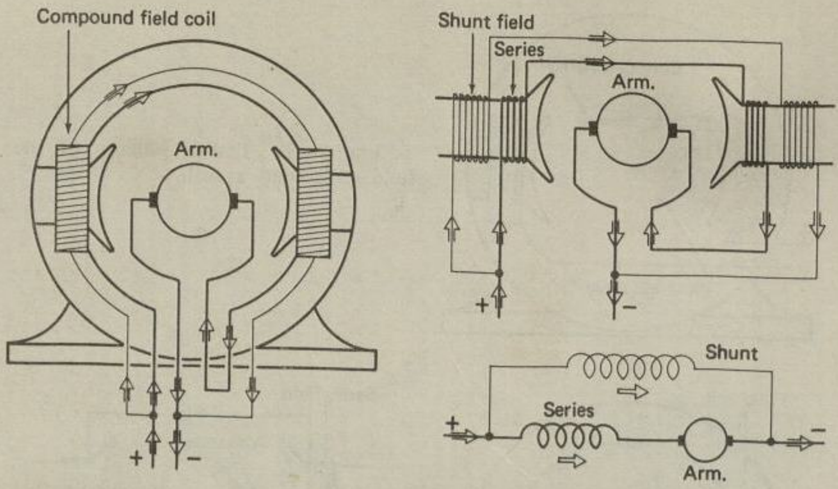


Fig. 7-31. Three methods of showing the connection of a two-pole compound motor.

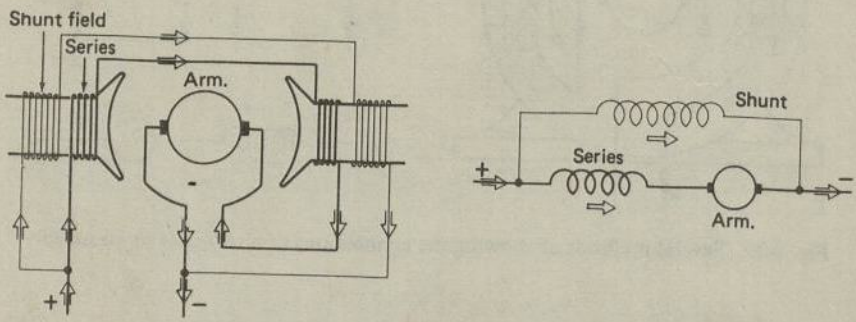


Fig. 7-32. A two-pole cumulatively compounded motor. If the current flow is in the same direction in both fields, it is called a *cumulative connection.*

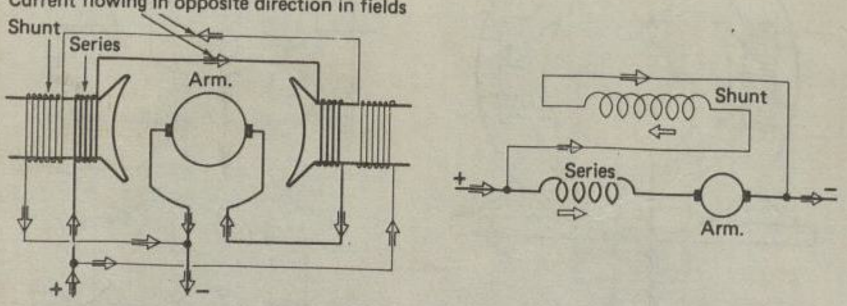


Fig. 7-33. A long-shunt, differentially connected compound motor with the current flow in opposite directions in the fields. When the shunt field is connected across the line, it is called a *long shunt.*

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Figures 7-31; 7-32; 7-33 cumulative (adj) [kjú mjulətiv]

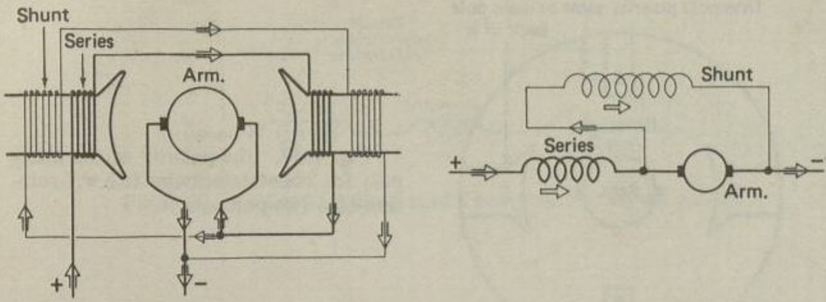


Fig. 7-34. A short-shunt cumulatively compound motor. The current in both the series and shunt fields flows in the same direction.

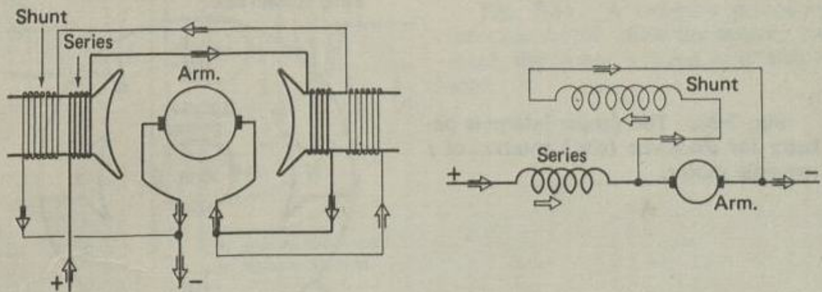


Fig. 7-35. A two-pole, short-shunt differentially compounded motor.

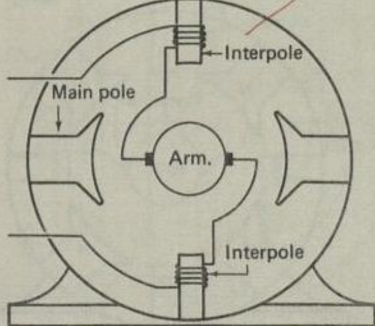


Fig. 7-36. Method of connecting the interpole in a two-pole motor.

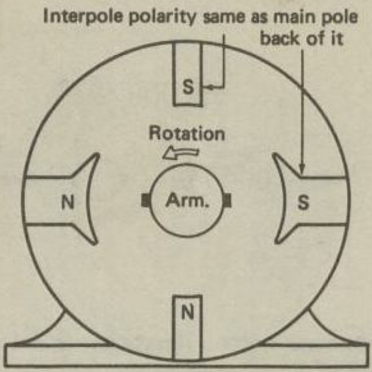


Fig. 7-37. The polarity of the interpole for counterclockwise (c.c.w.) rotation of a two-pole motor.

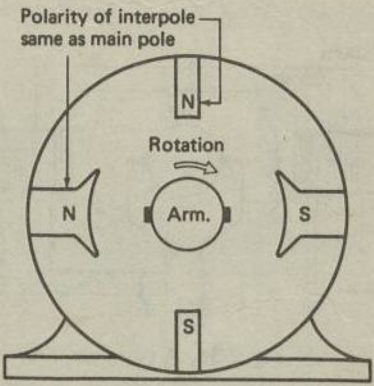


Fig. 7-38. The proper interpole polarity for clockwise (c.w.) rotation of a two-pole motor.

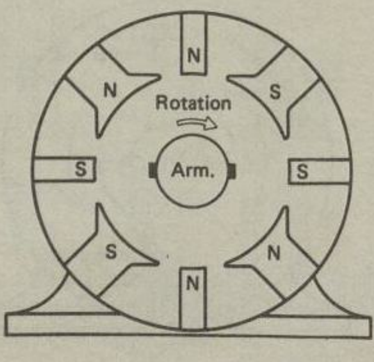


Fig. 7-39. The polarity of the interpole for clockwise (c.w.) rotation of a four-pole motor.

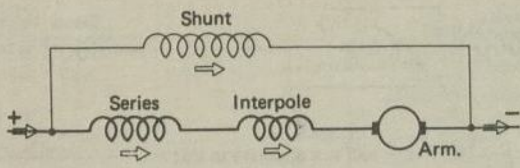


Fig. 7-40. A schematic diagram of a compound-interpole motor.

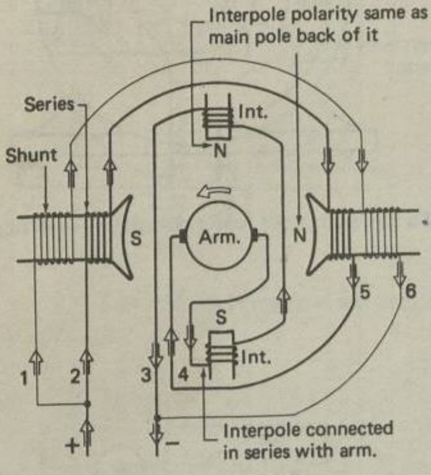


Fig. 7-41. A two-pole compound-interpole motor. With the polarity indicated, the motor will run counterclockwise.

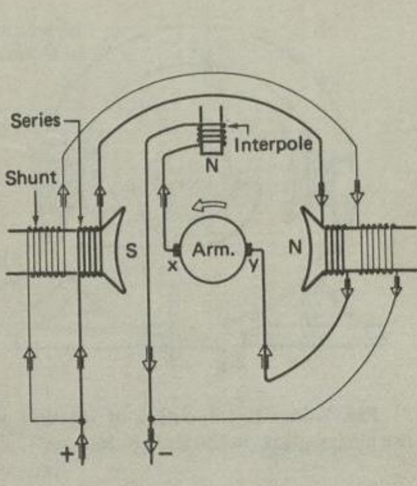


Fig. 7-42. A two-pole compound-interpole motor using one interpole connected in series with the armature.

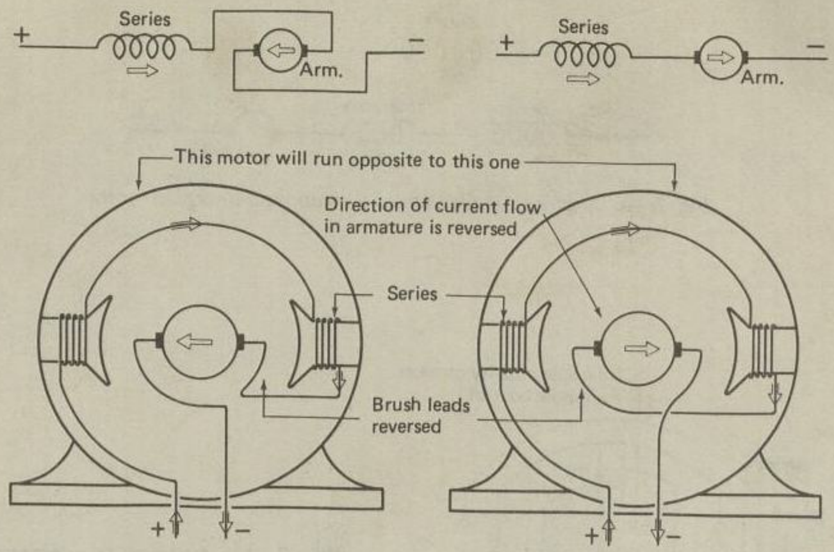


Fig. 7-43. The direction of rotation of a two-pole series motor changed by reversing the current flow in the armature.

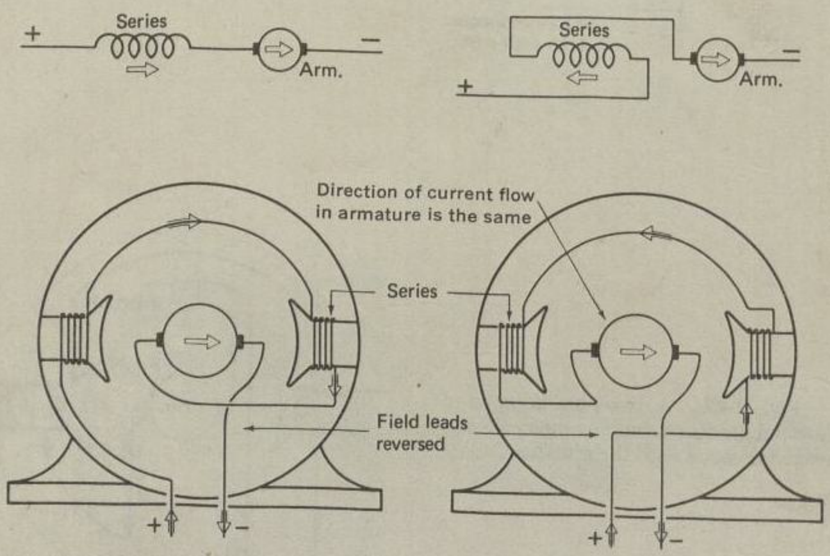


Fig. 7-44. The direction of rotation of a two-pole series motor changed by reversing the current flow in the field poles.

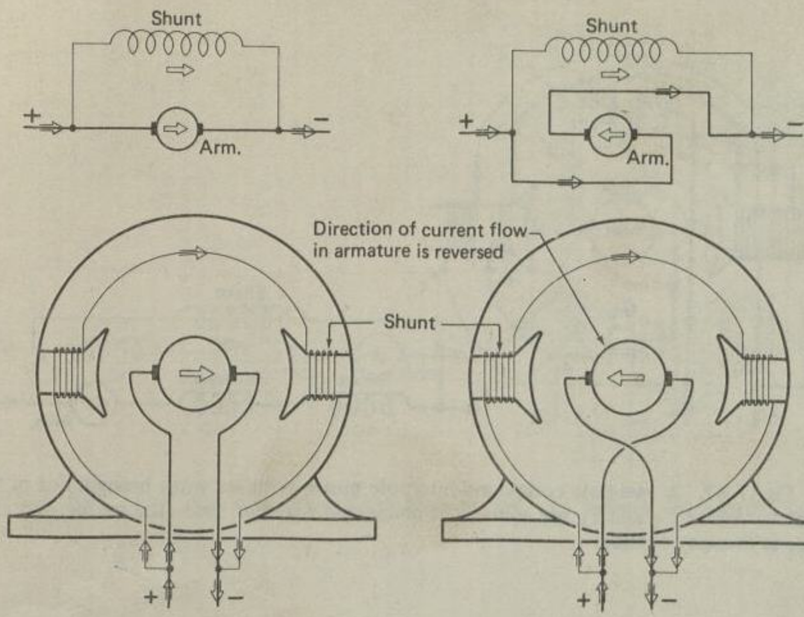


Fig. 7-45. A two-pole shunt motor reversed in the armature circuit.

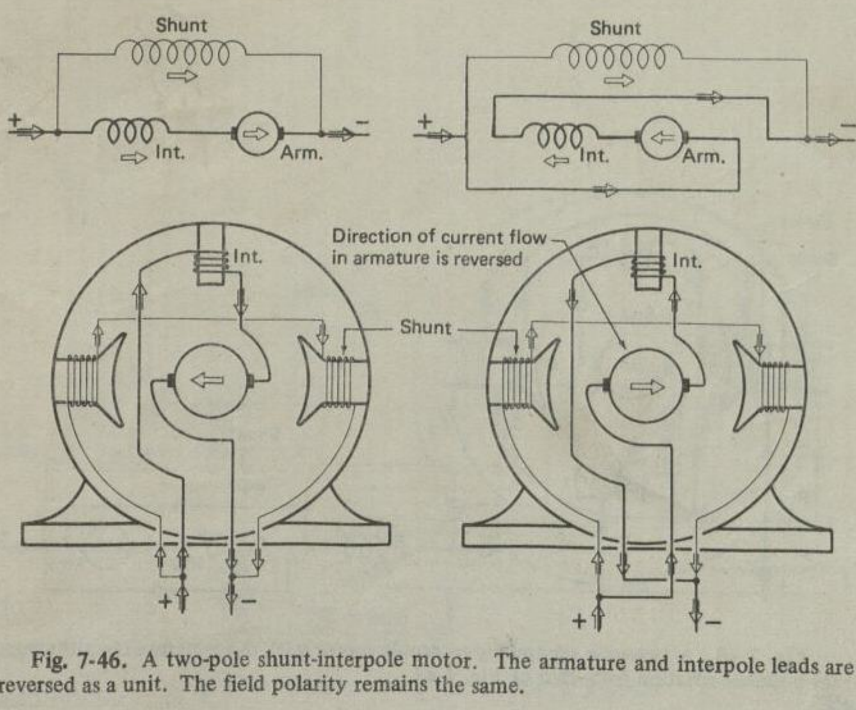


Fig. 7-46. A two-pole shunt-interpole motor. The armature and interpole leads are reversed as a unit. The field polarity remains the same.

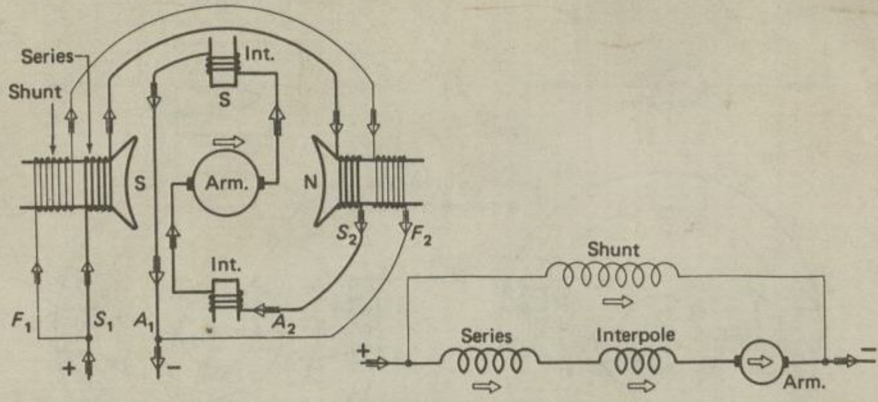


Fig. 7-47. A two-pole compound-interpole motor with six wires brought out of the motor. Wires F_1 and S_1 are sometimes connected together inside the motor, and one wire is brought outside.

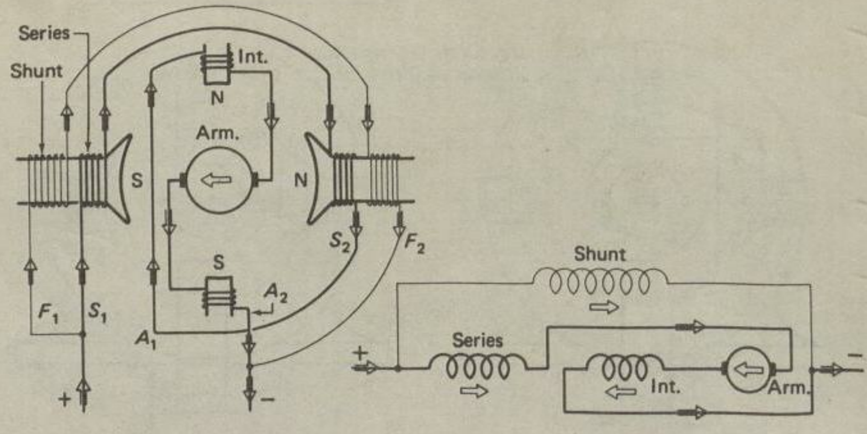


Fig. 7-48. A two-pole compound-interpole motor with the armature circuit reversed for opposite rotation from that of Fig. 7-47.

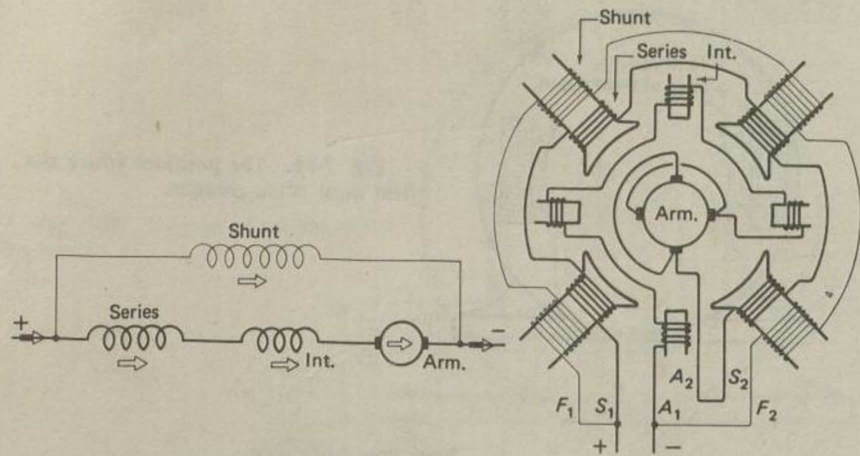


Fig. 7-49. A four-pole compound-interpole motor. To reverse, interchange leads A_1 and A_2.

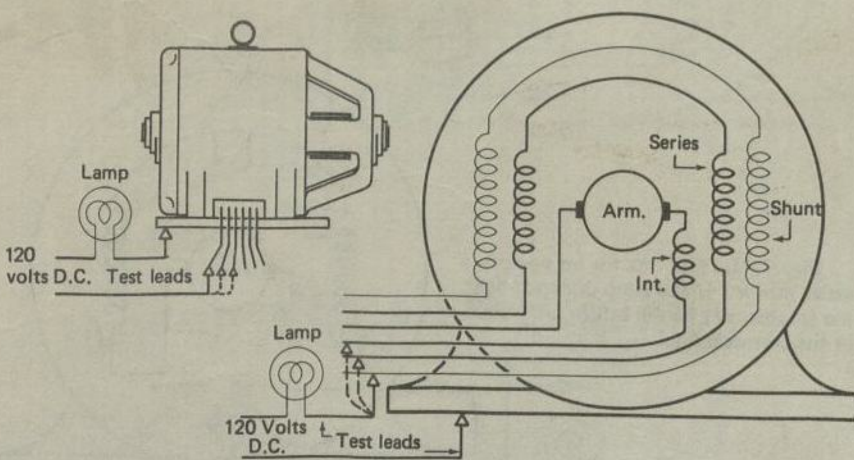


Fig. 7-50. Testing a compound motor for grounds.

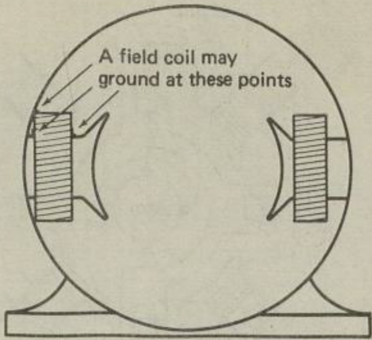


Fig. 7-51. The positions where the field most often grounds.

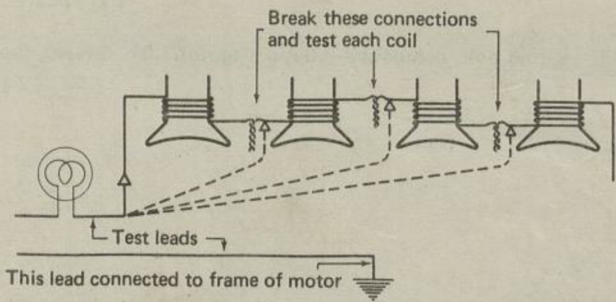
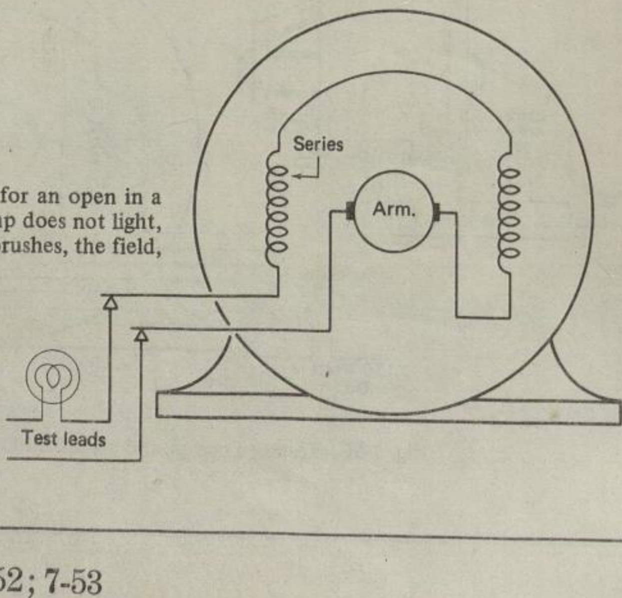


Fig. 7-52. To locate the grounded field coil, each coil is given a ground test.

Fig. 7-53. The test for an open in a series motor. If the lamp does not light, the trouble may be the brushes, the field, or the connections.



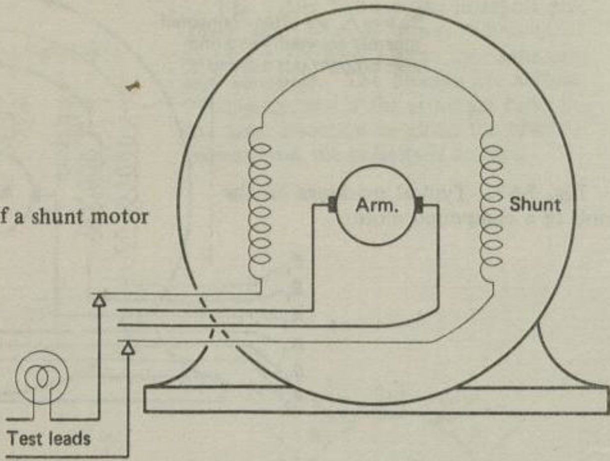


Fig. 7-54. The test of a shunt motor for opens.

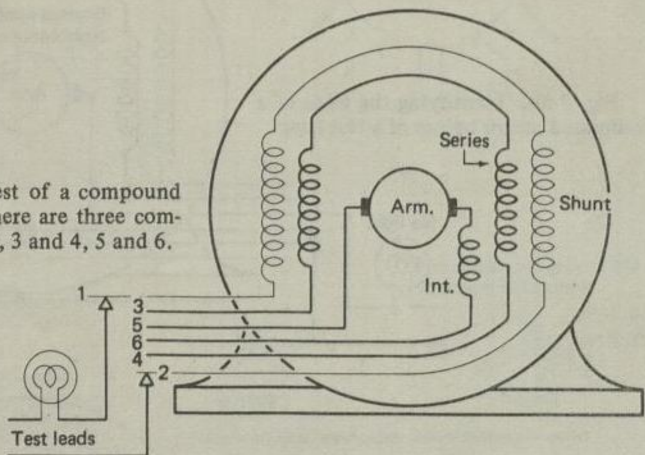


Fig. 7-55. The test of a compound motor for opens. There are three complete circuits: 1 and 2, 3 and 4, 5 and 6.

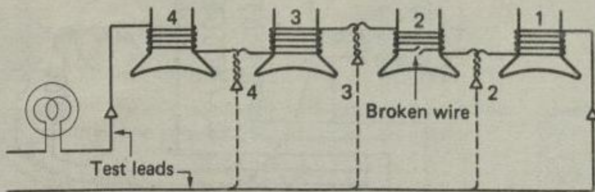


Fig. 7-56. The test for locating an open field coil in a four-pole motor.

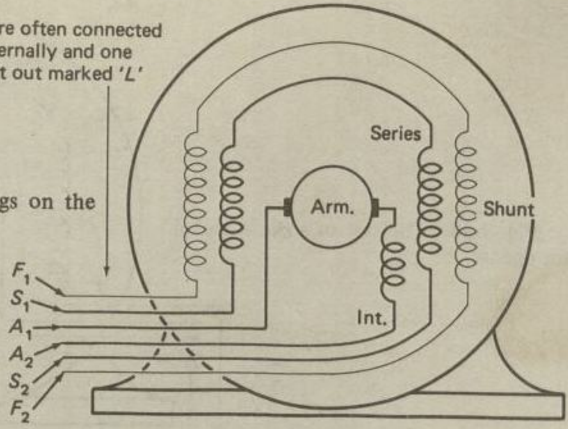


Fig. 7-57. Typical markings on the leads of a compound motor.

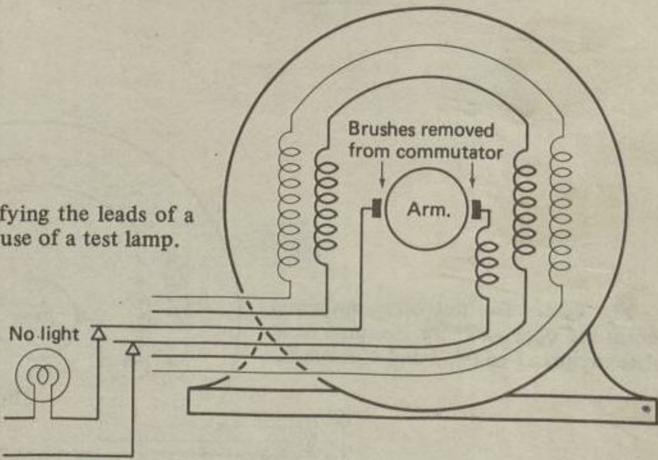


Fig. 7-58. Identifying the leads of a compound motor by use of a test lamp.

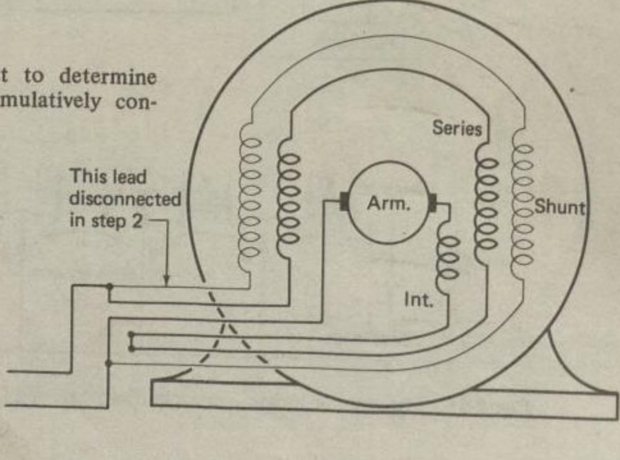


Fig. 7-59. The test to determine whether a motor is cumulatively connected.

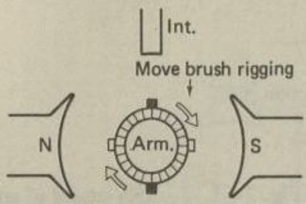


Fig. 7-60. The test for interpole polarity in a two-pole motor. All connections are removed except the armature and interpole. The brushes are shifted 90 degrees, and if the armature turns in the same direction in which the brushes were moved, the polarity is correct.

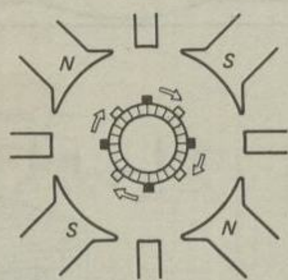


Fig. 7-61. The test for correct interpole polarity in a four-pole motor.

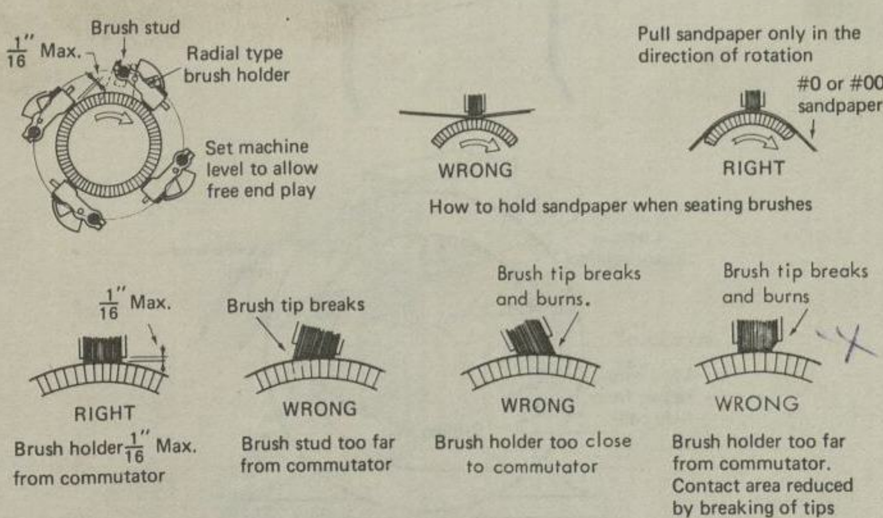


Fig. 7-62. The correct and incorrect positions of a carbon brush.

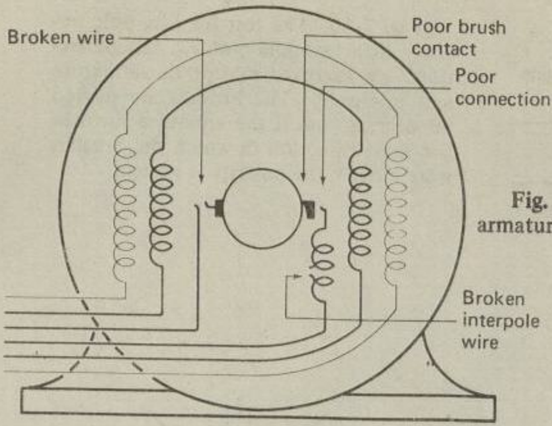
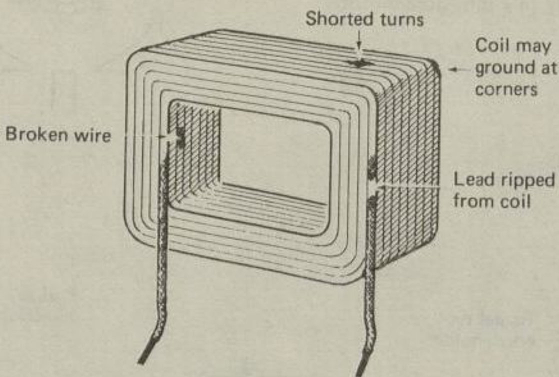


Fig. 7-63. Possible causes of an open armature circuit.



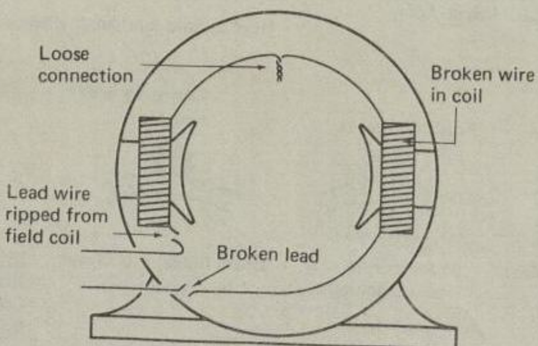


Fig. 7-64. Possible locations of opens in the field circuit and coil.

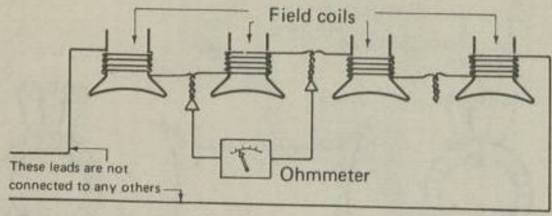


Fig. 7-65. The ohmmeter method of detecting a shorted coil.

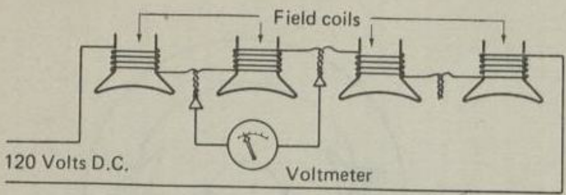


Fig. 7-66. The voltmeter method of locating a shorted coil.

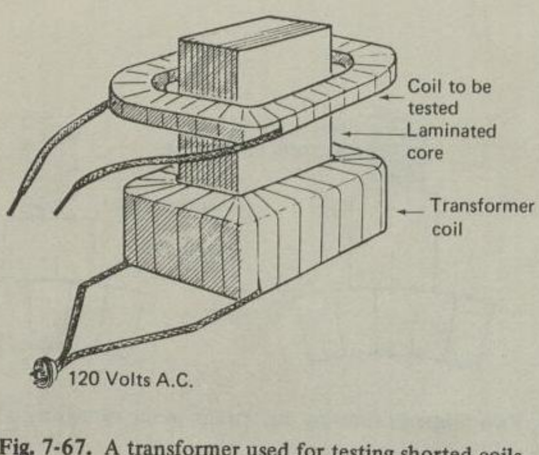


Fig. 7-67. A transformer used for testing shorted coils.

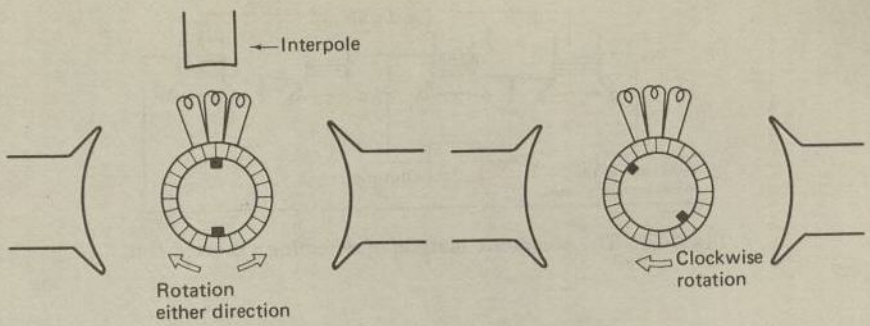


Fig. 7-68. The correct brush positions for interpole and noninterpole motors.

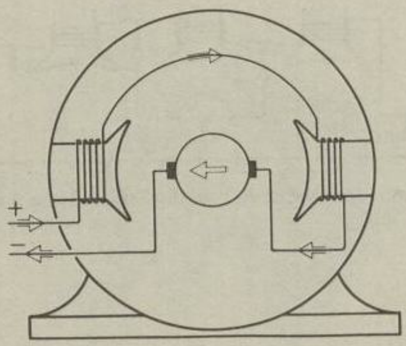


Fig. 7-69. The same amount of current flows through all elements of a series motor.

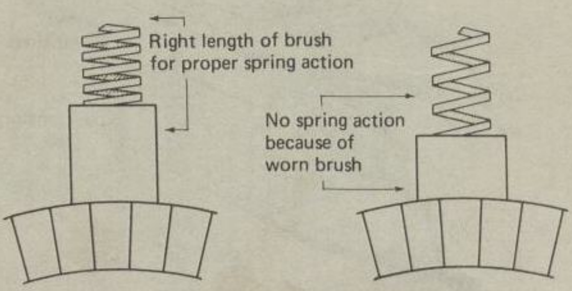


Fig. 7-70. Two diagrams showing the tension in the springs with brushes of different length.

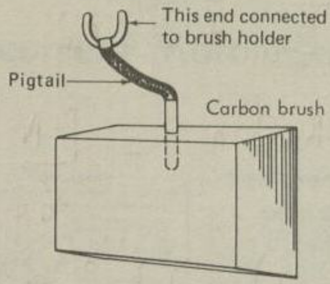


Fig. 7-71. A common type of pigtail brush.

CHAPTER 8

Direct-current Motor Control

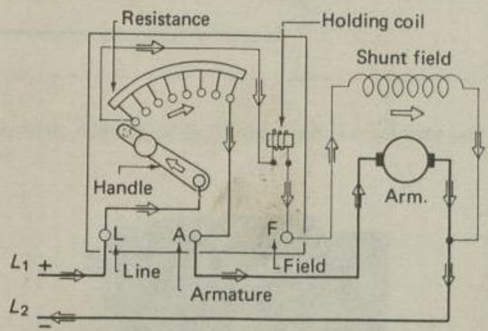


Fig. 8-1. A three-point starting box connected to a shunt motor.

Hộp điều khiển 3 điểm mô tơ Shunt.

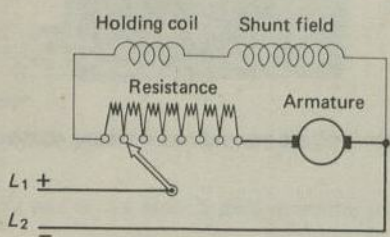


Fig. 8-2. A simplified diagram of Fig. 8-1.

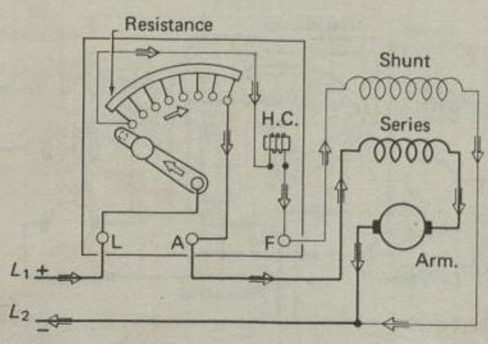
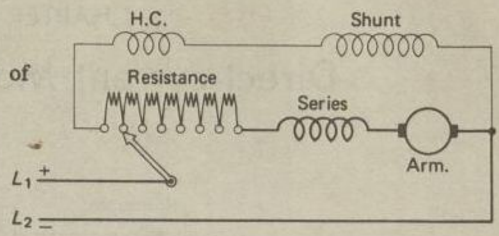


Fig. 8-3. A three-point starting box connected to a compound motor.

Fig. 8-4. A simplified diagram of Fig. 8-3.



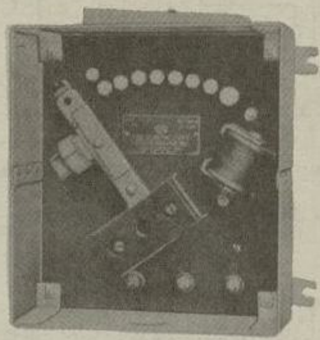


Fig. 8-5. A reduced voltage manual non-reversing starter. *(Cutler Hammer)*

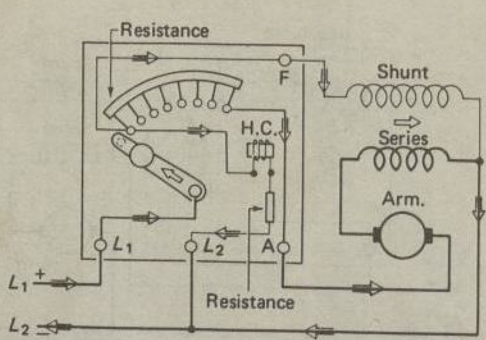


Fig. 8-6. A four-point starting box connected to a compound motor.

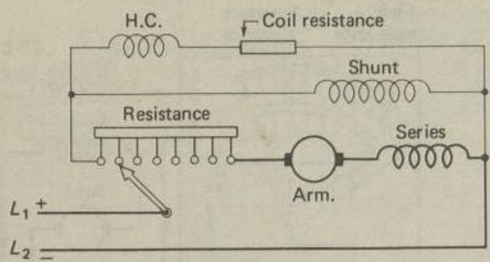


Fig. 8-7. A schematic diagram of the current paths for a four-point box connected to a compound motor.

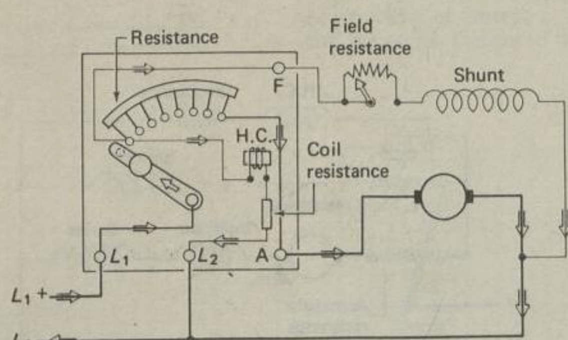
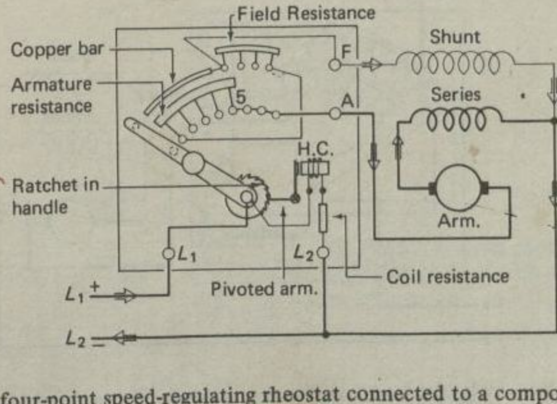


Fig. 8-8. A four-point box with a variable field resistance added for speed control.

resistance (n) [rizístəns] điện trở, sự chống lại



[rǽtʃit] cơ cấu bánh cóc

Fig. 8-9. A four-point speed-regulating rheostat connected to a compound motor.

[ríəstæt] biến trở

pivot (n) [pívət] quay trên 1 cái trục

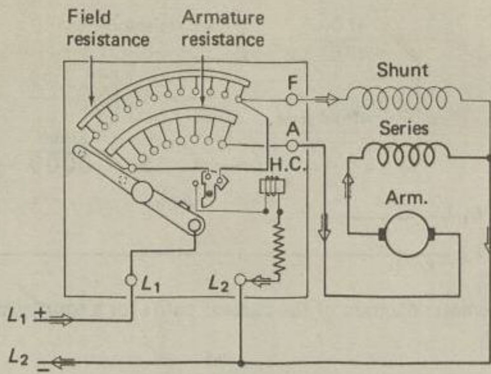


Fig. 8-10. A four-point starting box and speed-regulating rheostat connected to a compound motor.

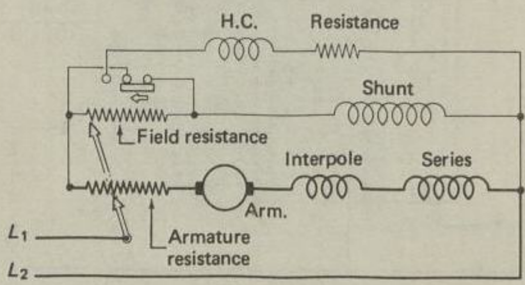


Fig. 8-11. A simplified diagram of Fig. 8-10.

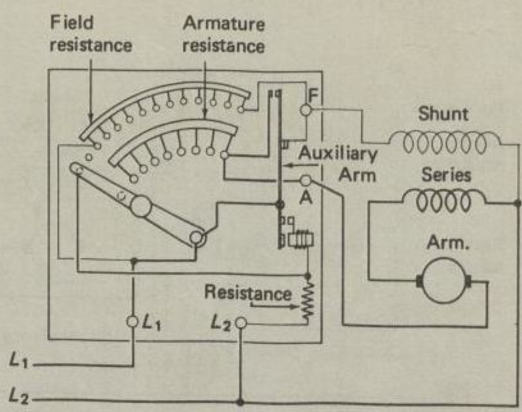


Fig. 8-12. A combination starter and speed regulator.

Figures 8-10; -11; 8-12

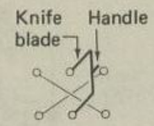


Fig. 8-13. A double-pole, double-throw knife switch.

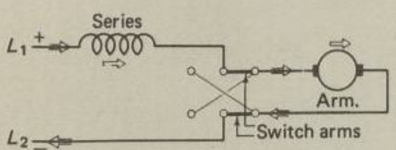
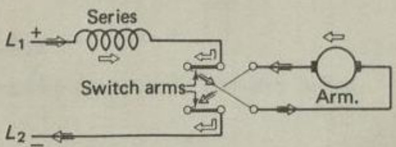


Fig. 8-14. A double-pole, double-throw switch connected to reverse the armature current of a series motor. Note the direction of current in the armature with the switch thrown to the right.

Fig. 8-15. A circuit of **Fig. 8-14** with the switch thrown in the opposite direction.



Arm (Armature)

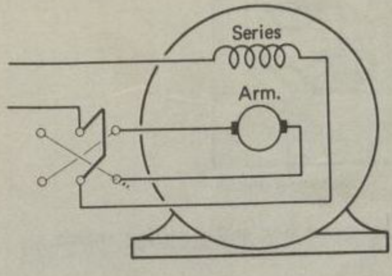


Fig. 8-16. A series motor connected to a double-pole, double-throw switch for reversing.

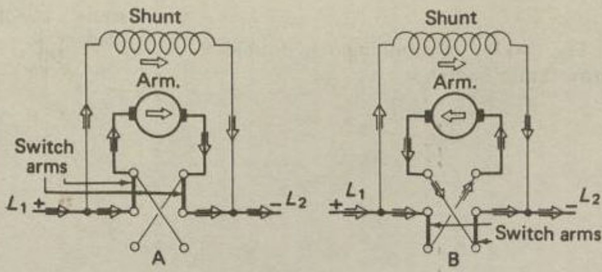


Fig. 8-17. At *(A)* with the switch thrown up, the armature current of a shunt motor is flowing to the right. At *(B)* with the switch thrown down, the armature current is flowing to the left.

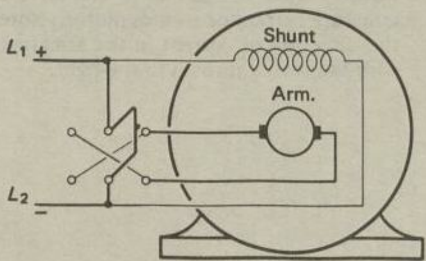


Fig. 8-18. A shunt motor connected to a double-pole, double-throw switch.

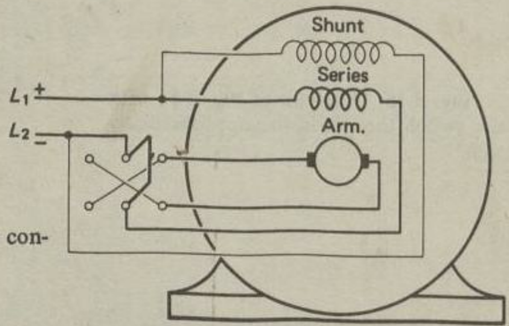


Fig. 8-19. A compound motor connected to a reversing switch.

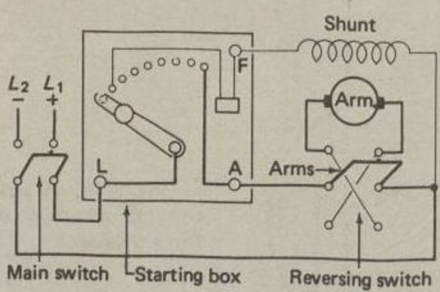


Fig. 8-20. A shunt motor connected to three-point box and reversing switch.

Int (interpole)

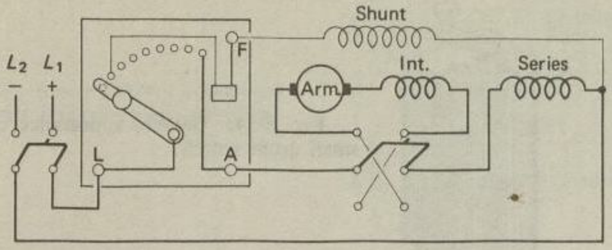


Fig. 8-21. A compound motor connected to three-point box and reversing switch. Note that the armature and interpole are reversed as a unit.

?

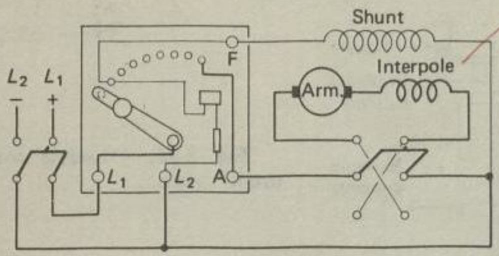


Fig. 8-22. A shunt motor connected to a four-point box and reversing switch.

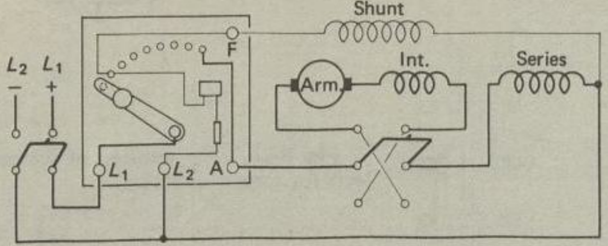


Fig. 8-23. A compound motor connected to a four-point box and reversing switch.

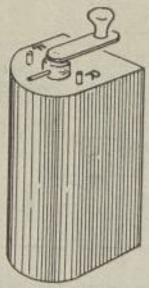
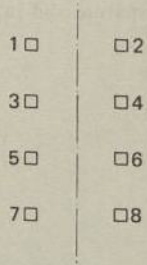


Fig. 8-24. General appearance of a small drum switch.

Fig. 8-25. Stationary contacts of a drum switch.



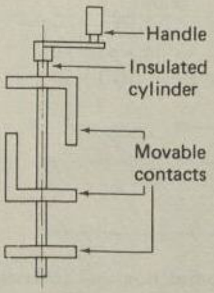
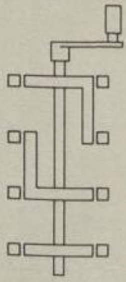


Fig. 8-26. Movable contacts of a drum switch.

Fig. 8-27. The position of the contacts for forward rotation.



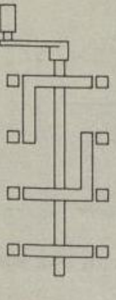


Fig. 8-28. The position of the contacts for reverse direction.

Figures 8-24; 8-25; 8-26; 8-27; 8-28

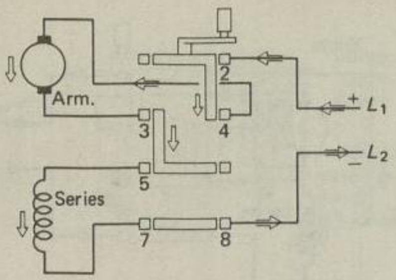


Fig. 8-29. A series motor connected to a drum switch for clockwise direction.

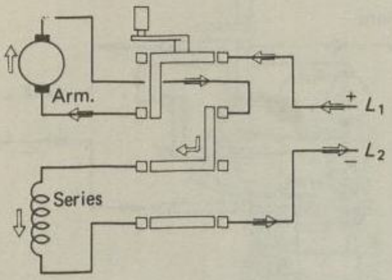


Fig. 8-30. A drum switch connection for counterclockwise rotation of a series motor.

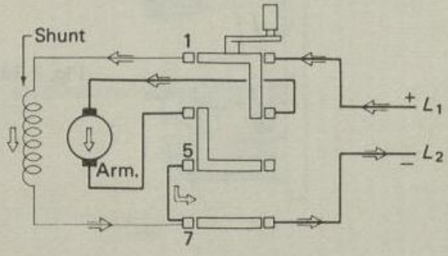


Fig. 8-31. A shunt motor connected to a drum switch.

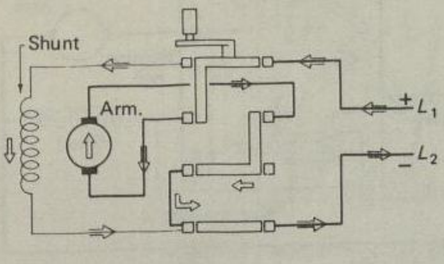


Fig. 8-32. A shunt motor of Fig. 8-31 reversed by drum switch.

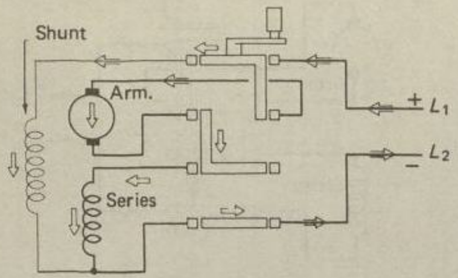


Fig. 8-33A. A compound motor connected to a drum switch for clockwise direction.

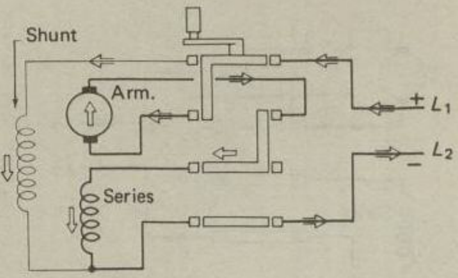


Fig. 8-33B. A compound motor connected for counterclockwise direction.

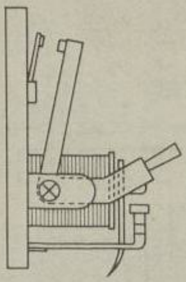


Fig. 8-34. A magnetic circuit breaker.

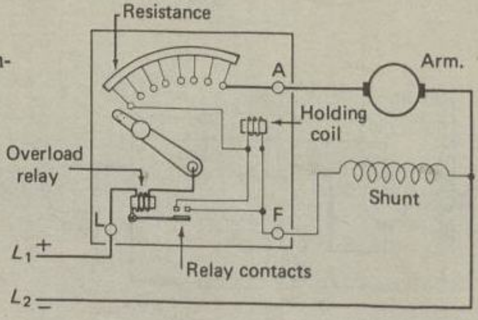
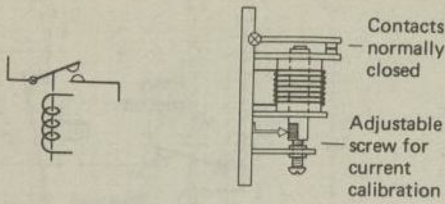


Fig. 8-35. An overload relay connected in a three-point starting box.

Fig. 8-36. An overload relay with a plunger to open the contacts.



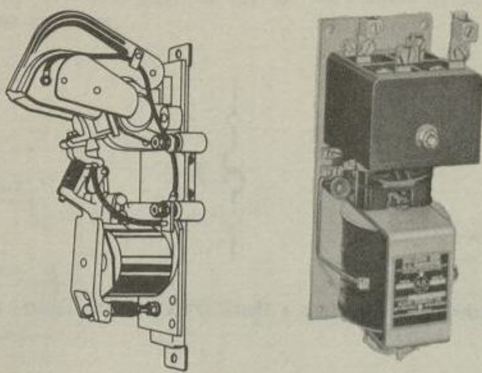


Fig. 8-37. A d-c magnetic contactor.

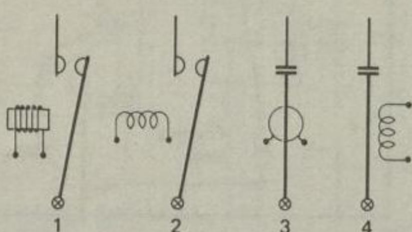


Fig. 8-38. Methods of denoting a magnetic contactor.

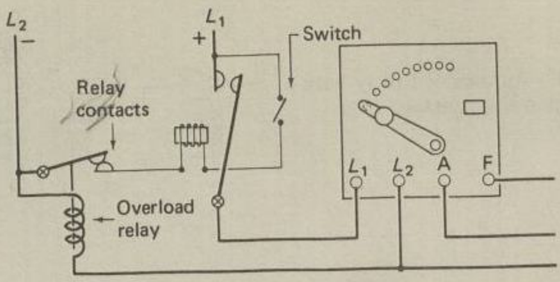


Fig. 8-39. A magnetic overload relay used in conjunction with a magnetic contactor.

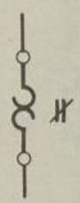


Fig. 8-40. Methods of denoting a thermal relay. The figures to the right indicate contacts.

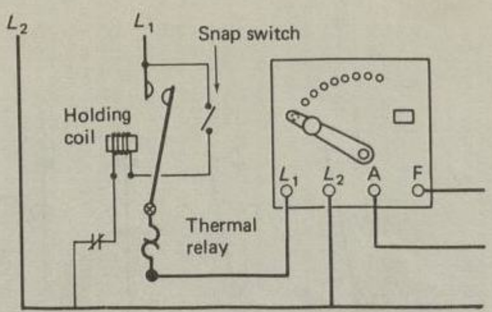


Fig. 8-41. A thermal overload relay used with a magnetic contactor.

Figures 8.39; -40; 8-41

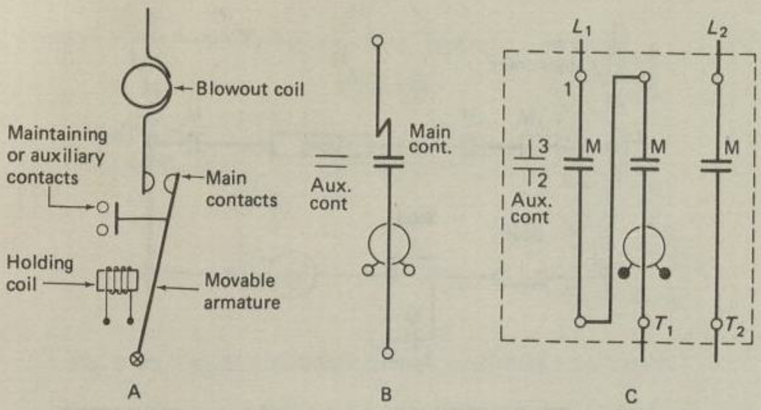


Fig. 8-42. *(A)* The parts of a magnetic switch. *(B)* Method of denoting a magnetic switch. *(C)* Two-pole contactor.

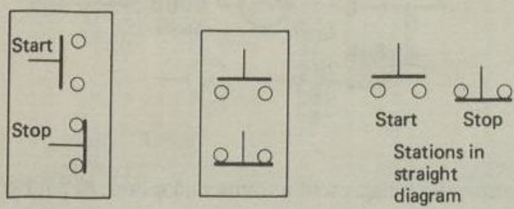


Fig. 8-43. Methods of showing four-contact, START-STOP, pushbutton stations.

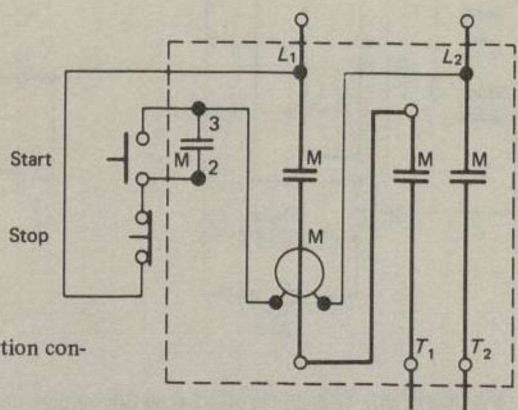


Fig. 8-44. A START-STOP station connected to a magnetic contactor.

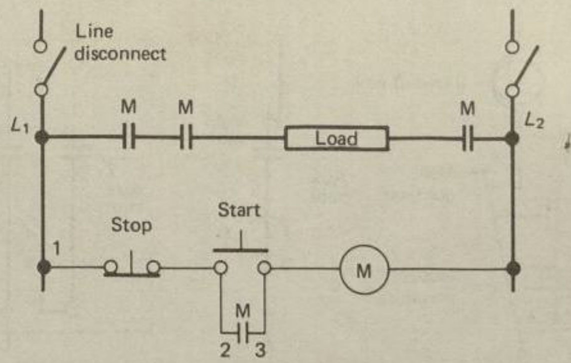


Fig. 8-45. A START-STOP station connected to a magnetic switch.

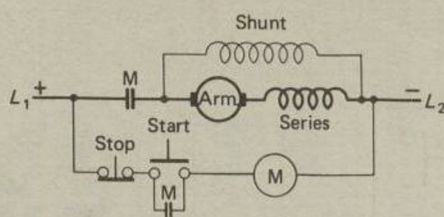


Fig. 8-46. An elementary diagram of a compound motor, START-STOP station and contactor.

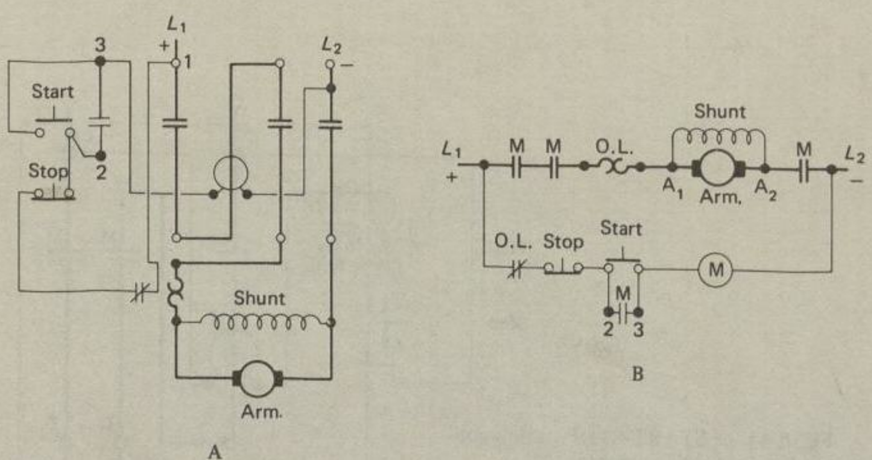


Fig. 8-47. Wiring diagram of a 2-pole full-voltage starter connected to a d-c motor.

Figures 8-45; 8-46; 8-47

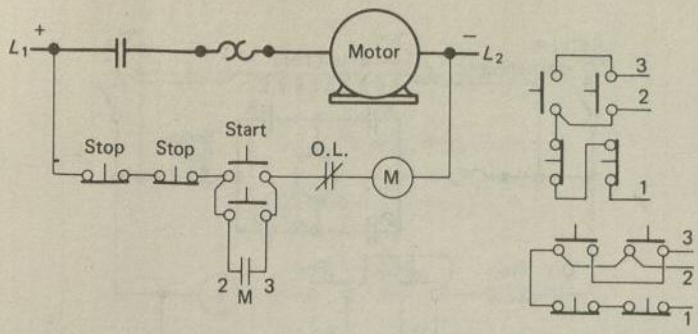


Fig. 8-48. Two START-STOP stations controlling a d-c starter.

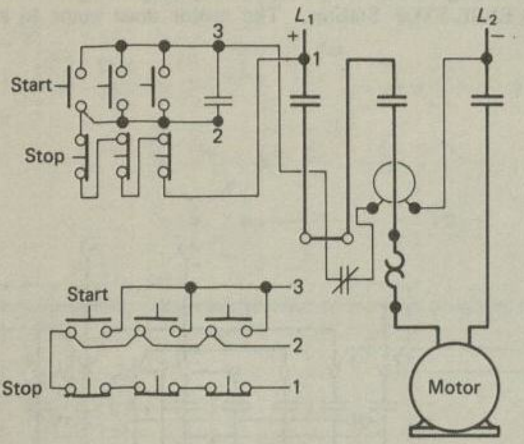


Fig. 8-49. Three START-STOP stations connected to a d-c starter.

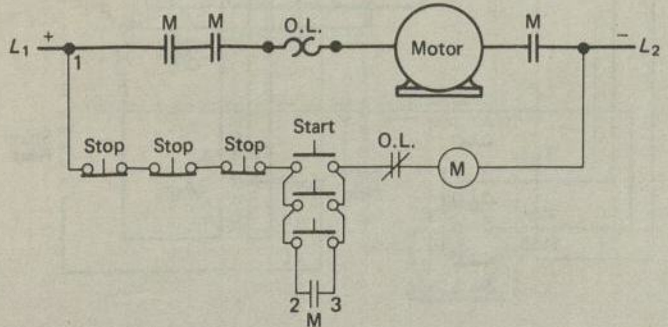


Fig. 8-50. Elementary diagram of 3 START-STOP station connected to a d-c starter.

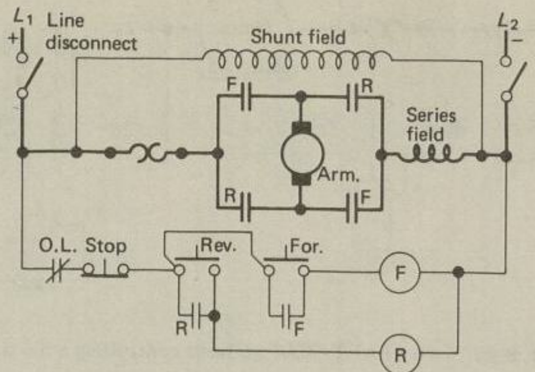


Fig. 8-51. Reversing a small compound motor, using a magnetic reversing starter and FORWARD-REVERSE-STOP Station. The motor must come to a full stop before reversing.

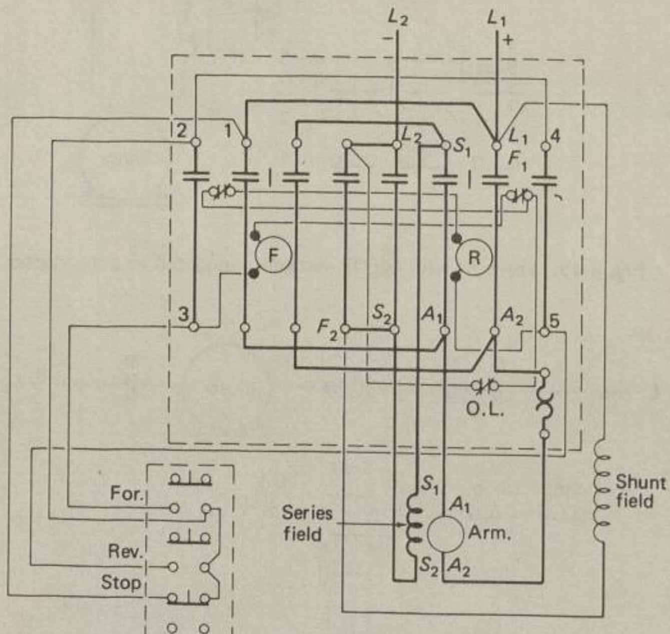


Fig. 8-52A. Wiring diagram of a reversing starter using overload protection and electrical interlocks.

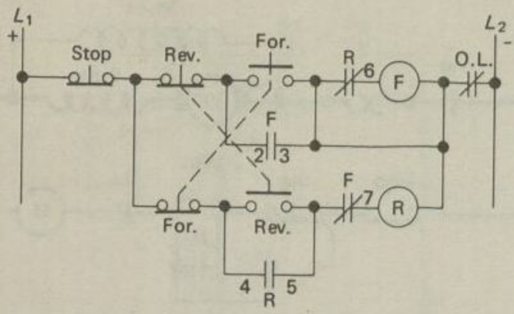


Fig. 8-52B. Control circuits for a reversing starter using front and rear contacts of the FORWARD and REVERSE buttons.

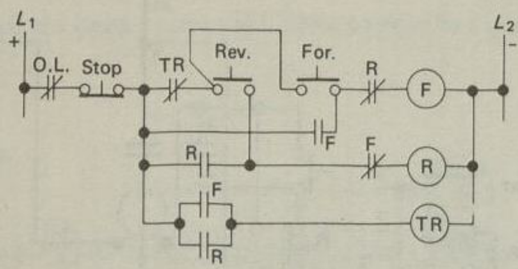


Fig. 8-53. Control circuit using timing relay to prevent reversing until motor comes to a full stop.

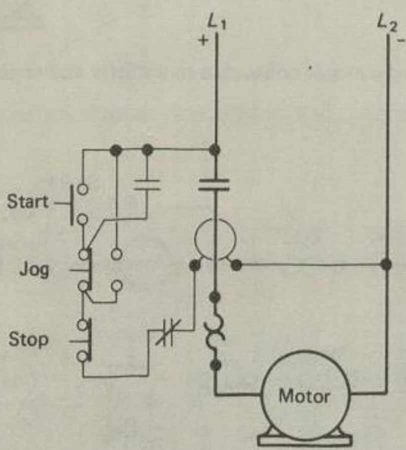


Fig. 8-54. A small d-c motor connected to a starter and START-JOG-STOP station.

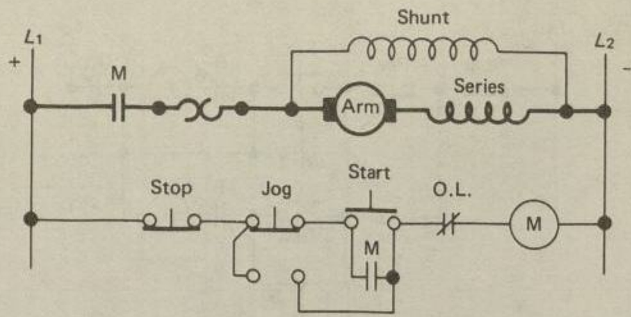


Fig. 8-55. An elementary diagram of a small motor connected to a d-c Starter and START-JOG-STOP station.

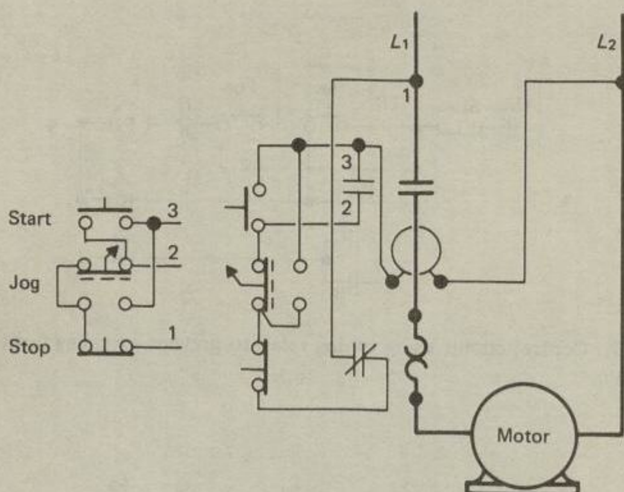


Fig. 8-56. A small d-c motor connected to a starter and station with a JOG selector push button.

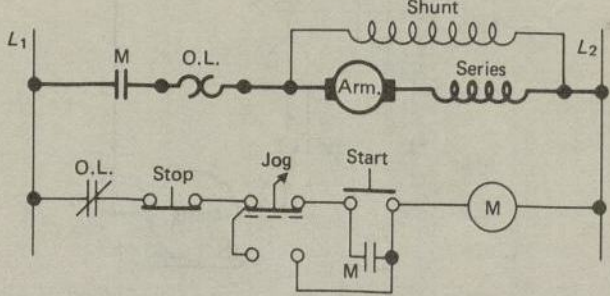


Fig. 8-57. START-JOG-STOP station with selector push button.

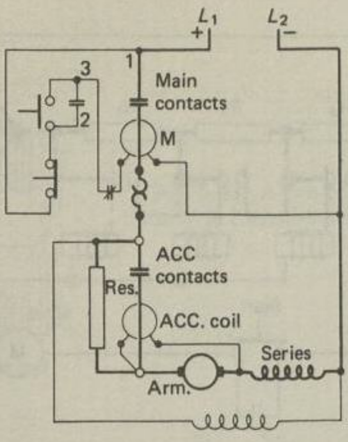


Fig. 8-58. Diagram of a simple counter e.m.f. starter operated by a magnetic switch.

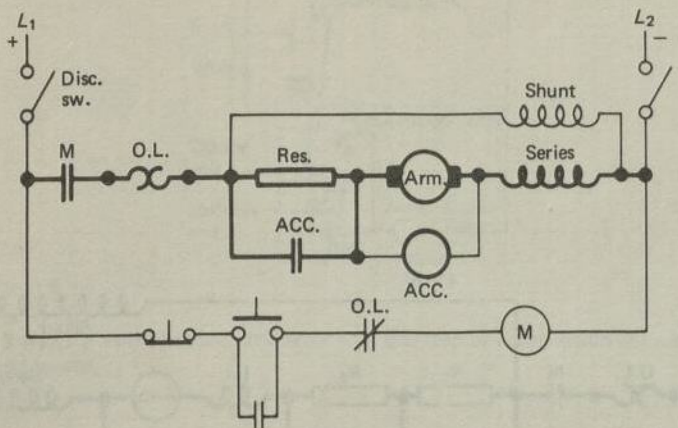


Fig. 8-59. An elementary diagram of a counter e.m.f. starter connected to a compound motor.

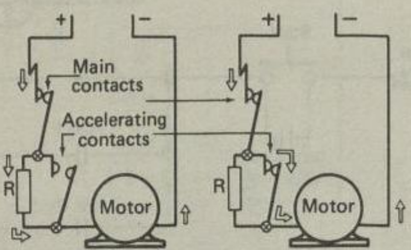


Fig. 8-60. Positions of the accelerating contact of a counter e.m.f. starter when the motor starts and after acceleration.

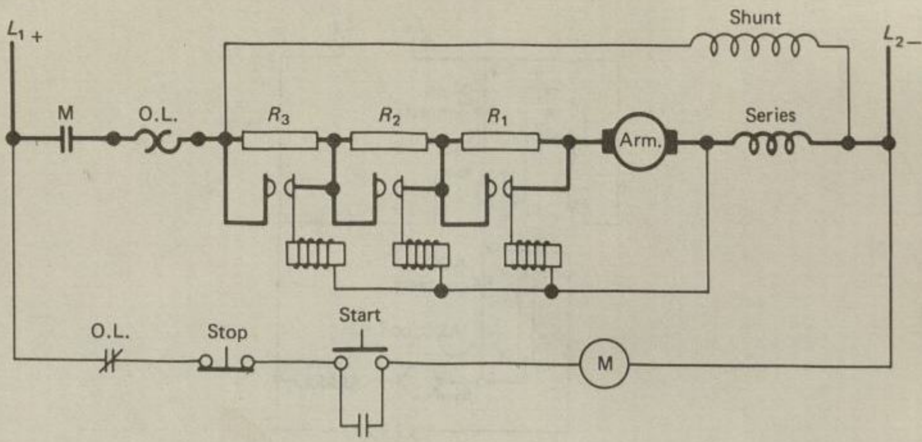


Fig. 8-61. A counter e.m.f. starter with three steps of acceleration connected to a compound motor.

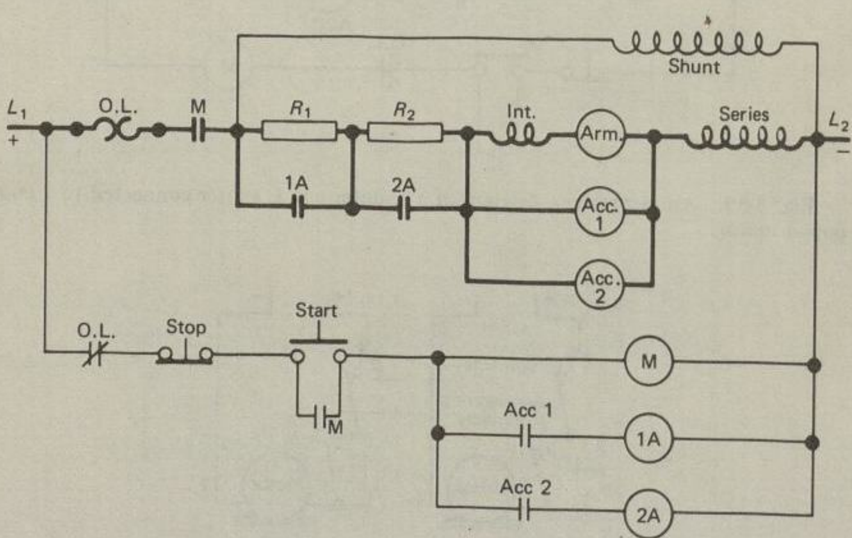


Fig. 8-62. Counter e.m.f. starter using relays.

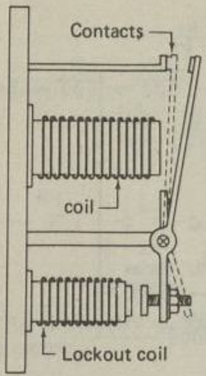


Fig. 8-63. A two-coil lockout contactor used in current-limit starters.

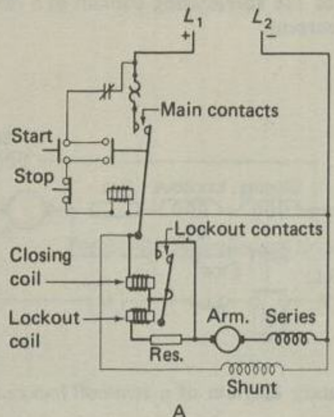


Fig. 8-64A. A two-coil lockout starter with one step of acceleration connected to a compound motor.

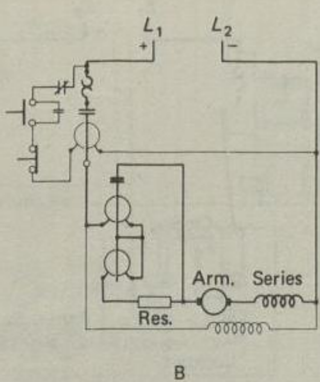


Fig. 8-64B. Different representation of a two-coil lockout starter with one step of acceleration connected to a compound motor.

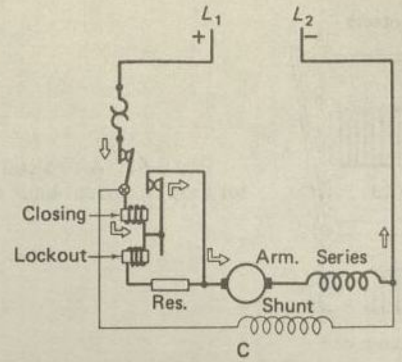


Fig. 8-64C. Position of the accelerating contact of a two-coil lockout starter when a motor is drawing normal current.

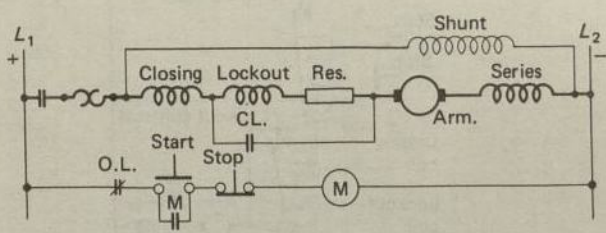


Fig. 8-65. An elementary diagram of a two-coil lockout starter connected to a compound motor.

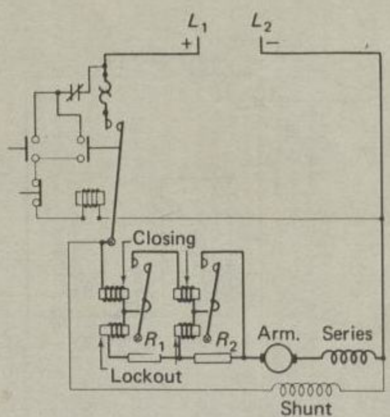


Fig. 8-66. A two-coil lockout controller with two steps of acceleration.

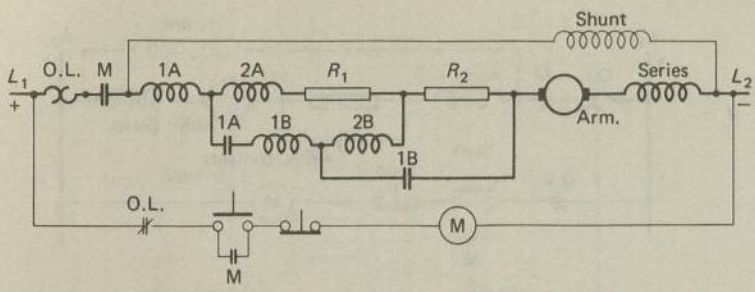


Fig. 8-67. An elementary diagram of a two-step, two-coil lockout starter connected to a compound motor.

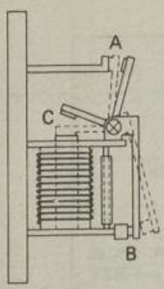


Fig. 8-68. A single-coil lockout contactor.

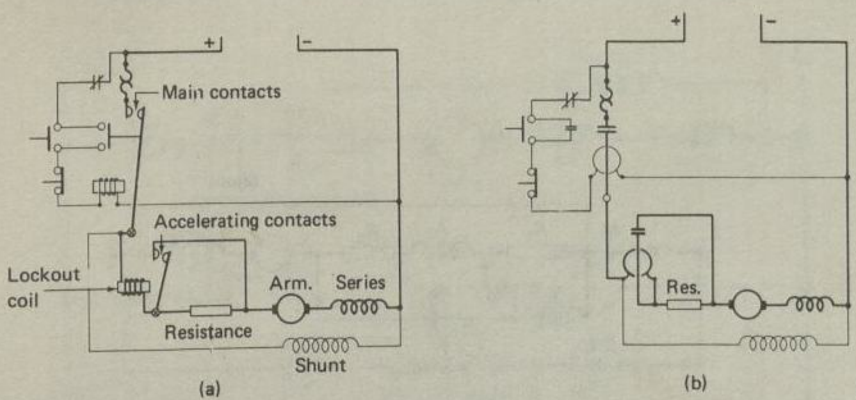


Fig. 8-69. Different representations of a single-coil lockout starter with one step of acceleration connected to a compound motor.

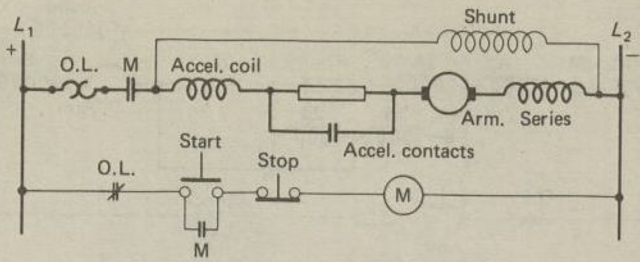


Fig. 8-70. An elementary diagram of a single-coil lockout starter connected to a compound motor.

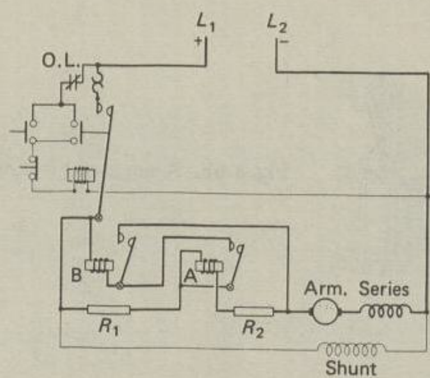


Fig. 8-71. A single-coil lockout starter with two steps of acceleration.

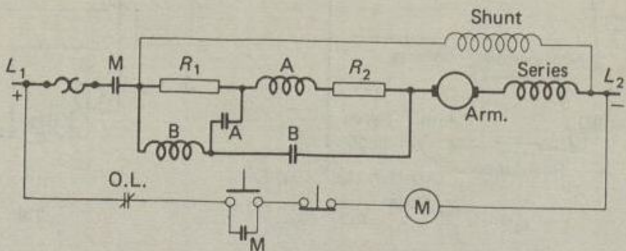


Fig. 8-72. A simplified diagram of Fig. 8-71.

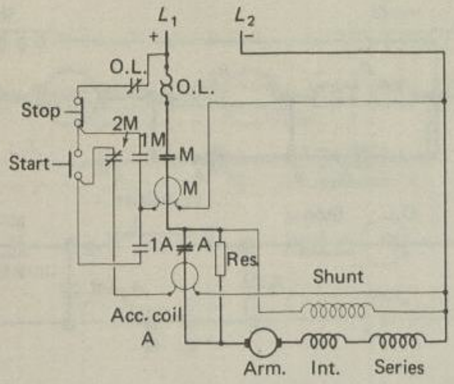


Fig. 8-73. A wiring diagram of a definite magnetic time starter connected to a compound motor.

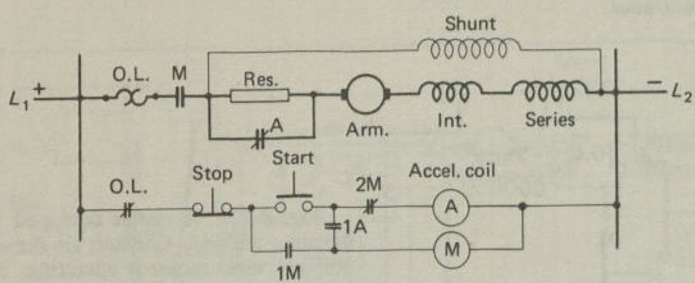


Fig. 8-74. An elementary diagram of the connection of Fig. 8-73.

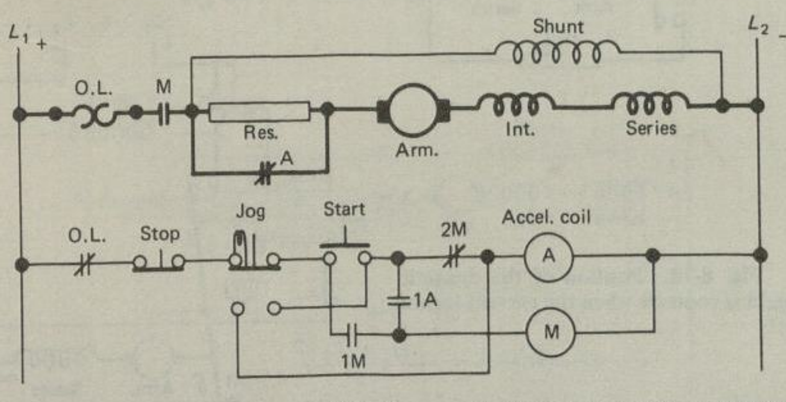


Fig. 8-75. A wiring diagram of a definite magnetic time starter with a START-JOG-STOP station.

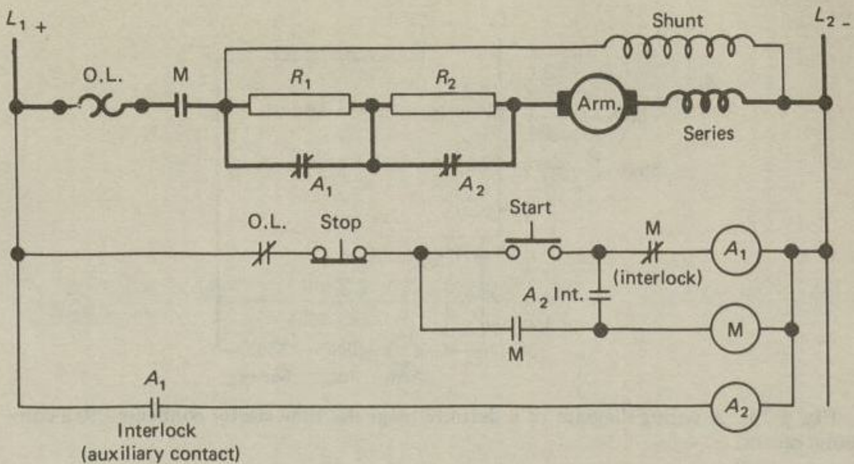


Fig. 8-76. An elementary diagram of a definite magnetic time starter having two steps of resistance.

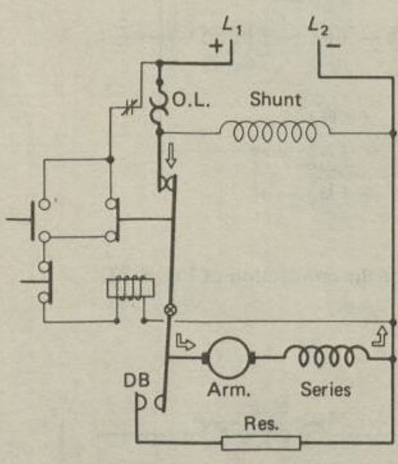


Fig. 8-77. A starter equipped with dynamic braking. Contacts are shown in position while motor is operating. Note the flow of current in the armature.

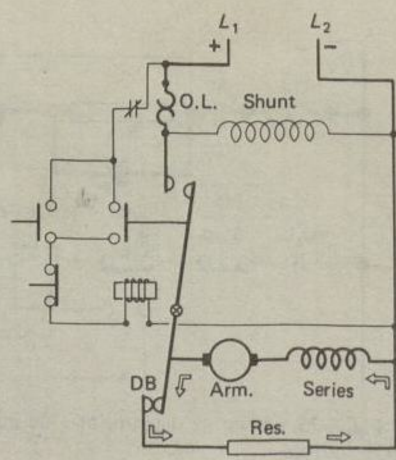


Fig. 8-78. Position of the dynamic braking contacts when the current is shut off.

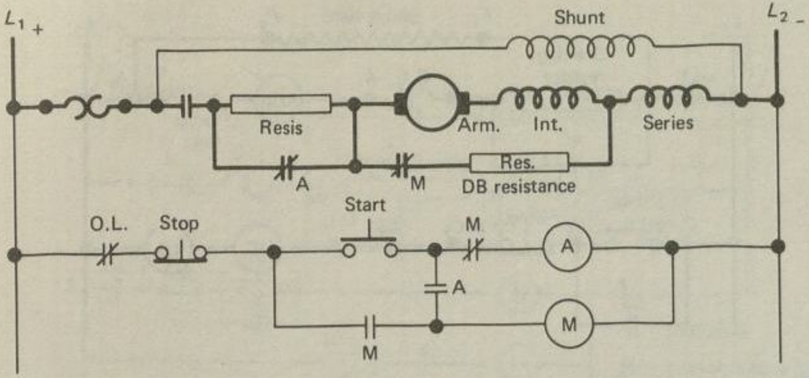


Fig. 8-79. A wiring diagram of a magnetic time delay starter with dynamic braking connected to a compound motor.

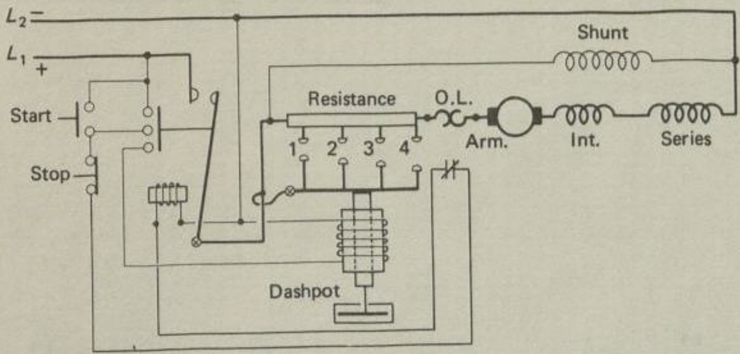


Fig. 8-80. A starter using dashpot acceleration.

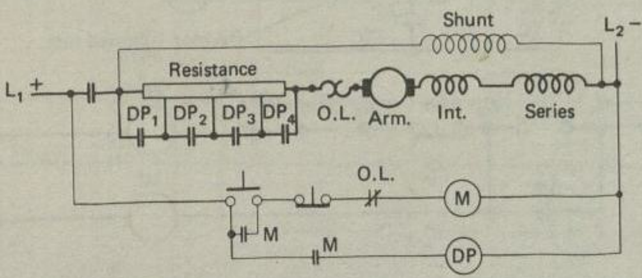


Fig. 8-81. A line diagram of a dashpot starter.

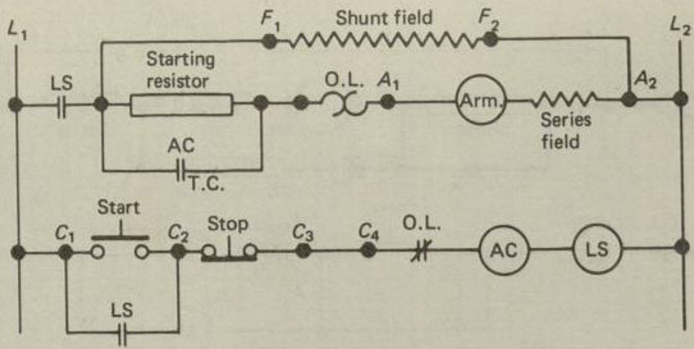


Fig. 8-82. Line diagram of a d-c reduced-voltage starter using a fluid dashpot accelerating mechanism. *(Allen-Bradley)*

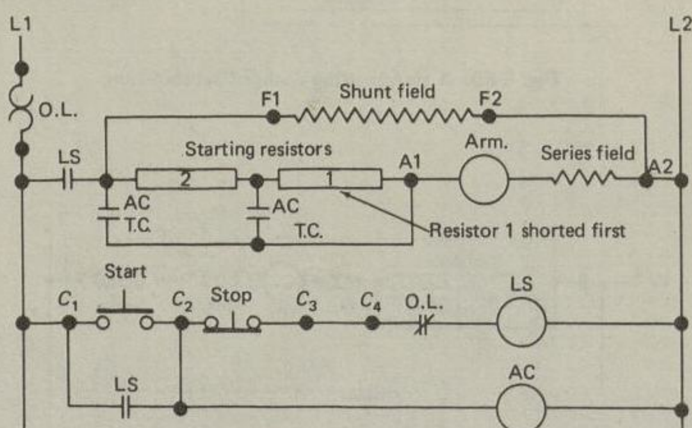


Fig. 8-83. Reduced-voltage starter with 2 increments of resistance in the circuit. *(Allen Bradley)*

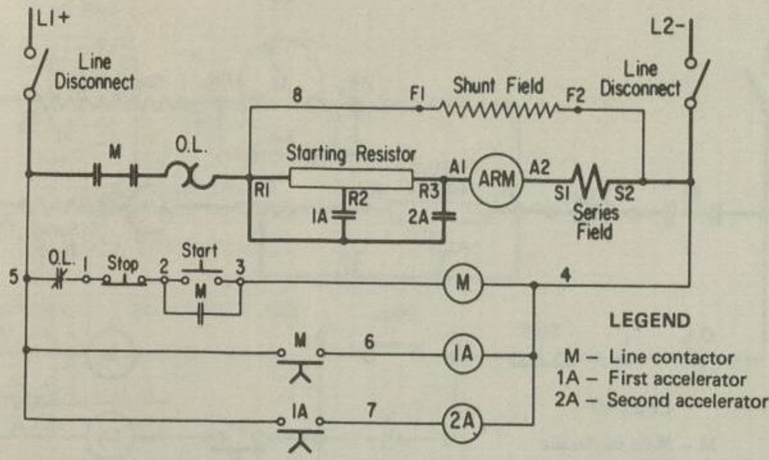


Fig. 8-84. A reduced-voltage starter with time limit acceleration. This starter uses a pneumatic timing mechanism. *(Allen Bradley)*

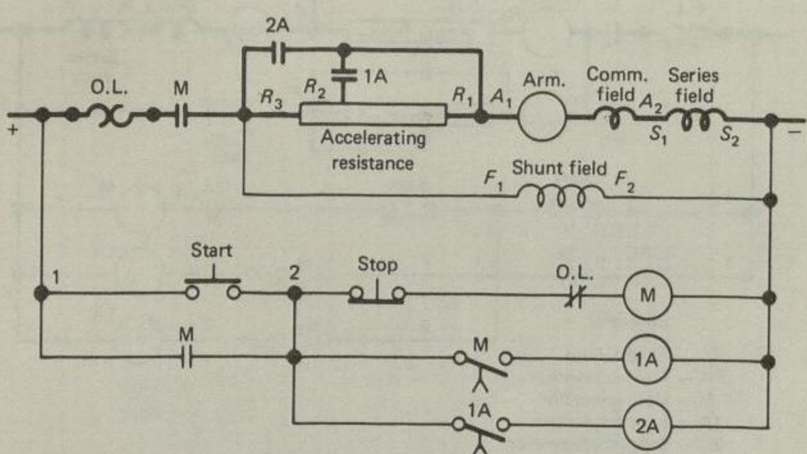


Fig. 8-85. A line diagram of a timed accelerating starter similar to the previous starter.

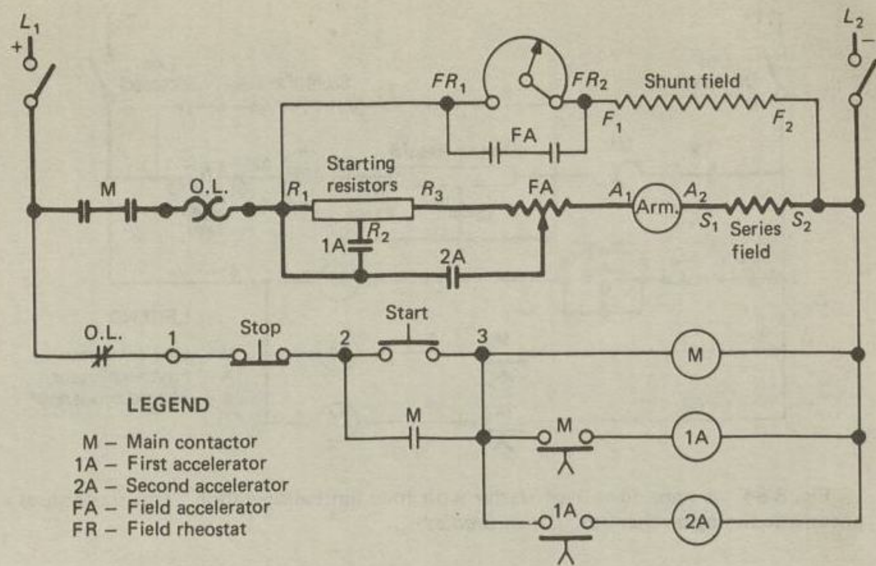


Fig. 8-86. An adjustable speed d-c starter with field accelerating relay. *(Allen Bradley)*

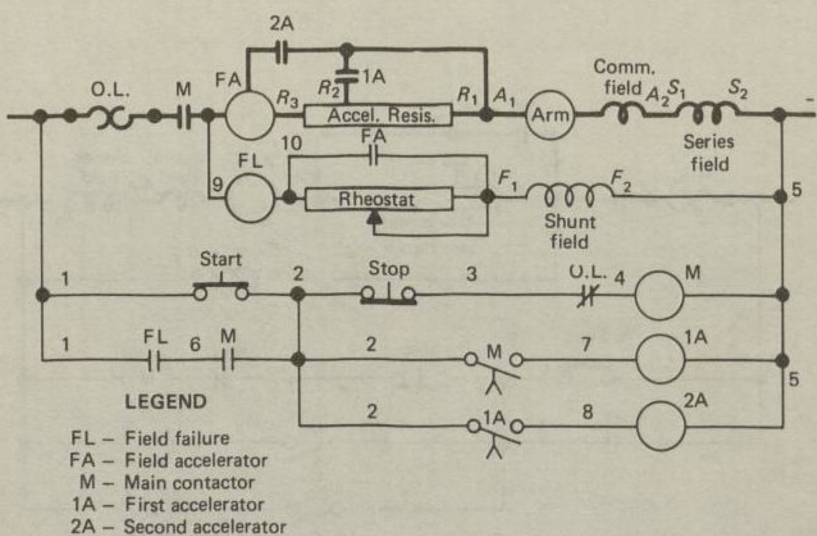
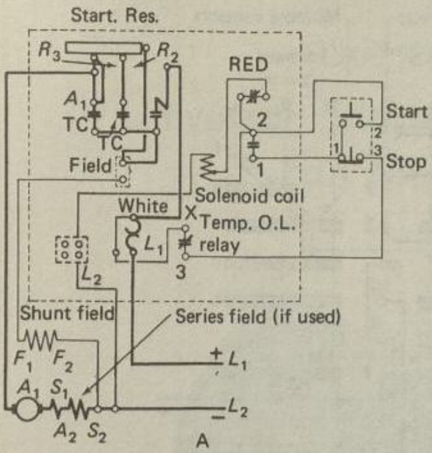


Fig. 8-87. An adjustable speed d-c starter with field accelerating relay and field failure relay. *(Square D)*



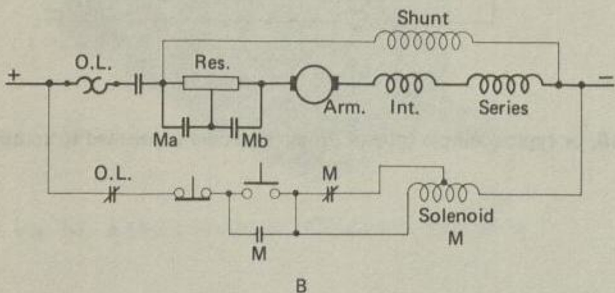


Fig. 8-88. Wiring diagrams of a definite mechanical time starter.

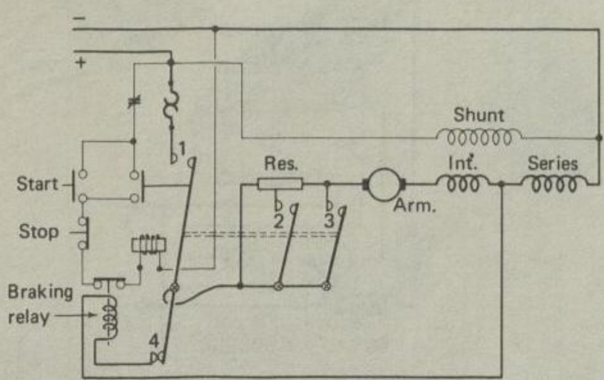


Fig. 8-89. A geared timing starter with dynamic braking.

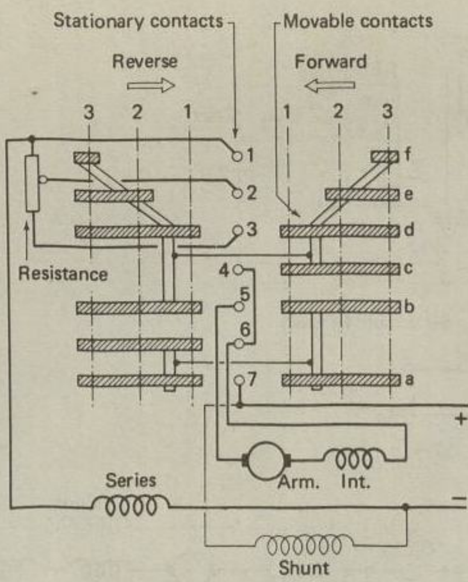


Fig. 8-90. A typical simple type of drum controller connected to compound motor.

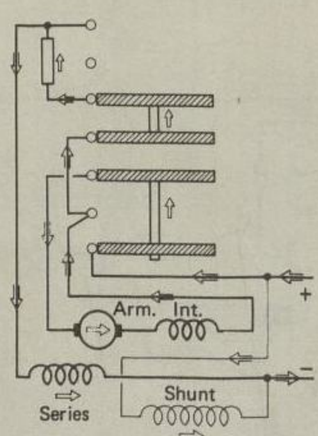


Fig. 8-91. First position of the controller of Fig. 8-90.

CHAPTER 9

Universal, Shaded-pole, and Fan Motors

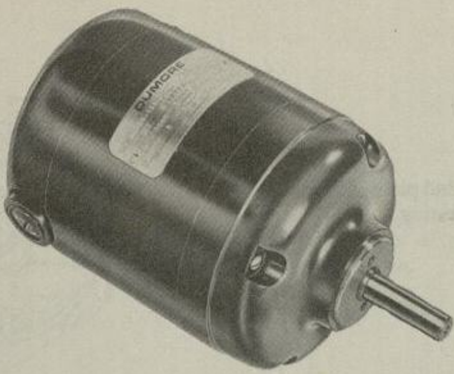


Fig. 9-1. A universal motor. *(The Dumore Company)*

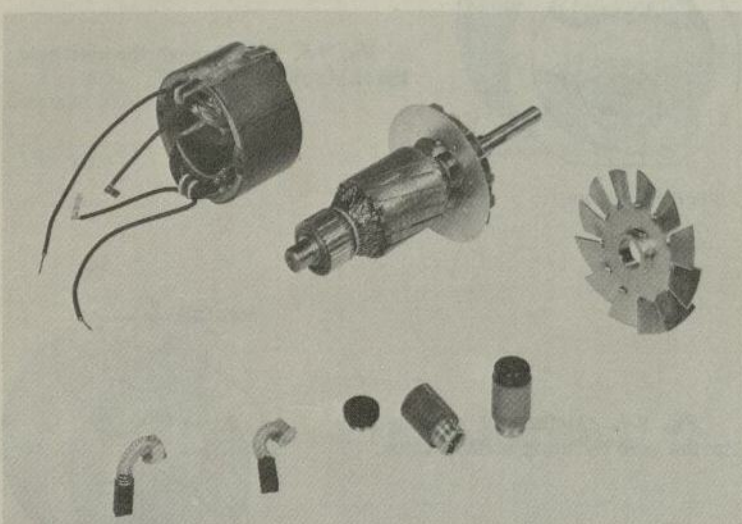


Fig. 9-2. Parts of a universal motor. *(The Dumore Company)*

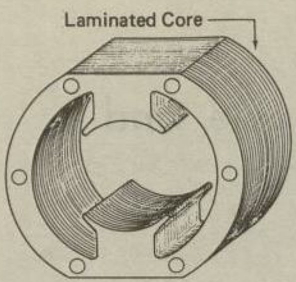


Fig. 9-3. Field core of a two-pole universal motor.

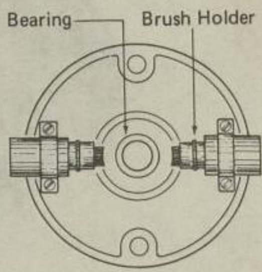


Fig. 9-4. End plate showing the brush holders and bearing.

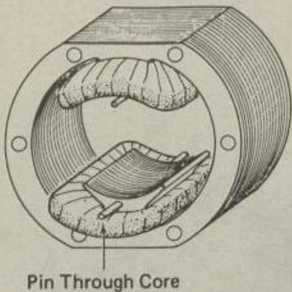


Fig. 9-5. Pins through the core hold the field coils in place.

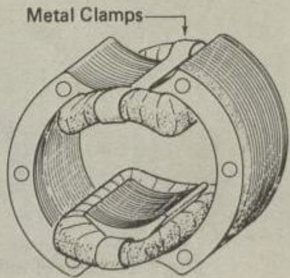


Fig. 9-6. Method of securing coils to the core by using metal clamps.

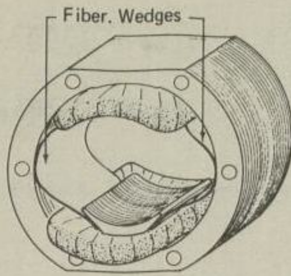


Fig. 9-7. Using fiber wedges to secure field coils to the core.

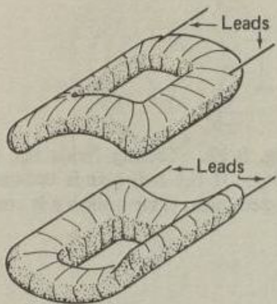
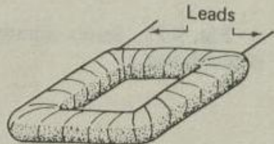


Fig. 9-8. Shape of coils after removal from the core.

Fig. 9-9. Shape of coil after it is flattened to obtain coil dimensions.



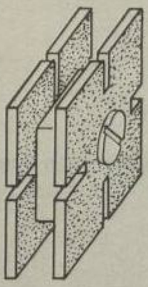


Fig. 9-10. Form for winding field coils.

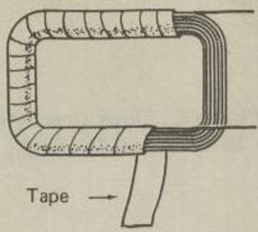


Fig. 9-11. Taping a field coil.

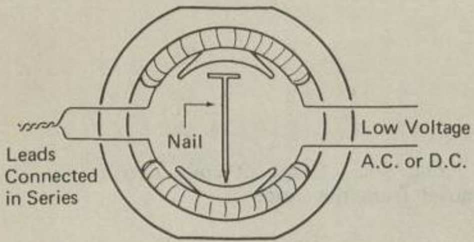


Fig. 9-12. Testing fields for proper polarity. If the nail stands between the energized coils, their polarity is correct.

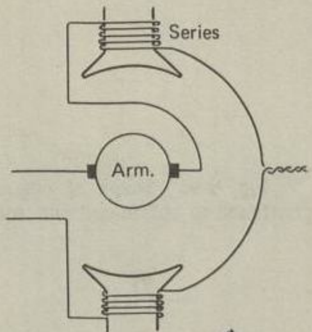


Fig. 9-13. Series connection of a universal motor.

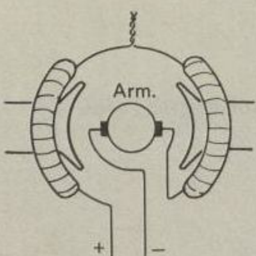


Fig. 9-14. Series connection showing taped field coils.

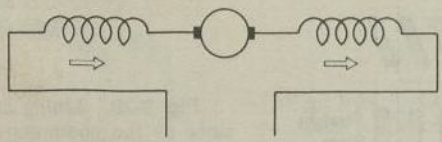


Fig. 9-15. Schematic connection of a universal motor. Note the armature is connected between the field poles.

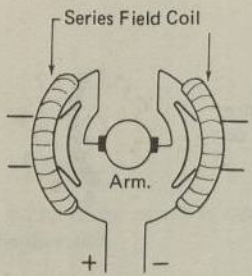


Fig. 9-16. Motor connection for clockwise rotation.

Fig. 9-17. Motor of Fig. 9-16 connected for counterclockwise rotation by interchanging armature connections.

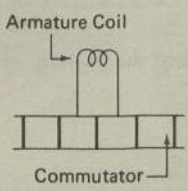


Fig. 9-18. In a lap-wound armature, each coil connects between adjacent bars.

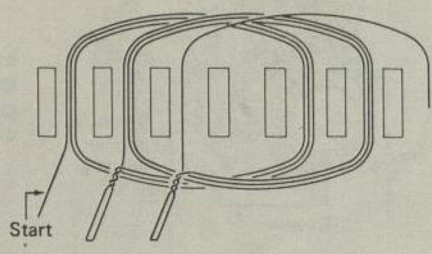


Fig. 9-19. A loop winding showing loops at the end of each coil.

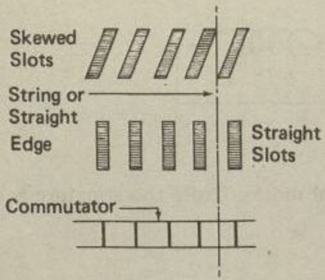


Fig. 9-20. Lining out the center of slots to the commutator to determine lead throw.

Fig. 9-21. View of the armature from the end opposite the commutator to determine the coil pitch.

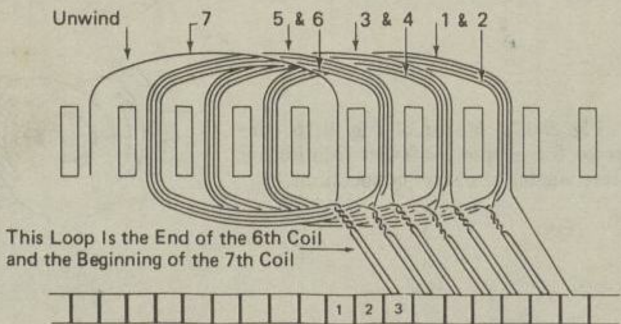


Fig. 9-22. Coils being unwound turn by turn to record the position of the leads to the commutator bars.

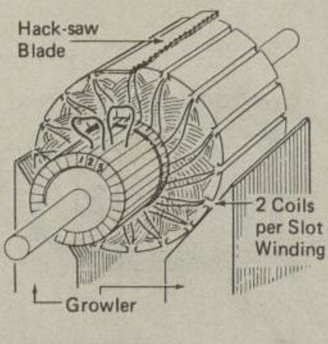


Fig. 9-23. The hack-saw blade vibrates if bars 1 and 2 and 2 and 3 are shorted while the armature is in the growler. This determines the lead throw of the coils.

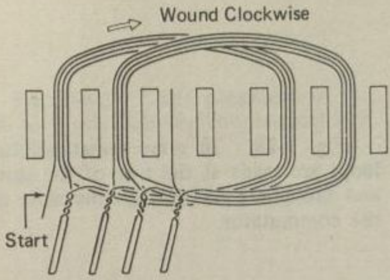


Fig. 9-24. Coils in an armature wound in a clockwise direction.

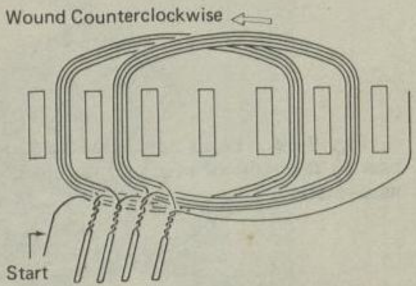


Fig. 9-25. Coils wound in a counter-clockwise direction.

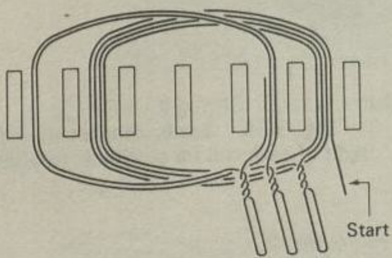


Fig. 9-26. Loops for making connections to commutator shown on the right side of the coils.

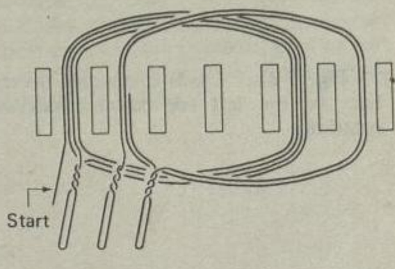


Fig. 9-27. Loops shown on the left side of each coil.

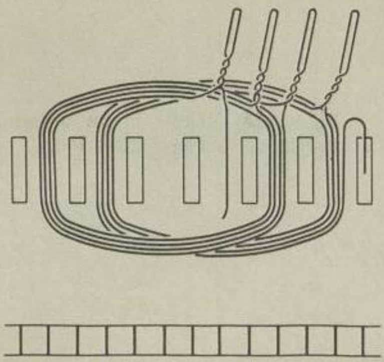


Fig. 9-28. In some armatures the loops are made at the rear of the slots and brought back through the slots to the commutator.

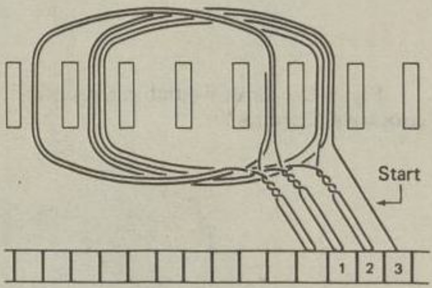


Fig. 9-29. Leads connected several bars to the right of each coil for clockwise rotation.

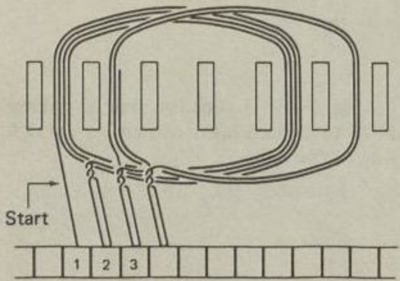


Fig. 9-30. Leads connected to the right of each coil for clockwise rotation.

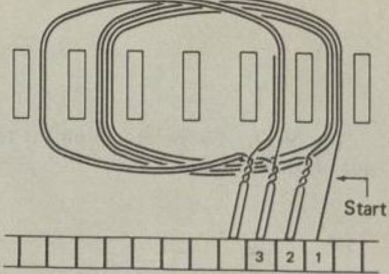
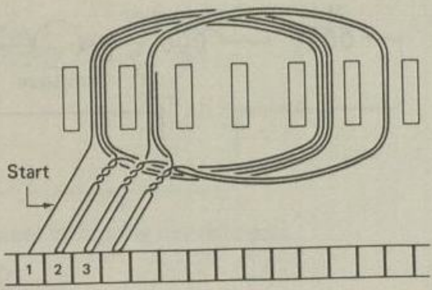


Fig. 9-31. Leads connected several bars to the left for counterclockwise rotation.

Figures 9-28; 9-29; 9-30; 9-31

Fig. 9-32. Leads connected to the left of each coil for counterclockwise rotation.



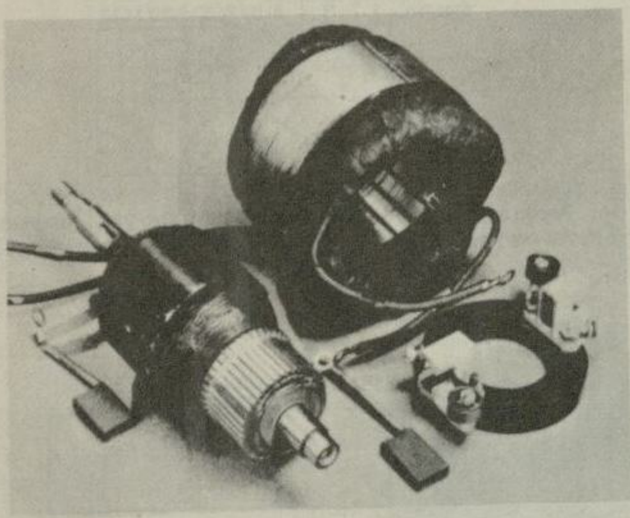


Fig. 9-33. Parts of a distributed-field universal motor.

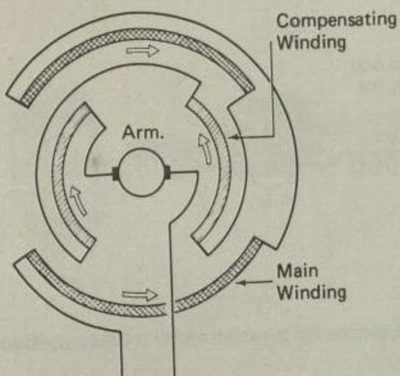


Fig. 9-34. Connections of a compensated universal motor. Note that the compensating winding is located 90 electrical degrees from the main winding and connected in series with the armature and main winding.

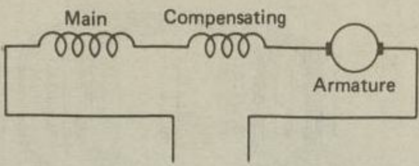


Fig. 9-35. Schematic diagram of a compensated universal motor.

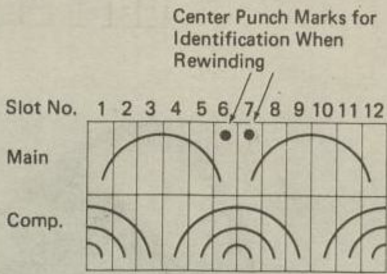


Fig. 9-36. Recording the windings of a twelve-slot, two-pole, compensated universal motor. Note the center-punch marks in the slots to locate the windings in the proper slots.

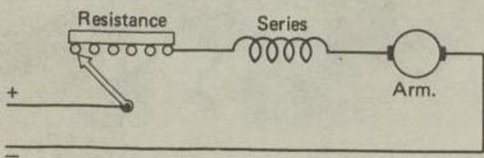


Fig. 9-37. Speed of a small universal motor controlled by connecting a variable resistor in series with the motor.

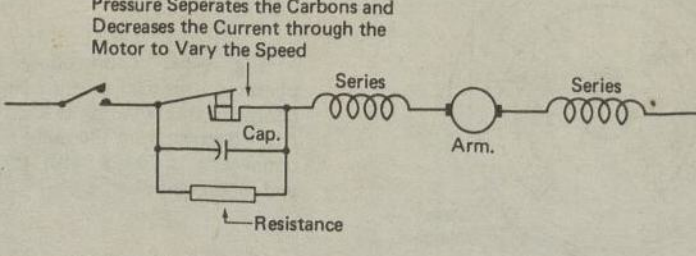


Fig. 9-38. Speed control of a universal motor by a variation in contact resistance between two carbon blocks.

Figures 9-35; 9-36; 9-37; 9-38

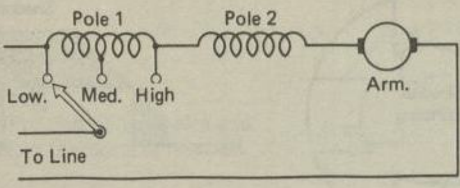


Fig. 9-39. Three speeds are obtained by tapping one field pole.

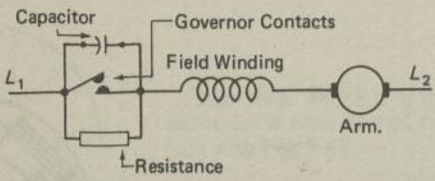


Fig. 9-40. Speed control of a universal motor by means of a centrifugal governor.

Fig. 9-41. A shaded-pole motor. *(Emerson Elec. Mfg. Co.)*

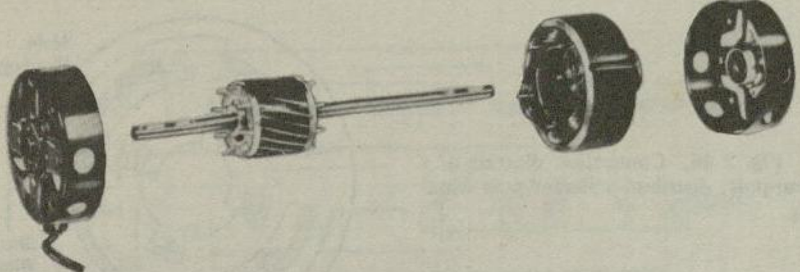


Fig. 9-42. Construction of the field and armature of a shaded-pole motor.

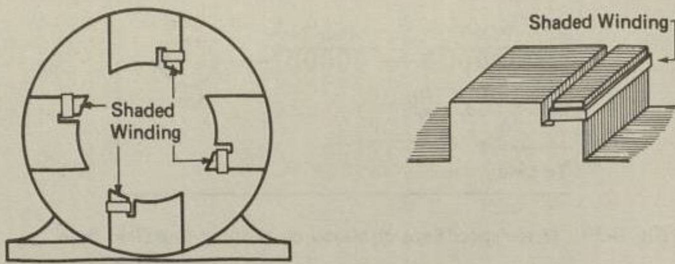


Fig. 9-43. A four-pole, shaded-pole motor showing the field poles and shading windings.

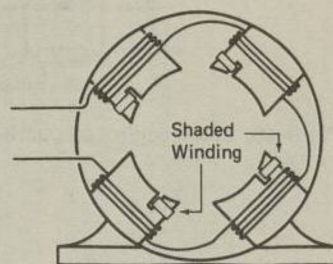


Fig. 9-44. A four-pole, shaded-pole motor with the field poles connected in series for alternate polarity.

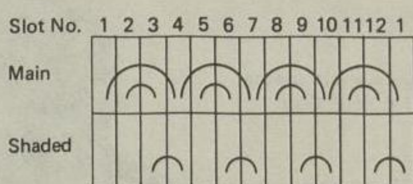


Fig. 9-45. Recording the windings of a four-pole, twelve-slot, distributed shaded-pole motor.

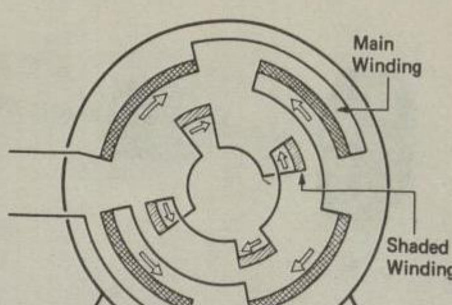


Fig. 9-46. Connection diagram of a four-pole, distributed shaded-pole winding.

Figures 9-43; 9-44; 9-45; 9-46

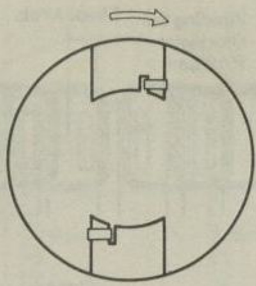


Fig. 9-47. Position of the poles and shading coils before the stator is reversed.

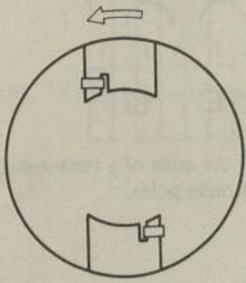


Fig. 9-48. Position of the poles after the stator is reversed end for end. Compare with **Fig. 9-47.**

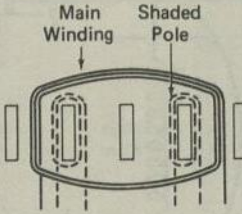


Fig. 9-49. One pole of a twelve-slot, reversible shaded-pole motor. Note the two shading coils.

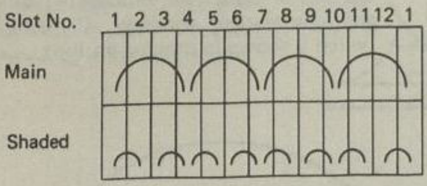


Fig. 9-50. Coil layout of a reversible shaded-pole motor.

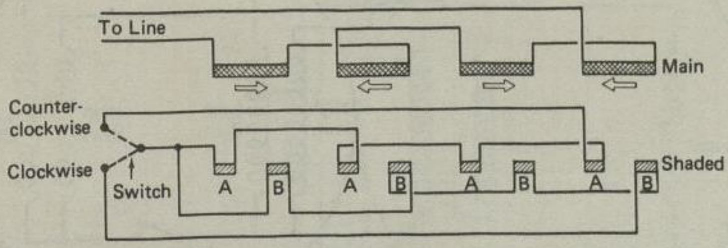


Fig. 9-51. Wiring diagram of a reversible shaded-pole motor. To reverse a shaded-pole motor, one series of shading coils is opened and the other series closed.

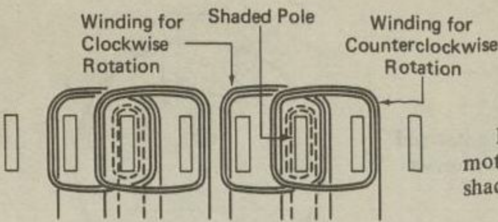


Fig. 9-52. Reversible shaded-pole motor with two main poles for each shaded coil.

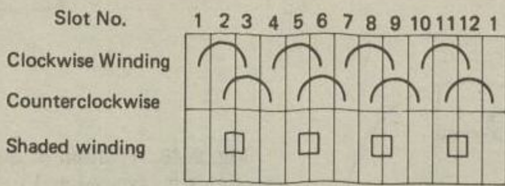


Fig. 9-53. Method of recording the layout of the coils of a twelve-slot, four-pole, reversible shaded-pole motor having two sets of main poles.

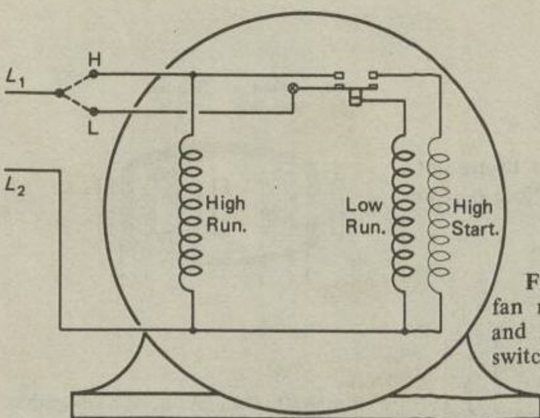


Fig. 9-54. A two-speed, split-phase fan motor with two running windings and one starting winding. Centrifugal switch is shown in running position.

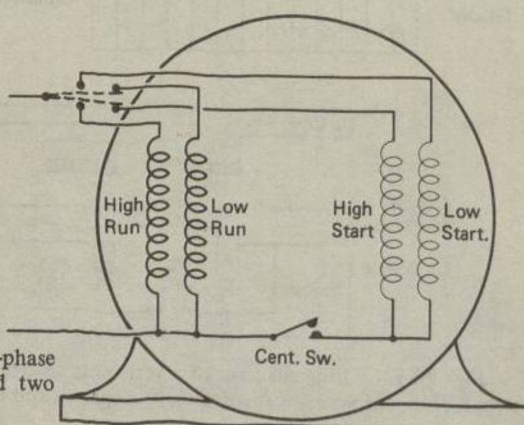


Fig. 9-55. A two-speed, split-phase fan motor with two running and two starting windings.

Figures 9-52; 9-53; 9-54; 9-55

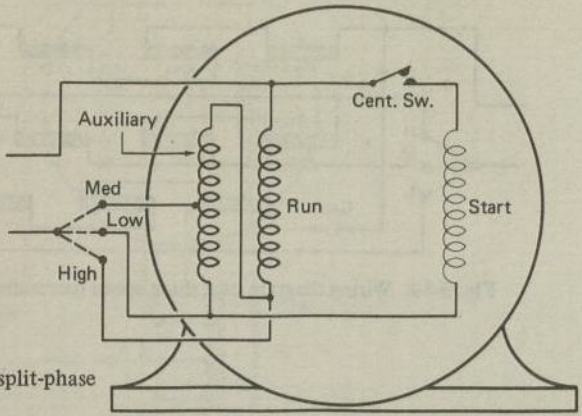


Fig. 9-56. A three-speed split-phase motor.

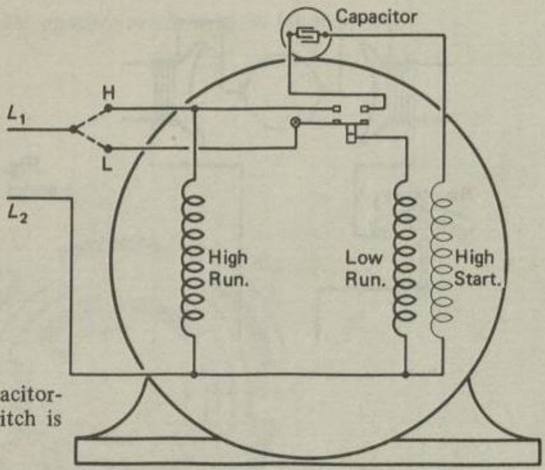


Fig. 9-57. A two-speed, capacitor-start fan motor. Centrifugal switch is shown in running position.

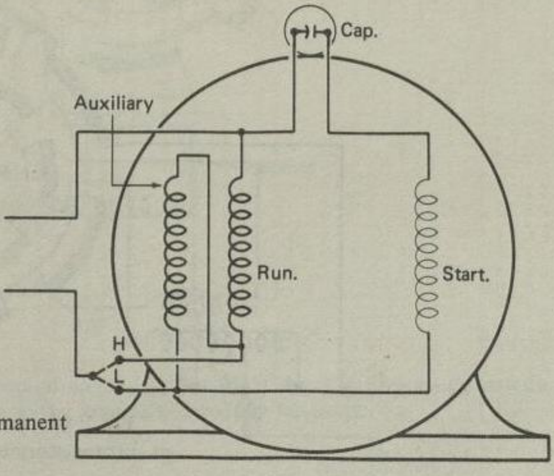


Fig. 9-58. A two-speed, (permanent Split) capacitor fan motor.

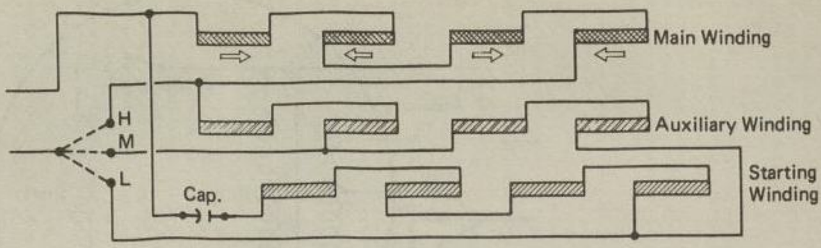


Fig. 9-59. Wiring diagram of a three-speed (permanent-split) capacitor motor.

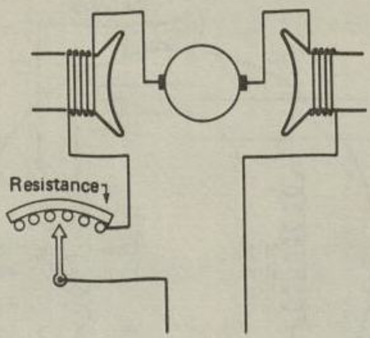


Fig. 9-60. Universal fan motor with a series resistance for speed control.

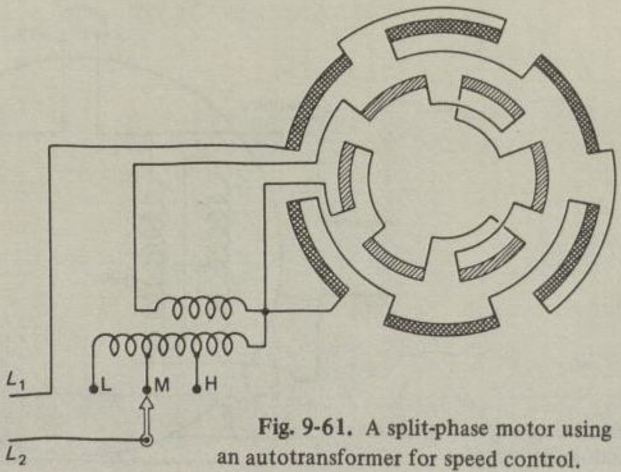


Fig. 9-61. A split-phase motor using an autotransformer for speed control.

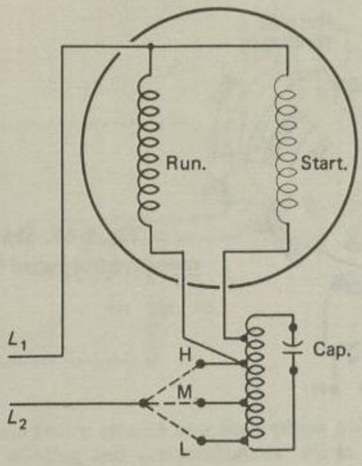


Fig. 9-62. Diagram of a capacitor motor used for fan service.

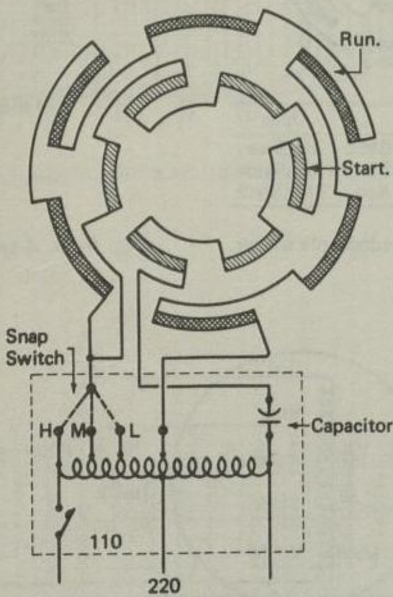


Fig. 9-63 Unit-heater three-speed motor. The speed is varied by impressing various voltages from an autotransformer to the running and starting windings.

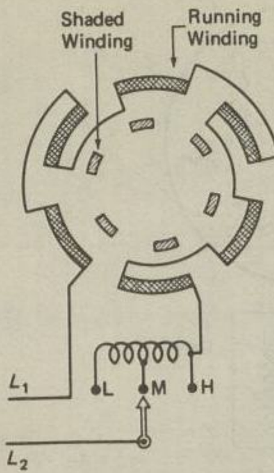


Fig. 9-64. Shaded-pole fan motor with speed control varied by means of a choke coil.

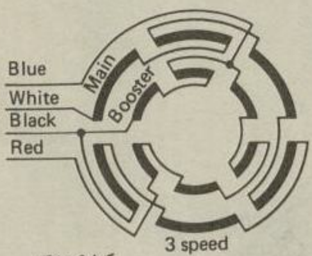


FIG. 9.65

	L_1	L_2	Open
High speed	White	Black	Red,Blue
Int. speed	White	Blue	Red,Black
Low speed	White	Red	Blue,Black

Fig. 9-65. 3-speed shaded-pole motor.

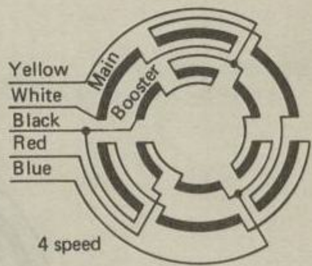


Fig. 9-66. 4-speed shaded-pole motor.

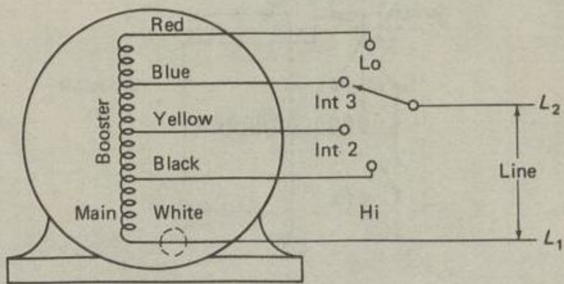


Fig. 9-67. External connection of a 4-speed shaded-pole motor.

Figures 9-64; 9-65; 9-66; 9-67

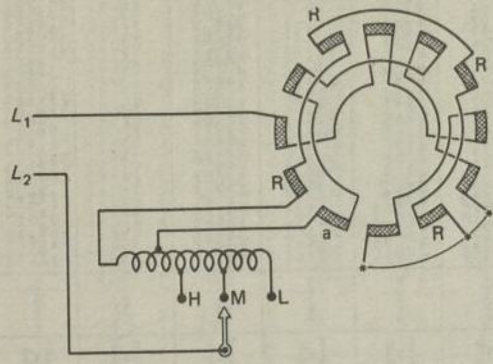


Fig. 9-68. A single-phase motor wound as a three-phase motor. By using resistance wire for the coils of one winding and a tapped-choke coil in series with another, this motor can be run at various speeds on a single-phase line.

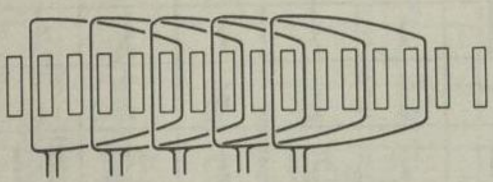


Fig. 9-69. Basket winding for a 48-slot, 24-coil, three-phase motor.

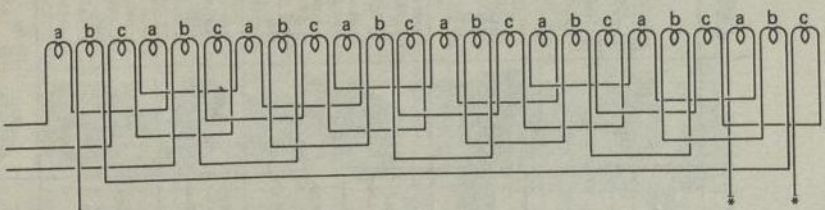
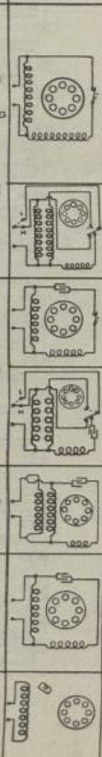
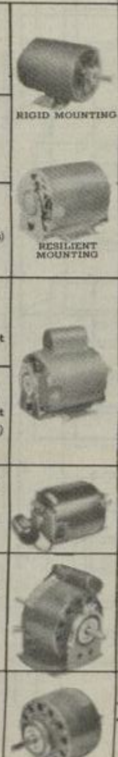


Fig. 9-70. A 48-slot, eight-pole, three-phase motor connected series star.

Westinghouse SMALL MOTOR SELECTION GUIDE





ALTERNATING CURRENT		TYPE OF MOTOR	(W) TYPE	HP. Range	SPEED DATA: Rated Speed	SPEED DATA: Speed Characteristics	SPEED DATA: Speed Control	Approximate Torque (4-Pole Motors): Starting	Approximate Torque (4-Pole Motors): Break-down	Built-in Starting Mechanism	REVERSIBILITY: At Rest	REVERSIBILITY: In Motion	Radio Interference	Approximate Comparative Price	Bearings	Mountings	APPLICATION DATA
SINGLE PHASE	SPLIT PHASE	GENERAL PURPOSE	FH	1/20 to 3/4	3450 1725 1140 860	Constant	None	Medium to Low	Medium	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	85%	Sleeve or Ball	Various	For oil burners, office appliances, fans, blowers, low locked-rotor current minimizes light flicker making motor suitable for frequent starting. For applications up to 1/3 hp. where medium starting and breakdown torques are sufficient. Thermoguard available for ratings from 1/12 hp. up.
SINGLE PHASE	SPLIT PHASE	HIGH TORQUE	FHT	1/16 to 1/2	1725	Constant	None	Medium	High	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	65%	Sleeve or Ball	Various	Ideal for washing machines, ironers, sump pumps, home workshops. For continuous and intermittent duty where operation is infrequent and locked-rotor current in excess of N.E.M.A. values is not objectionable. May cause light flicker on underwired or overloaded lighting circuits.
SINGLE PHASE	SPLIT PHASE	TWO-SPEED (Two Windings)	FH	1/8 to 3/4	1725/1140 1725/860	Two-Speed	1-Pole Double-Throw Switch	Medium	Medium	Centrifugal Switch	Yes—Change Connections	No	None	165%	Sleeve or Ball	Various	For belted furnace blowers, attic ventilating fans, similar belted medium-torque jobs. Simplicity permits operation with any 1-pole, double-throw switch or relay. Starts well on either speed—thus used with thermostatic or other automatic control. Thermoguard recommended, as tight belt or incorrect pulley ratio may overload motor.
SINGLE PHASE	CAPACITOR	GENERAL PURPOSE Capacitor-Start	FJ	1/6 to 3/4	3450 1725 1140 860	Constant	None	High	High	Centrifugal Switch	Yes—Change Connections	No—Except with Special Design and Relay	None	100%	Sleeve or Ball	Various	Ideal for all heavy-duty drives, such as compressors, pumps, stokers, refrigerators, air conditioning. All purpose motor for high starting torque, low starting current. Quiet, economical. High efficiency and power factor. Single voltage in 1/6, 1/4 hp., 1725 rpm. ratings—dual voltage in others. All sizes obtainable with thermoguard.
SINGLE PHASE	CAPACITOR	TWO-SPEED Capacitor-Start (Two Windings)	FJ	1/6 to 3/4	1725/1140 1725/860	Two-Speed	1-Pole Double-Throw Switch	Medium	Medium	Centrifugal Switch	Yes—Change Connections	No	None	200%	Sleeve or Ball	Various	Supplements line of 2-speed split-phase motors (see Type FH, 2-speed). Used on identical applications requiring horsepower ratings from 1/3 to 3/4 hp.
SINGLE PHASE	CAPACITOR	PERMANENT SPLIT (Single Value)	FL	1/20 to 3/4	1620 1080 820	Constant or Adjustable Varying	Two-Speed Switch or Autotransformer	Very Low	Low	None	Yes—Change Connections	Yes	None	155%	Sleeve or Ball	Resilient	For direct connected an drives . . . particularly unit heaters. Not for belt drives. Same motor adaptable for 115 or 230 volts for 1-speed, 2-speed, or multi-speed service by use of 1-pole, single-throw switch, 2-pole, double-throw switch, or speed controller, respectively. Fan load must be accurately matched to motor output for proper speed control. All ratings dual voltage and dual rotation.
SINGLE PHASE	CAPACITOR	PERMANENT SPLIT Capacitor	FLL	1/25 to 1/4	1625 to 1075	Varying or Adjustable Varying	Tapped Winding or Choke Coil	Low	Low	None	Yes	Yes	None	—	Vertical Sleeve	Various	Companion to type FE shaded-pole motor. Their higher efficiency and power factor make this type motor ideal for driving fans in room air conditioners and window fans.
SINGLE PHASE	SHADED POLE	SHADED POLE	FE	1/30 to 1/8	1550 1060	Constant or Adjustable Varying	Tapped Winding or Choke Coil	Very Low	Low	None	No	No	None	—	Sleeve	Rigid or Resilient	Constant speed, switchless motor for low-power applications. Used for fans, small blowers, unit heaters, hair driers. With fan load accurately matched to motor output, proper speed control can be obtained by means of series choke or resistance.

Figure 9-71

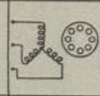
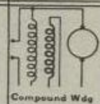
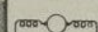
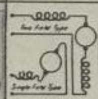
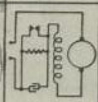
1, 2, 3 PHASE	SYNCHRONOUS	SPLIT-PHASE		Refer to FH	FBH	1/250 to 1/3	3600 1800 1200 900	Absolutely Constant	None	Low	Medium (See Note)	Centrifugal Switch	See FH	See FH	None	375%	Sleeve or Ball	Rigid	Used mostly on instruments, sound recording and reproducing apparatus, teleprinters, facsimile printers. Definitely constant speed. Type selected depends largely on starting torque. Type FBL recommended where low watts input desirable and low starting torque sufficient. Type FBH or FBJ recommended where higher starting torque needed. Pull-in torque on all types affected by inertia of connected load. Note: The "breakdown" torque refers to torque at point where motor speed drops below synchronous speed.
		CAPACITOR-START		Refer to FJ	FBJ					Medium	Medium (See Note)	Centrifugal Switch	See FJ	See FJ					
		PERMANENT SPLIT CAPACITOR		Refer to FL	FBL					Very Low	Medium (See Note)	None	See FL	See FL					
		POLYPHASE		Refer to FS	FBS					Medium	Medium (See Note)	None	See FS	See FS					
POLYPHASE	2 or 3 PHASE	SQUIRREL CAGE			FS	1/4 to 3	3450 1725 1140 860	Constant	None	High to Medium	Extra High	None	Yes—Change Connections	Yes—Change Connections	None	110%	Sleeve or Ball	Various	For all applications where polyphase circuits are available. Special designs with extra high starting torque for hoists, door operators, tool traverse and clamp devices. High frequency motors are used for high speed applications such as rayon spinning machines and portable tools.
D-C		SHUNT WOUND AND COMPOUND WOUND			FK	1/12 to 3/4	3450 1725 1140 860	Constant or Adjustable Varying	Armature Resistance	Extra High	—	None	Yes—Change Connections	No—Except with Special Design	Yes	195%	Sleeve or Ball	Rigid or Resilient	For all applications operated from D-C circuits. Companion D-C motor to single phase and polyphase A-C motors. Ratings of 1/12 hp., 1725 rpm. and smaller shunt-wound. Larger ratings compound wound. Starting rheostats recommended for ratings 1/2 hp. and up.
A-C OR D-C	UNIVERSAL	NON-COMPENSATED (Salient Pole Winding)				1/150 to 3/4	1500 to 15000	Varying	Voltage Control Using Resistance or Transformer	Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	Sleeve	Rigid	Especially suitable for sewing machines, portable tools, vacuum cleaners, motion picture projectors, and mixers. Operates on A-C or D-C circuits. Inherent characteristics are high-starting torque, high speed, varying speed regulation and small size and light weight for given hp. output.
		COMPENSATED (Distributed Winding)				1/40 to 2 1/2	2500 to 15000	Varying		Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	—	—	Compensated parts recommended when higher power at lower speeds required as for larger commercial type vacuum cleaners, large portable tools. Wide variety of electrical characteristics and housing designs available.
		GOVERNOR CONTROLLED				1/50 to 1/8	2000 to 7500	Adjustable Constant	Adjustable Governor	Extra High	—	None	No—Except with Special Design	No—Except with Special Design	Yes	—	Sleeve	Rigid	Governor permits utilizing light-weight, high-speed, universal motor for constant speed applications. Two types governors supplied. One permits adjustment while running—used on electric typewriters, motion picture projectors, cameras. Other type adjustable at standstill only—used for adding machines, calculating machines, other constant speed office machines.

Fig. 9-71. Small motor selection guide. *(continued)*

Figure 9-71

CHAPTER 10

Direct-current Generators; Synchronous Motors and Generators; Synchros; Electronic Control of Motors

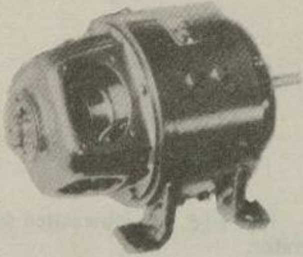


Fig. 10-1. A d-c generator.

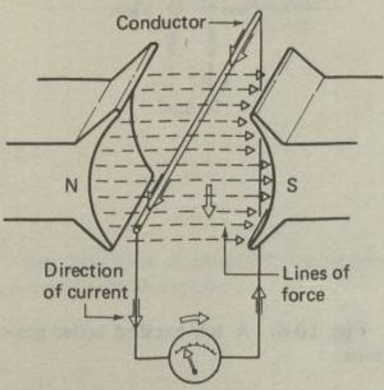


Fig. 10-2. A potential is induced in the conductor when it cuts lines of force.

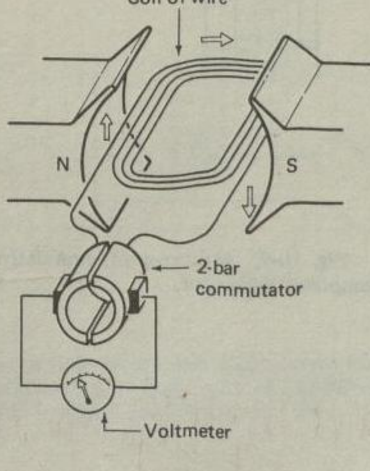


Fig. 10-3. A coil of wire used as the conductor and rotated in a magnetic field. The leads of the coil are connected to a commutator to produce direct current.

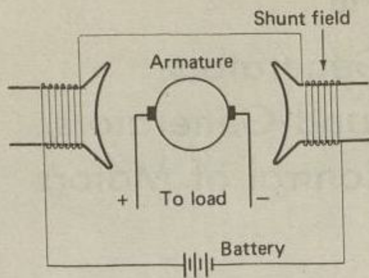
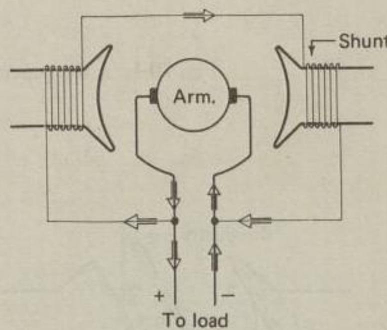


Fig. 10-4. A separately excited shunt generator.

Fig. 10-5. A self-excited shunt generator.



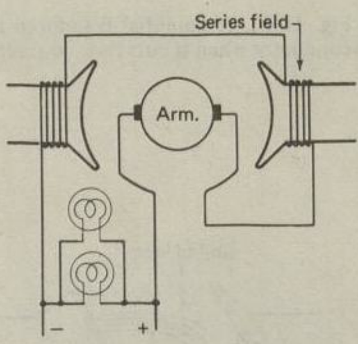
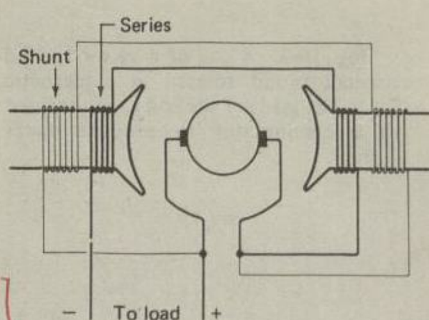


Fig. 10-6. A self-excited series generator.

Fig. 10-7. A short-shunt cumulative compound generator.



Figures 10-4; 10-5; 10-6; 10-7

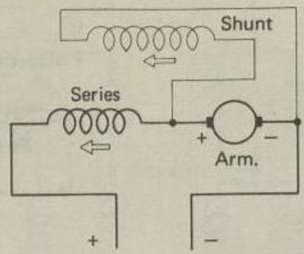


Fig. 10-8. Wiring of a compound short-shunt generator.

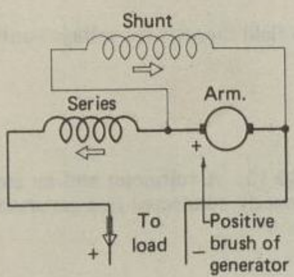


Fig. 10-9. A short-shunt differential generator.

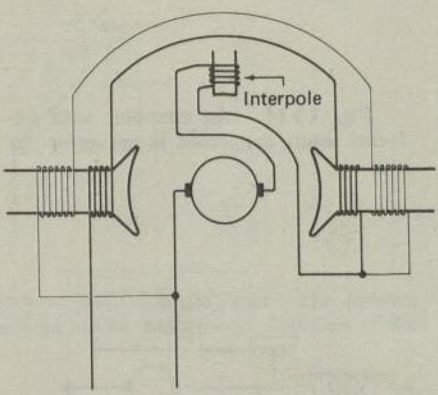


Fig. 10-10. A short-shunt cumulative generator with interpole.

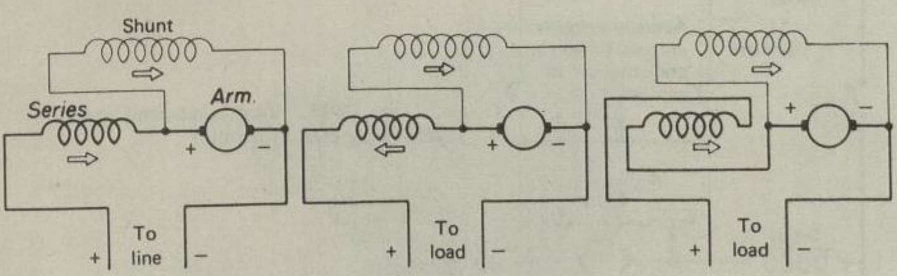


Fig. 10-11. At the left is shown the direction of flow of the two field currents of a compound motor. This motor is cumulative, but if used as a generator, it will be differential, as shown in the center. If the series field is reversed, as shown at the right, the generator will be cumulative.

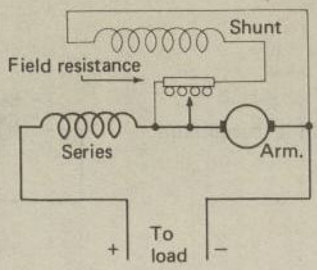


Fig. 10-12. A short-shunt cumulative generator with field rheostat for voltage control.

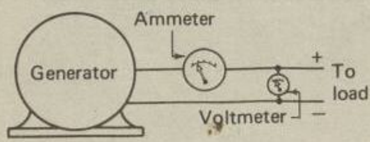
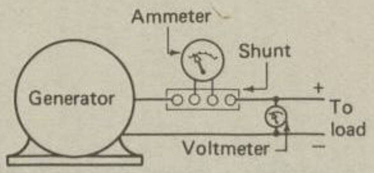


Fig. 10-13. A voltmeter and an ammeter properly connected in a generator circuit.

Fig. 10-14. An ammeter with external shunt connected in generator circuit.



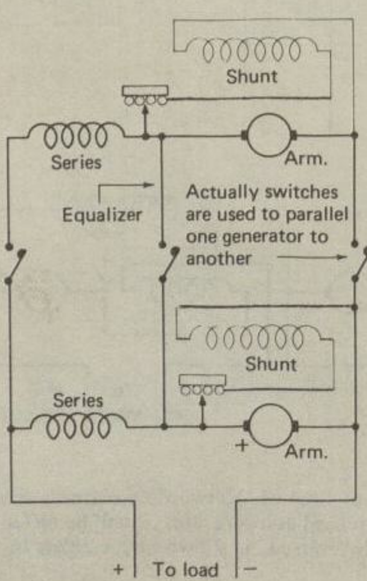


Fig. 10-15. Two compound generators connected in parallel.

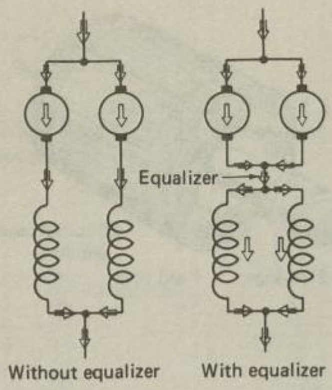


Fig. 10-16. A diagram showing how the load is divided equally between two generators if equalizer is used.

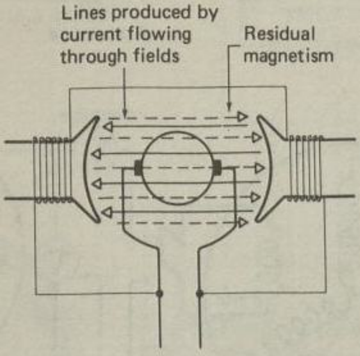


Fig. 10-17. An incorrect connection of shunt field in a generator. The residual lines of force oppose the lines caused by the field current and prevent build-up of the field strength.

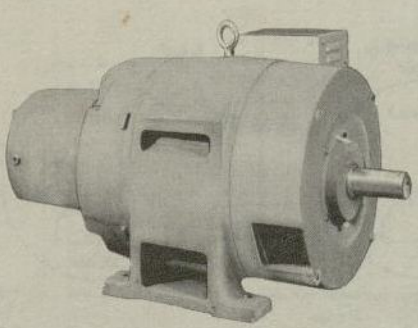


Fig. 10-18. A synchronous motor for general-purpose application. *(General Electric Company)*

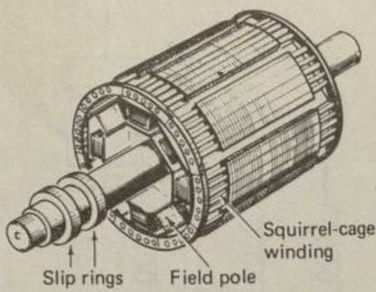
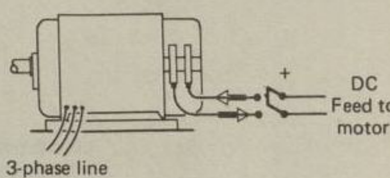


Fig. 10-19. A rotor of a synchronous motor.

Fig. 10-20. Synchronous-motor power connections.



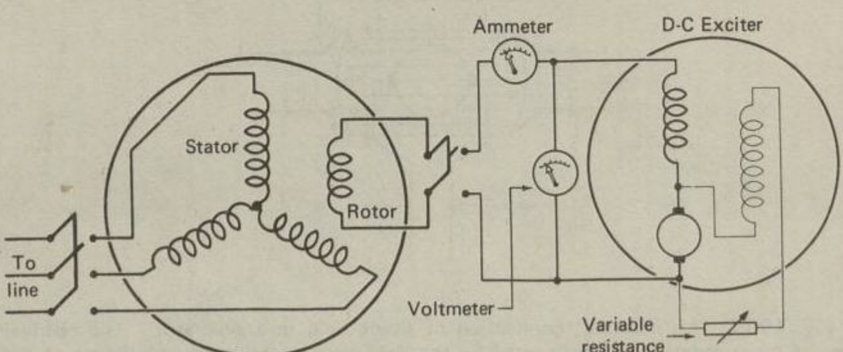


Fig. 10-21. A synchronous motor showing rotor supplied from a small exciter.

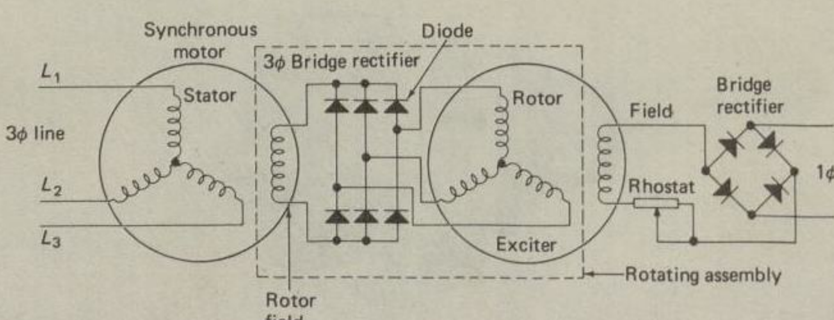


Fig. 10-22. Connections for a brushless synchronous motor.

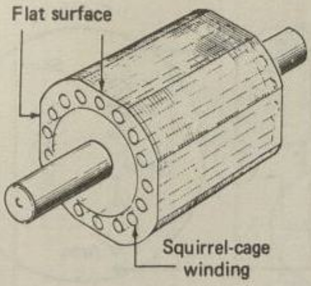


Fig. 10-23. A flat-faced rotor of a self-starting, nonexcited, split-phase synchronous motor.

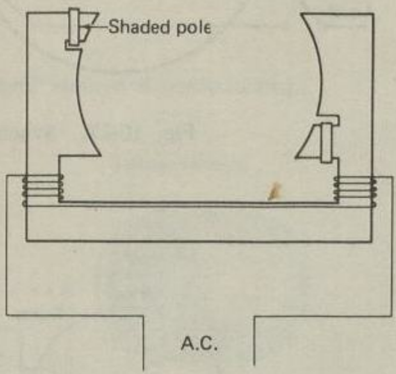


Fig. 10-24. A stator with shaded poles for a synchronous clock motor.

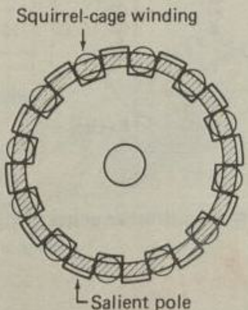


Fig. 10-25. A rotor for a self-starting synchronous motor.

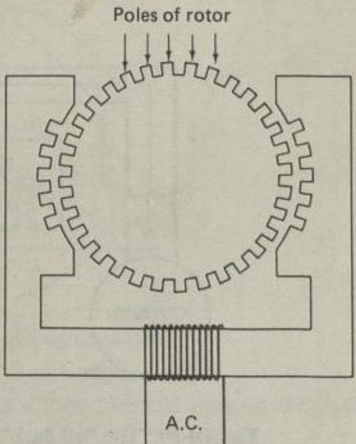


Fig. 10-26. A synchronous clock motor having 32 poles.

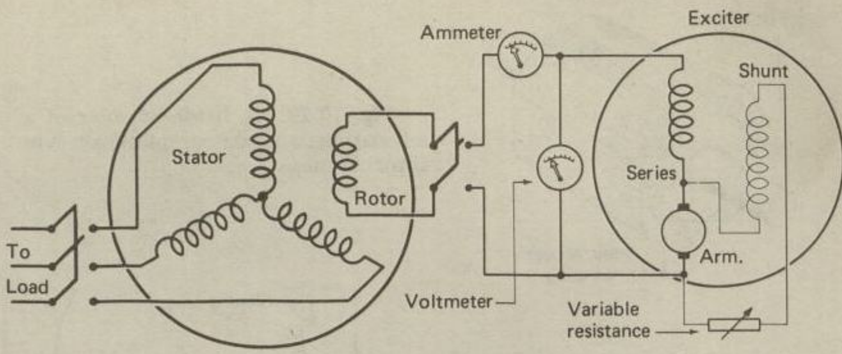


Fig. 10-27. Synchronous-generator connections.

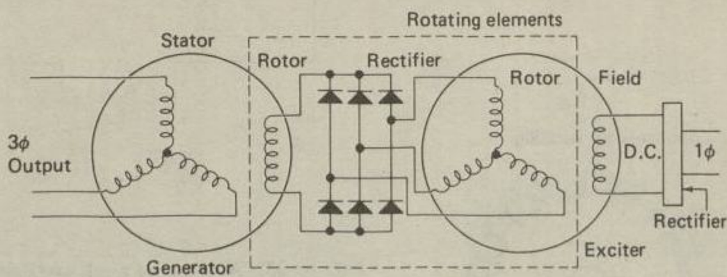


Fig. 10-28. Elementary diagram of a brushless synchronous generator.

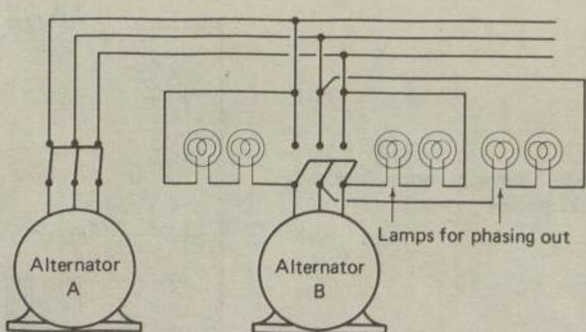


Fig. 10-29. The "all dark" method of synchronizing two alternators.

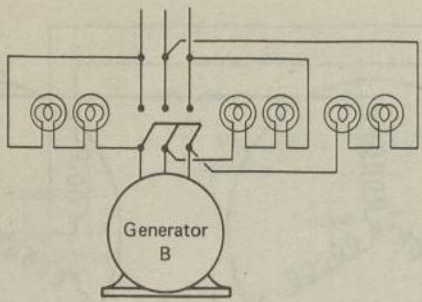


Fig. 10-30. The "one dark and two bright" method of synchronizing.

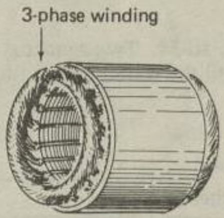


Fig. 10-31. A stator of a synchro.

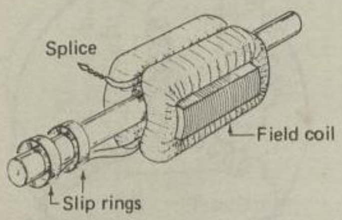


Fig. 10-32. A rotor of a synchro.

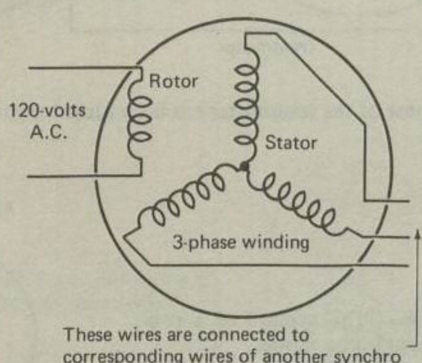


Fig. 10-33. Connections of a synchro showing a three-phase winding on the stator and a single-phase winding on the rotor.

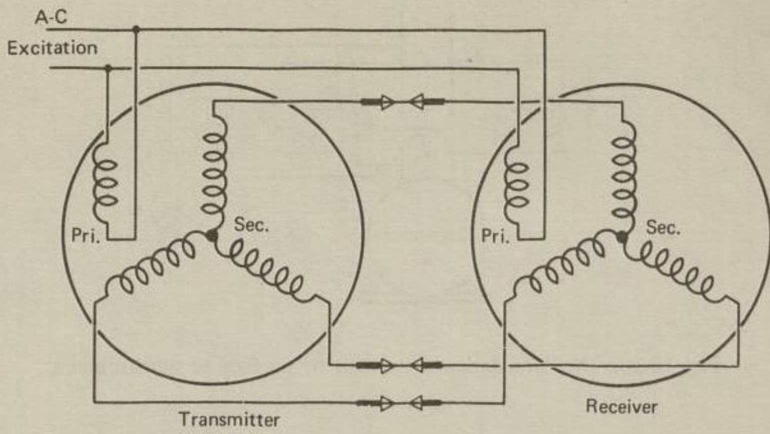


Fig. 10-34. Two synchros connected for operation. The receiver will remain motionless until the transmitter is turned.

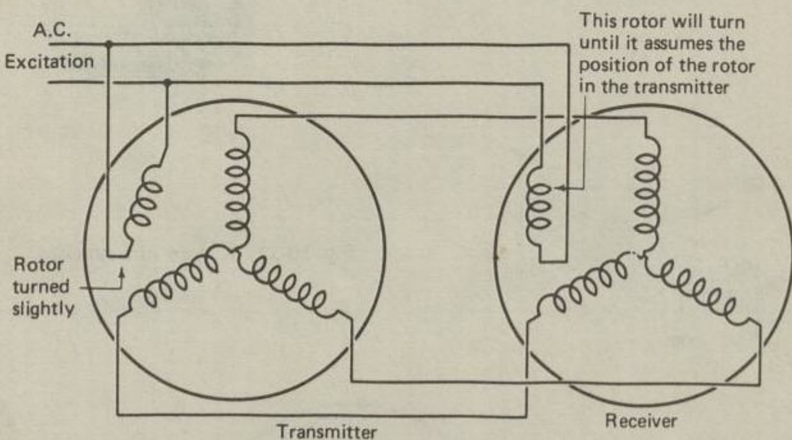
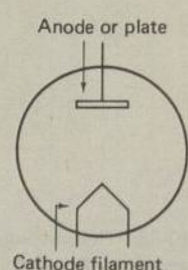


Fig. 10-35. The rotor of the transmitter has been turned slightly, causing the receiver to turn.

Fig. 10-36. The symbol of a two-element vacuum-tube diode.



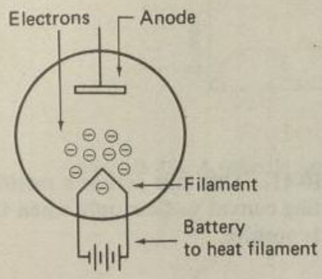


Fig. 10-37. Heated filament emits electrons.

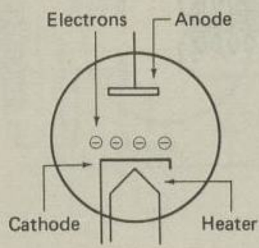


Fig. 10-38. A diode with an indirectly heated cathode.

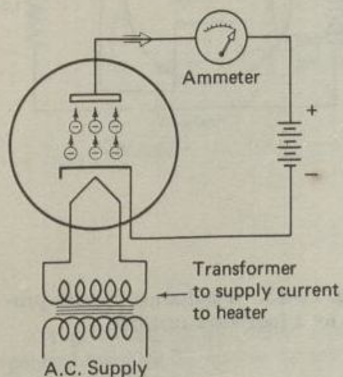


Fig. 10-39. Electrons will flow from the cathode to the anode when the anode is given a positive charge.

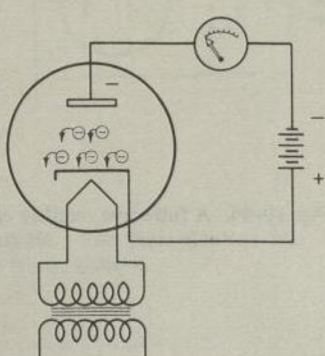


Fig. 10-40. When the anode is made negative, the electrons will be repelled.

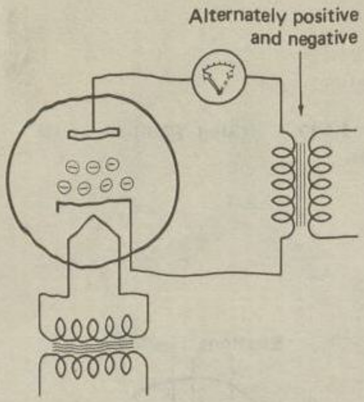


Fig. 10-41. This tube acts as a rectifier permitting current to flow only when the anode is positive.

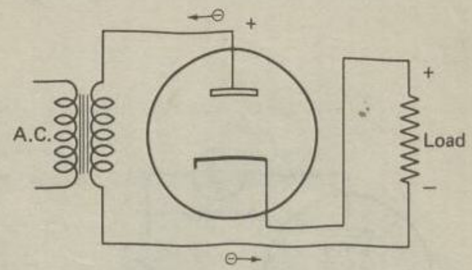


Fig. 10-42. A half-wave rectifier circuit.

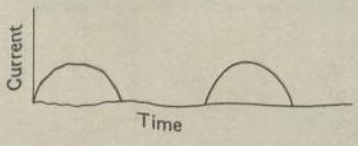


Fig. 10-43. A pulsating current produced by a half-wave rectifier.

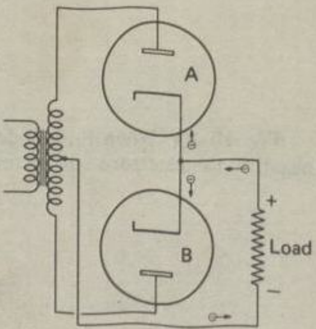


Fig. 10-44. A full-wave rectifier circuit.

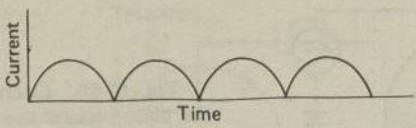
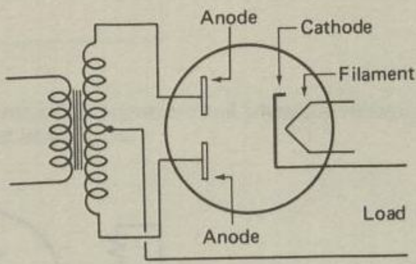


Fig. 10-45. A pulsating current produced by a full-wave rectifier.

Fig. 10-46. A full-wave rectifier in one envelope.



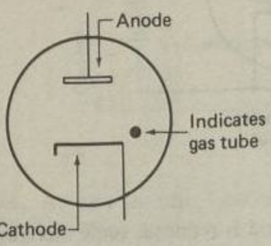
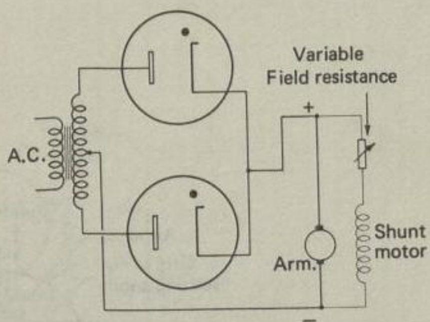


Fig. 10-47. The gas-diode symbol.

Fig. 10-48. A d-c motor can be operated from an a-c source by using a full-wave rectifier.



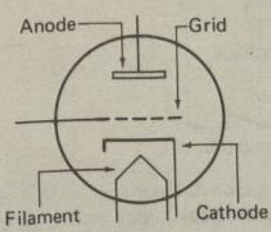


Fig. 10-49. The three-element vacuum-tube triode symbol.

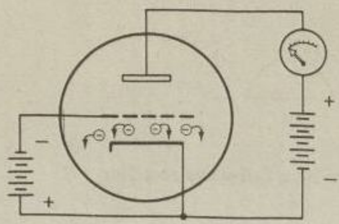


Fig. 10-50. Electrons will not reach the plate because the negatively charged grid repels them.

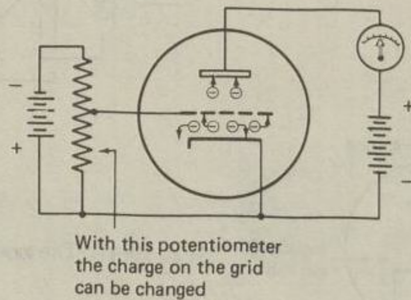


Fig. 10-51. If the negative charge on the grid is reduced, some electrons will flow to the anode.

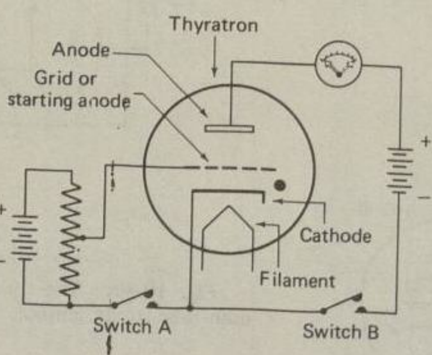


Fig. 10-52. To stop the current flow in the anode circuit, open switch *B*.

Figures 10-50; 10-51; 10-52

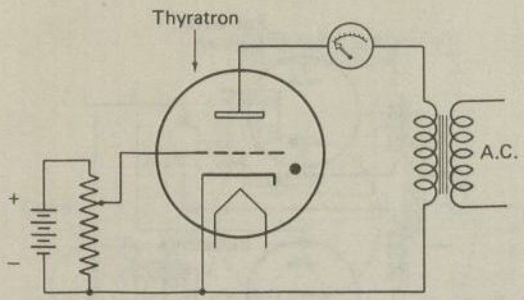


Fig. 10-53. Current will flow only when the anode is positive and when the voltage is of the proper value. This may be for less than half a cycle.

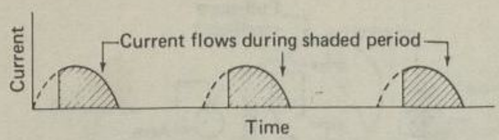


Fig. 10-54. A curve showing how current can be made to flow in a thyratron for a portion of a half wave.

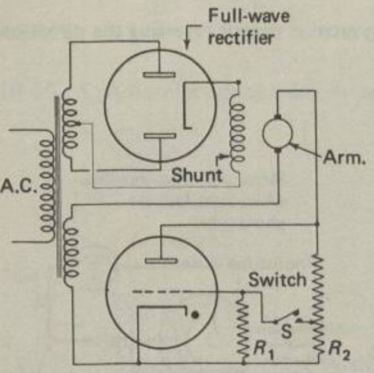


Fig. 10-55. A circuit showing a thyratron used on alternating current to operate a d-c motor.

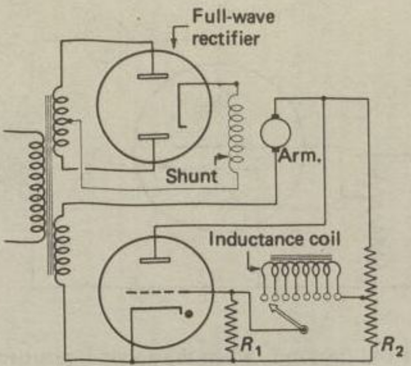


Fig. 10-56. Different speeds can be obtained by varying an inductance in the grid circuit of the thyratron.

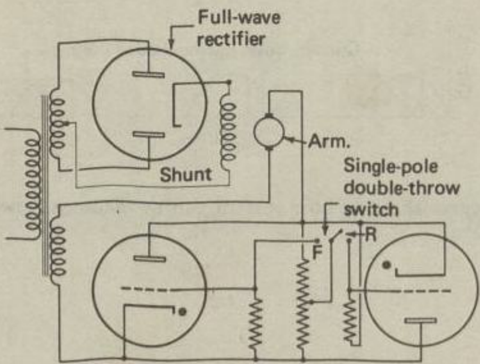


Fig. 10-57. Two thyratrons permit reversing the direction of rotation of a d-c motor with a simple switch.

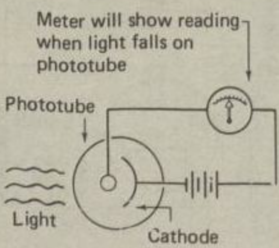


Fig. 10-58. A basic phototube circuit.

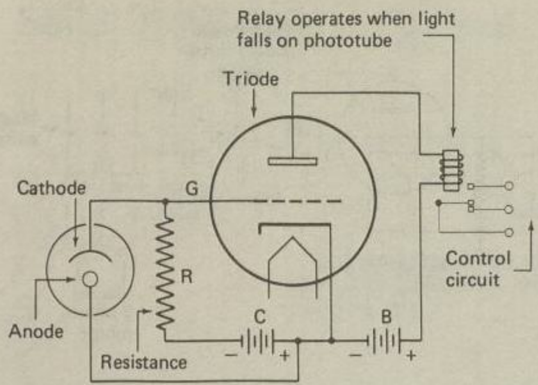


Fig. 10-59. A circuit showing how a phototube controls a relay.

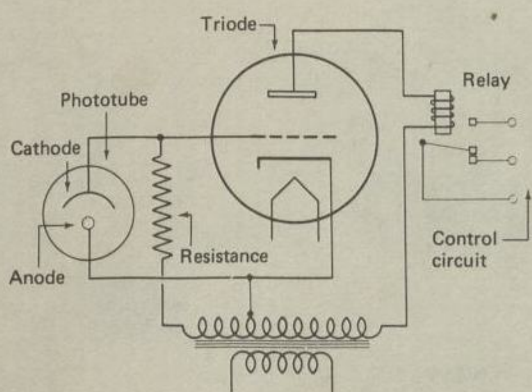


Fig. 10-60. A phototube circuit using a-c supply.

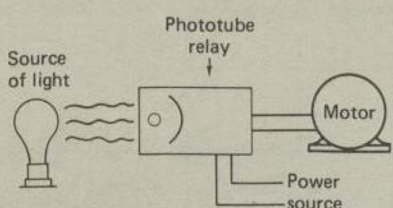


Fig. 10-61. The motor operates when the light source is interrupted.

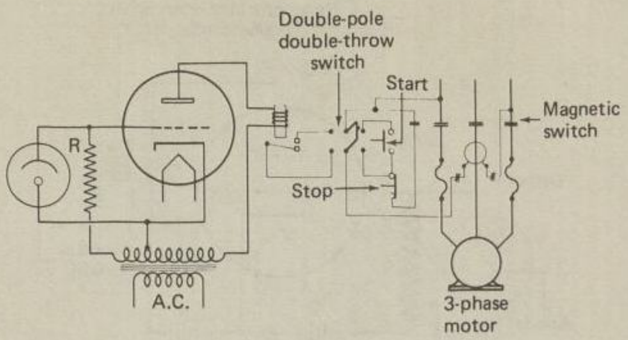


Fig. 10-62. A circuit showing a phototube operating a magnetic switch.

Figure 10-62

CHAPTER 11

Solid State Motor Control

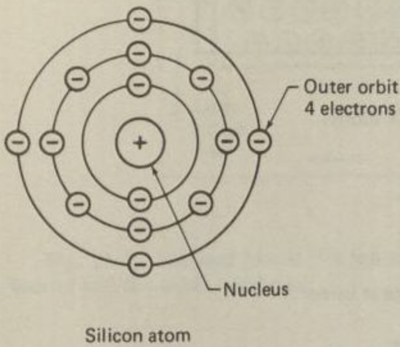


Fig. 11-1. A silicon atom. The electrons in the outer orbit are called valence electrons.

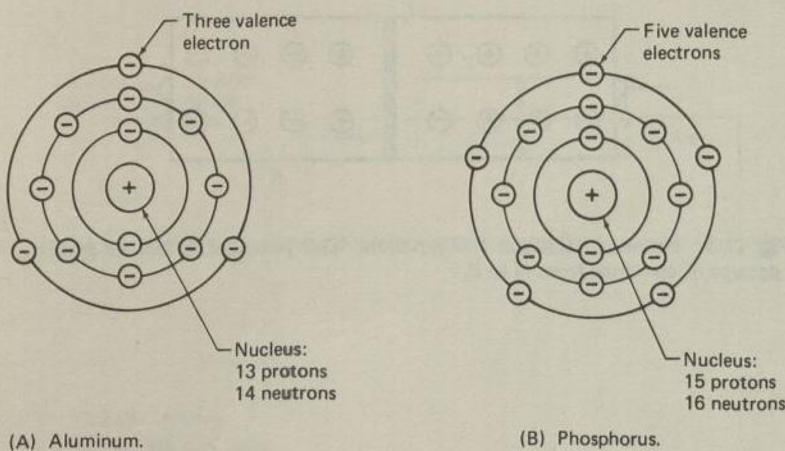


Fig. 11-2. Atoms of aluminum and phosphorons.

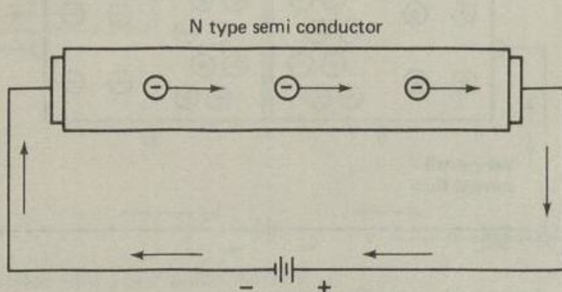


Fig. 11-3. Electron movement in an N type semiconductor.

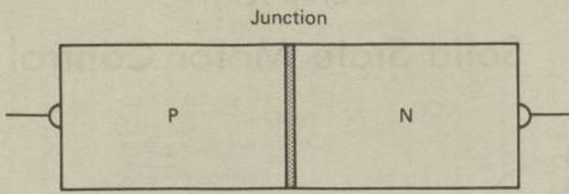


Fig. 11-4. P-N diode.

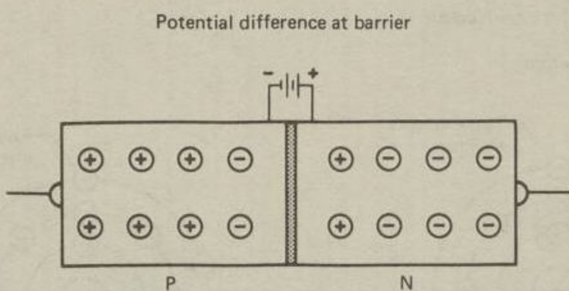


Fig. 11-5. Potential barrier at P-N junction. This potential difference prevents further passage of electrons from N to P.

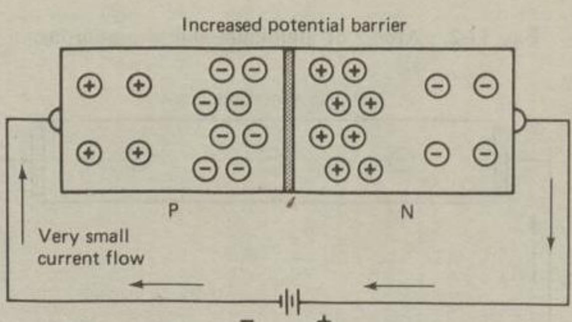


Fig. 11-6. Reverse biased P-N junction. This increases the difference in potential at the junction and causes a stronger barrier. The diode does not conduct.

Figures 11-4; 11-5; 11-6

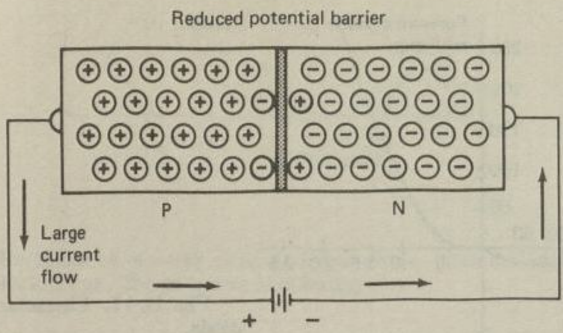


Fig. 11-7. Forward biased P-N junction. This reduces the potential difference at the barrier and the diode conducts.

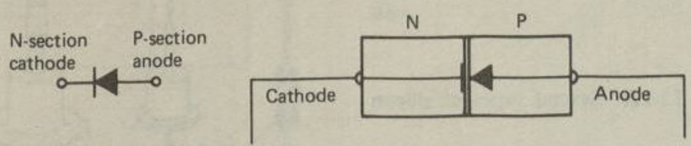


Fig. 11-8. Symbol of a diode. Electron current flows from cathode to anode.

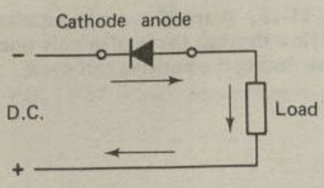
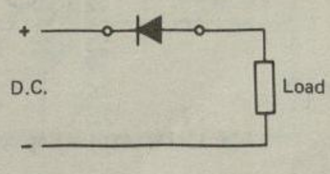


Fig. 11-9. Direction of current flow through diode rectifier and circuit.

Fig. 11-10. No appreciable current flow.



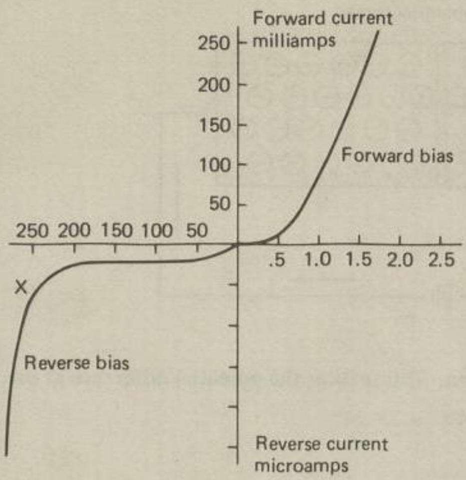


Fig. 11-11. Characteristic curve of a diode.

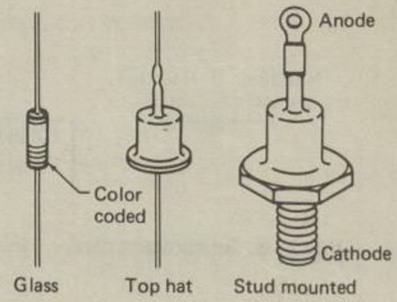


Fig. 11-12. Several types of silicon diodes.

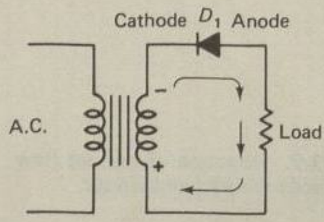


Fig. 11-13. A rectifier diode permits current flow through the load in only one direction during the positive half cycle.

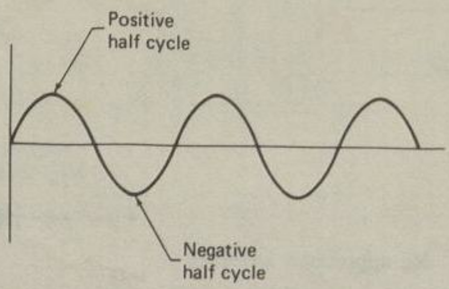


Fig. 11-14. Alternating current alternations before rectification.

Figures 11-11; 11-12; 11-13; 11-14

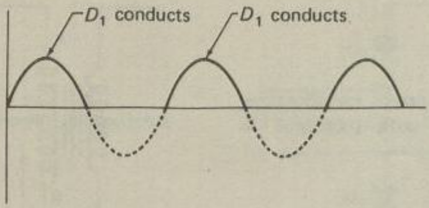


Fig. 11-15. Rectification of a-c by using a rectifier diode. Note that all of the negative half cycles are blocked out. This is known as pulsating d-c.

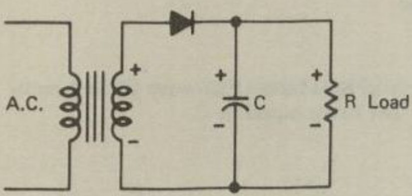


Fig. 11-16. Half-wave filtered rectification. Capacitor C eliminates the ripples.

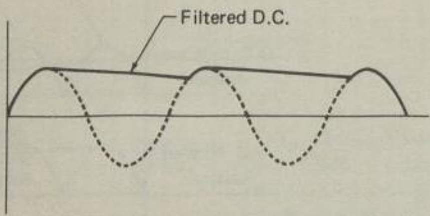
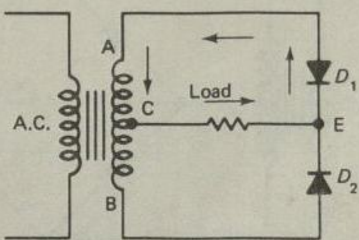


Fig. 11-17. Graph showing how pulsations are reduced by using a capacitor.

Fig. 11-18. Full-wave rectifier using a center tap transformer. Point A is positive with reference to point C.



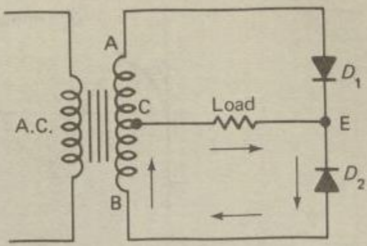


Fig. 11-19. Full-wave rectification. Point B is positive with reference to point C.

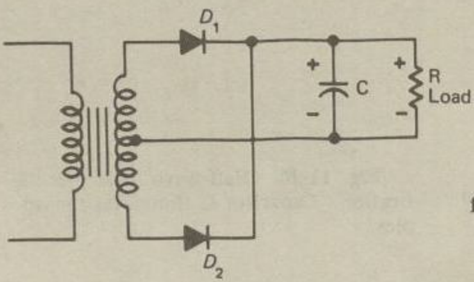


Fig. 11-20. Full-wave filtered rectifier using capacitor C.

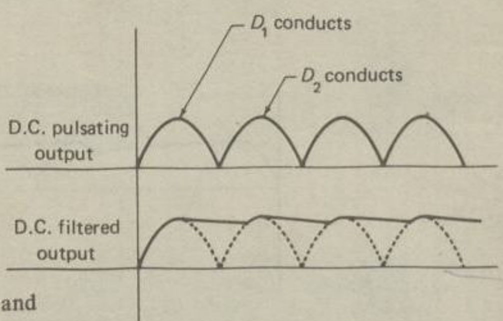


Fig. 11-21. Full-wave unfiltered and filtered output.

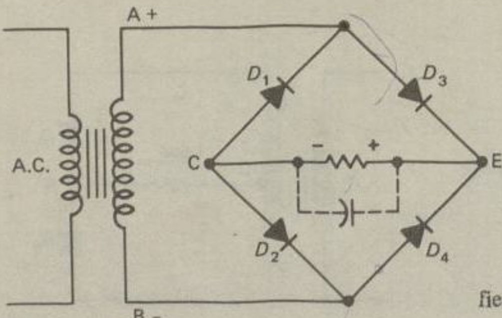


Fig. 11-22A. Full-wave bridge rectifier. Capacitor is used for filtering.

Figures 11-19; 11-20; 11-21; 11-22A

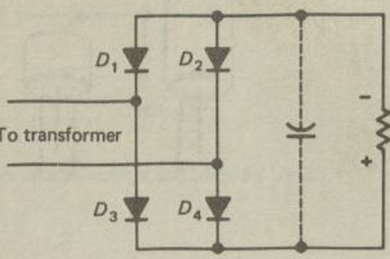


Fig. 11-22B. Full-wave bridge rectifier.

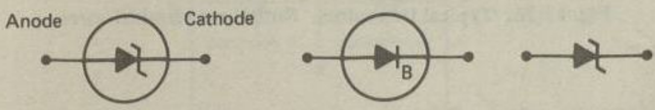


Fig. 11-23. Symbols of a zener diode.

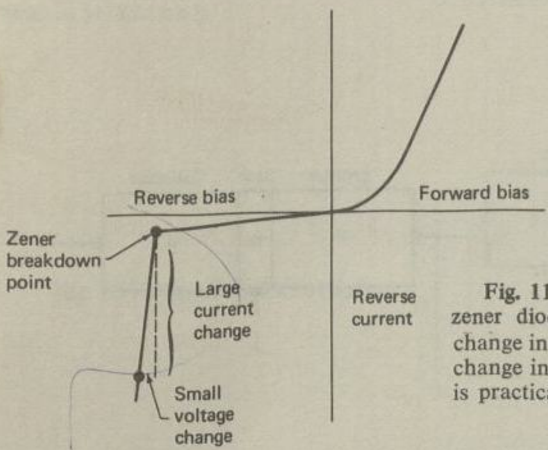


Fig. 11-24. Characteristic curve of a zener diode. Note how a very small change in voltage produces a very large change in current. The voltage change is practically nil.

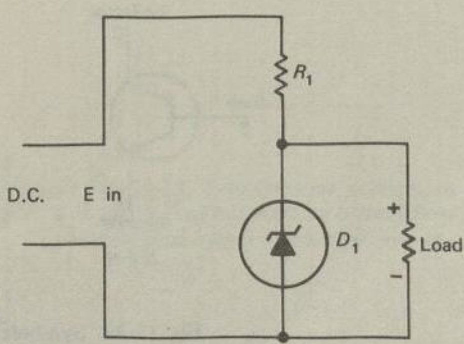


Fig. 11-25. Using a zener diode for voltage regulation. The zener is connected in series with R_1. The constant voltage output is taken across D_1.

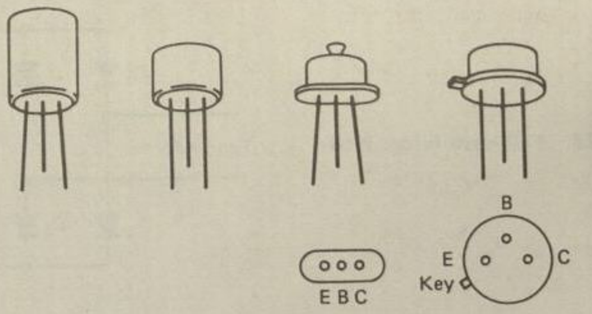


Fig. 11-26. Typical transistors. Note three terminal wires.

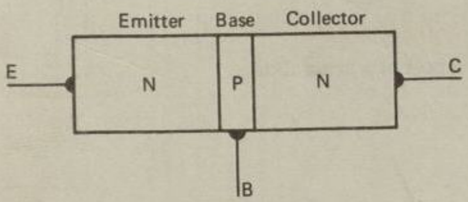
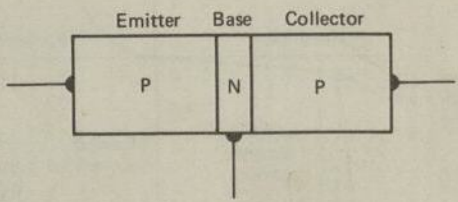


Fig. 11-27. NPN transistor.

Fig. 11-28. PNP transistor.



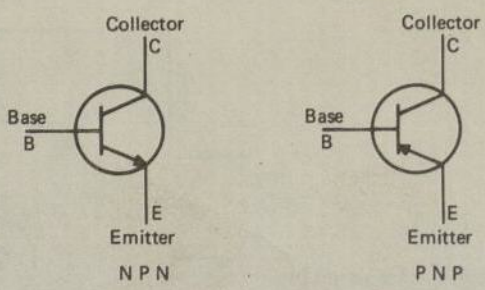


Fig. 11-29. Symbols of transistors.

Figures 11-26; 11-27; 11-28; 11-29

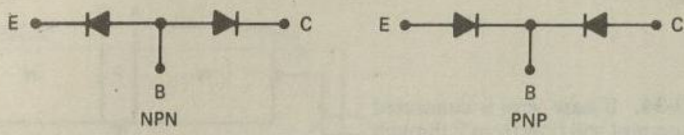


Fig. 11-30. Transistors can be considered PN diodes connected back to back.

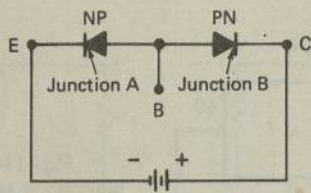
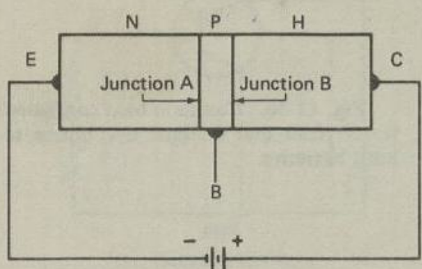


Fig. 11-31. Electron current flow is forward at junction A but reversed and therefore blocked at junction B.

Fig. 11-32. Same results as **Fig. 31.**



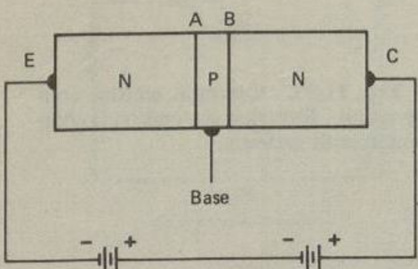


Fig. 11-33. Two batteries, acting as in this circuit does not produce current flow because junction B is reverse biased.

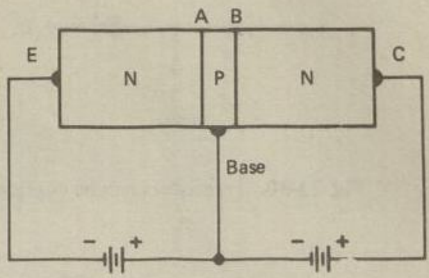


Fig. 11-34. If base wire is connected as shown, current will flow from E through both junctions to C.

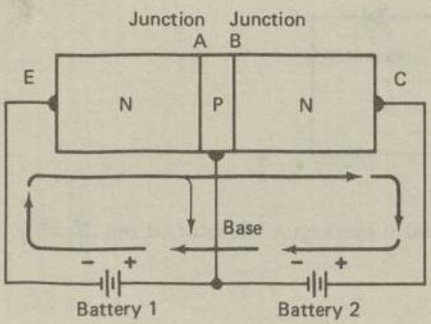


Fig. 11-35. Electron flow through junction A continues through junction B to the positive terminal of battery 2.

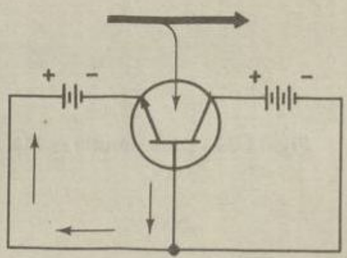


Fig. 11-36. Common base configuration. Note that the base is common to both batteries.

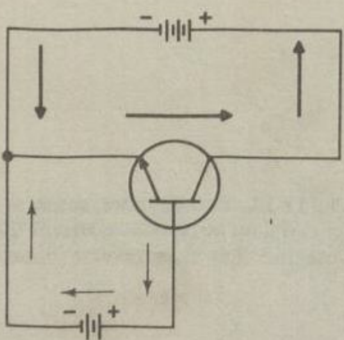


Fig. 11-37. Common emitter configuration. Note that the emitter is common to both batteries.

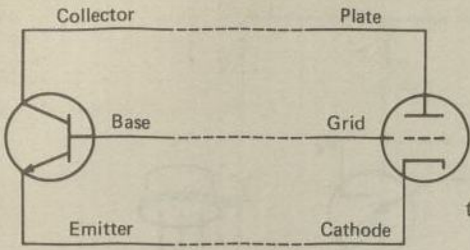


Fig. 11-38. Comparison of 3-element tube and transistor.

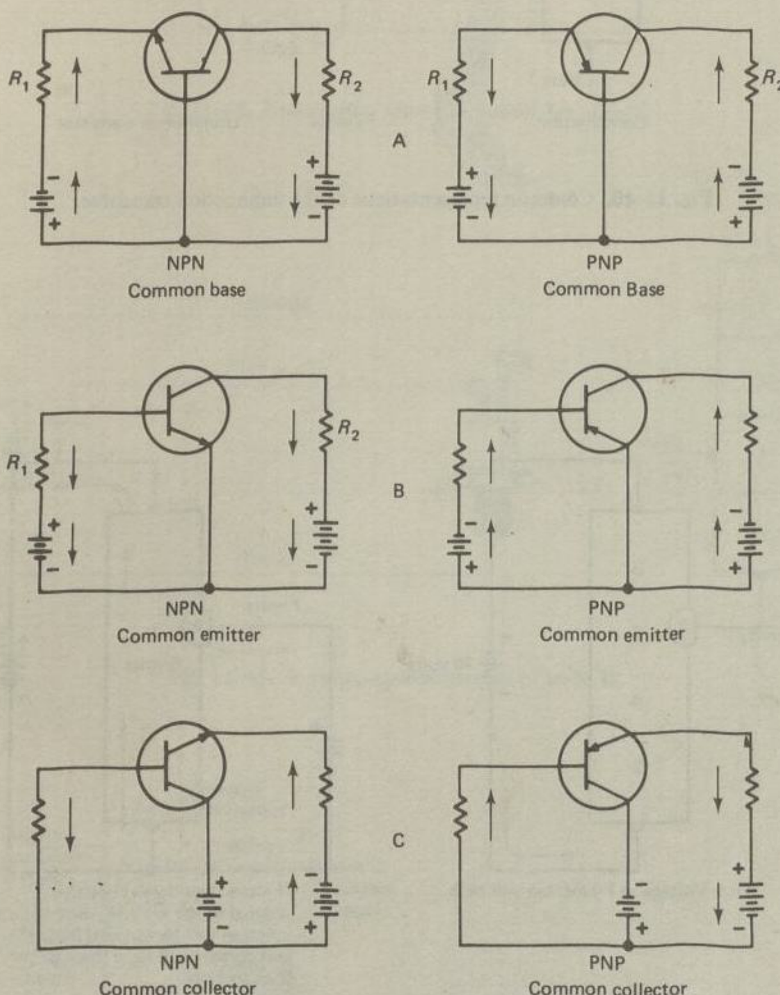


Fig. 11-39A,B,C. Transistor circuit configurations.

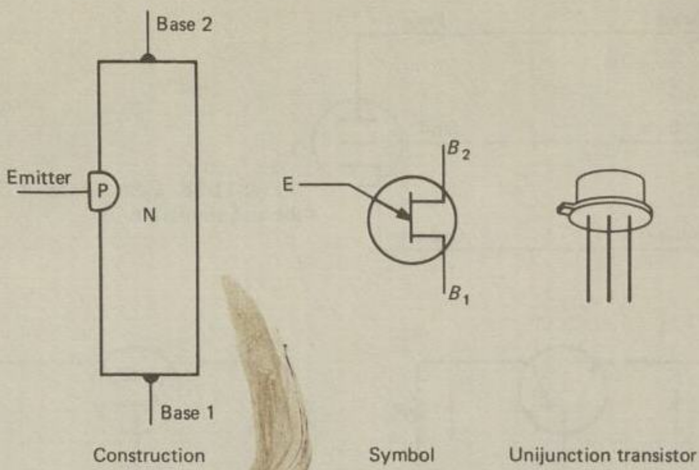


Fig. 11-40. Common representations of the unijunction transistor.

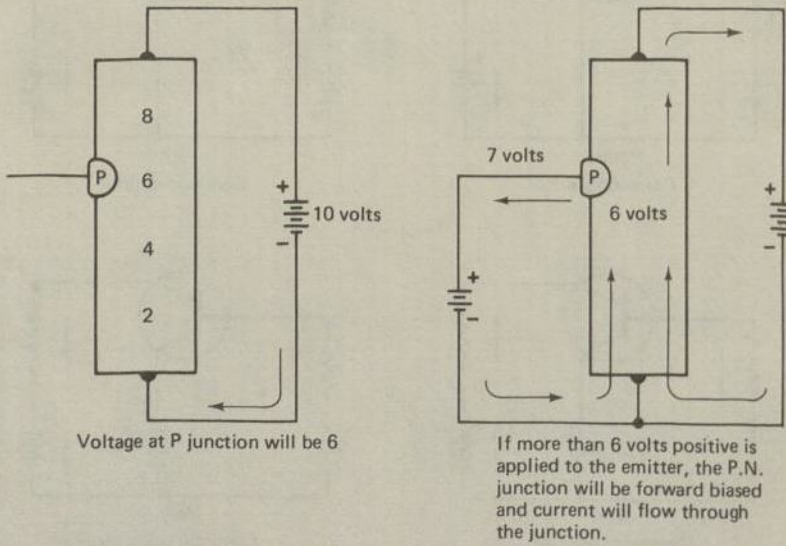


Fig. 11-41. Voltage division in the unijunction transistor.

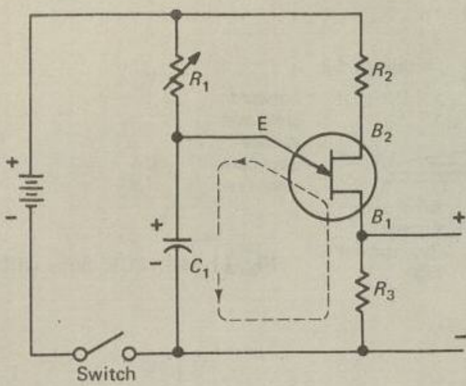


Fig. 11-42. Unijunction relaxation oscillator circuit.

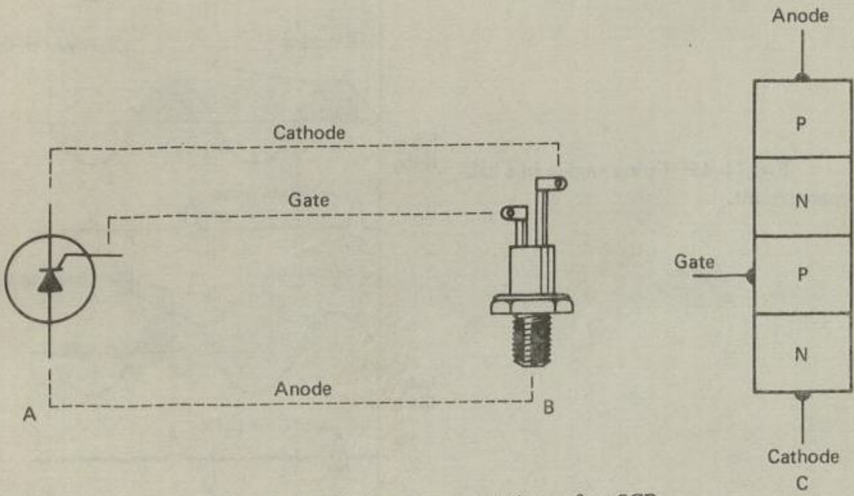


Fig. 11-43. Various representations of an SCR.

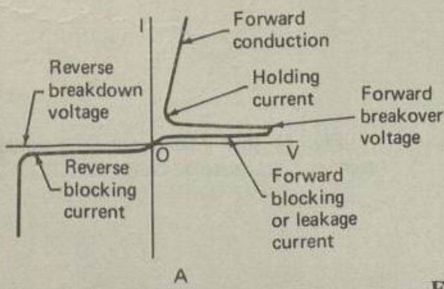


Fig. 11-44A. Characteristic curve of an SCR.

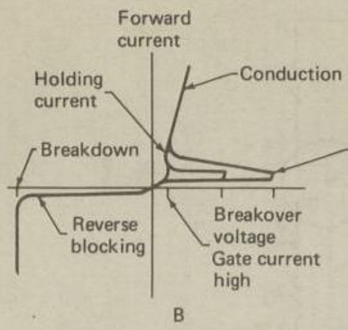


Fig. 11-44B. SCR curve with various gate currents.

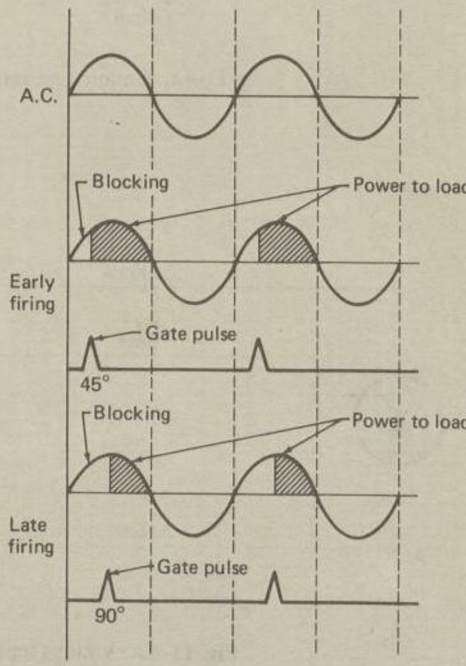


Fig. 11-45. Firing angles in a half-wave circuit.

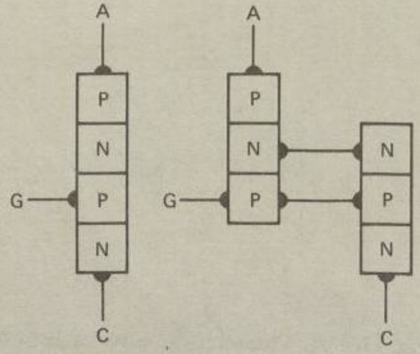


Fig. 11-46. Four layer SCR considered as 2 transistors, PNP and NPN.

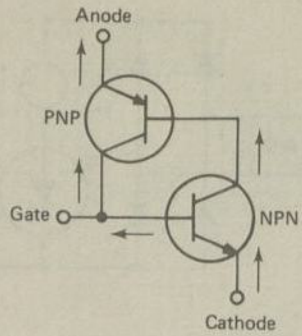


Fig. 11-47. SCR shown as 2 transistors to explain its operation.

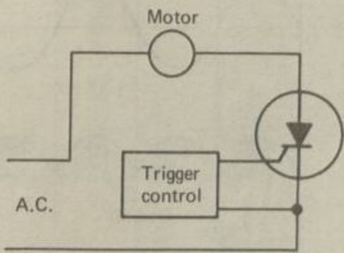


Fig. 11-48. Half-wave control.

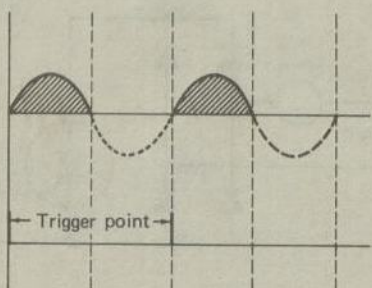


Fig. 11-49. Trigger pulse at 0°. SCR fires at the beginning of each positive half cycle.

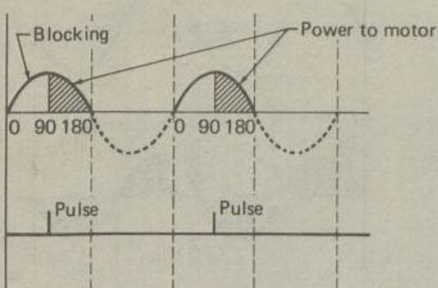


Fig. 11-50. Trigger pulse at 90°. SCR fires at this point.

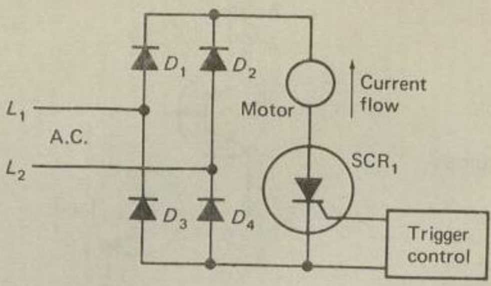


Fig. 11-51. Full-wave d-c control.

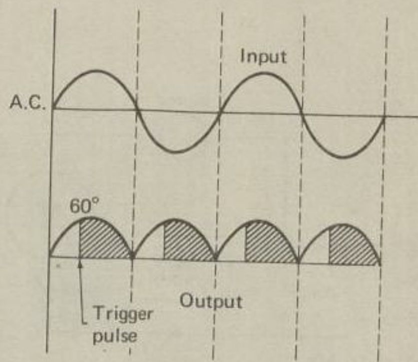


Fig. 11-52. Output wave form for full wave. Trigger pulse at 60°.

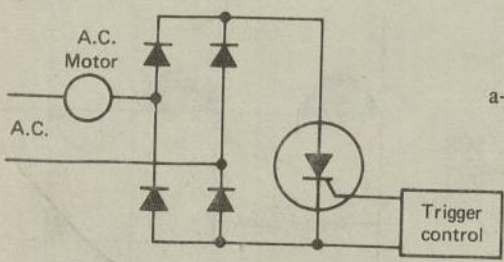


Fig. 11-53A. Full wave controlled a-c.

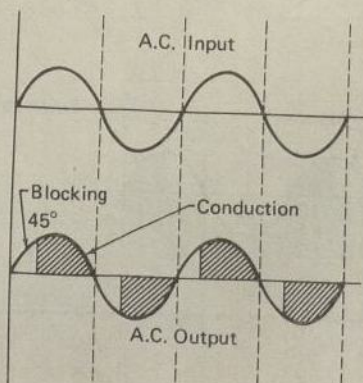
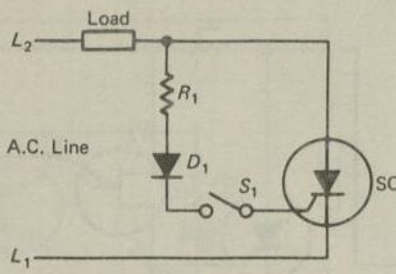


Fig. 11-53B. Output wave form.

Figures 11-51; 11-52; 11-53

Fig. 11-54A. Resistance triggering.



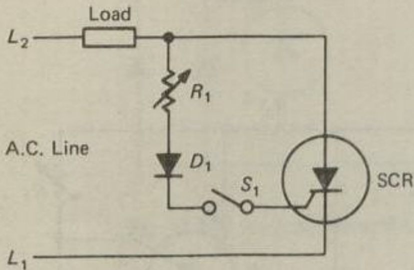
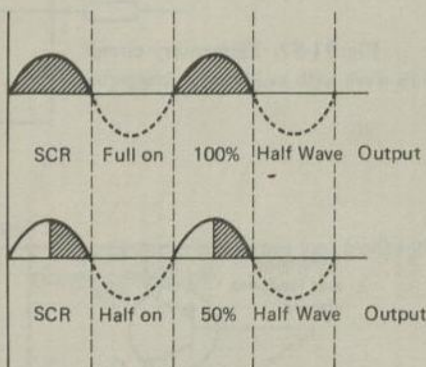


Fig. 11-54B. Resistance triggering using a variable resistance.

Fig. 11-54C. Waveforms for maximum and minimum power.



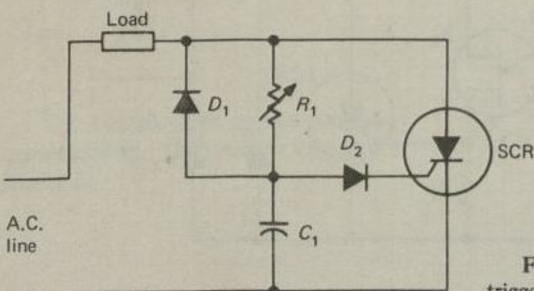


Fig. 11-55. Resistor-capacitor triggering.

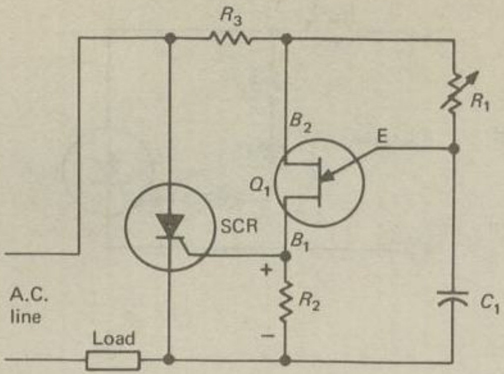


Fig. 11-56. Elementary circuits. Half wave with unijunction triggering.

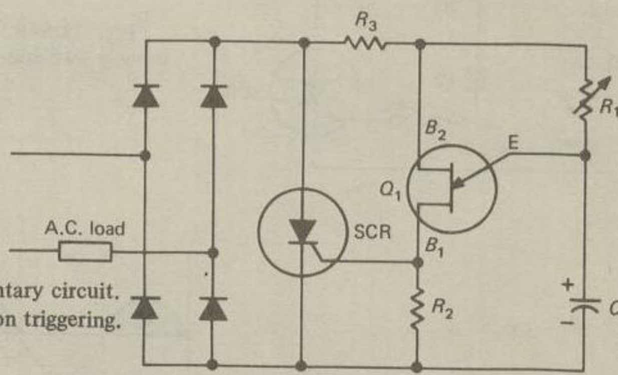


Fig. 11-57. Elementary circuit. Full wave with unijunction triggering.

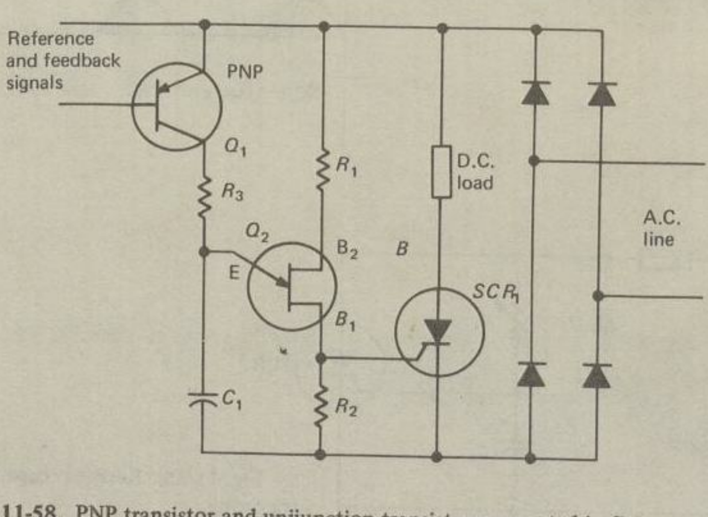


Fig. 11-58. PNP transistor and unijunction transistor connected in firing circuit.

Figures 11-56; 11-57; 11-58

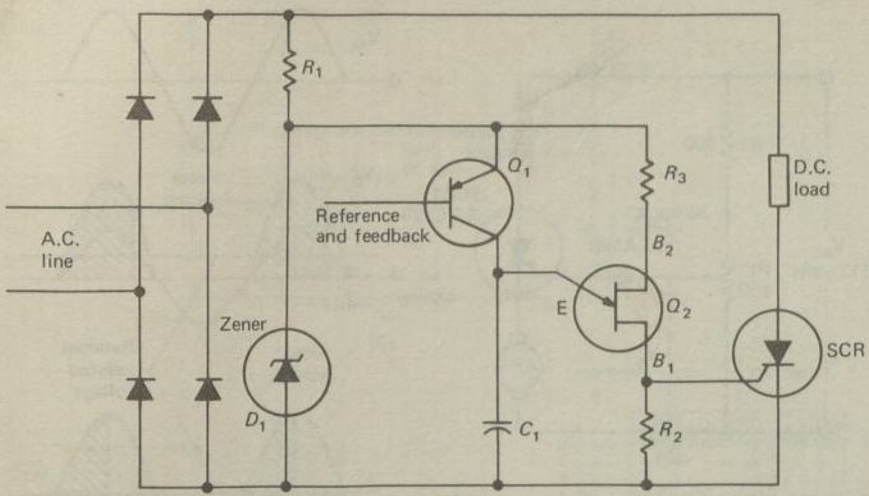


Fig. 11-59. Unijunction and transistor control using zener voltage.

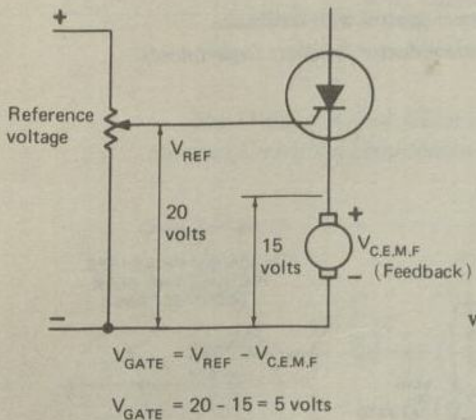
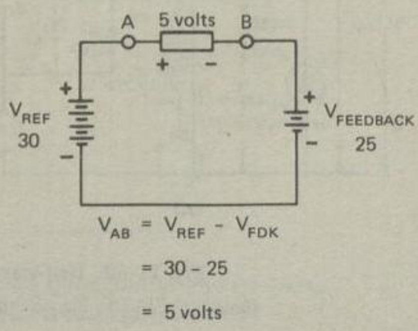


Fig. 11-60A. Reference and feedback voltage comparison.

Fig. 11-60B. Two voltages connected series opposing. The resultant voltage is 5, plus at A.



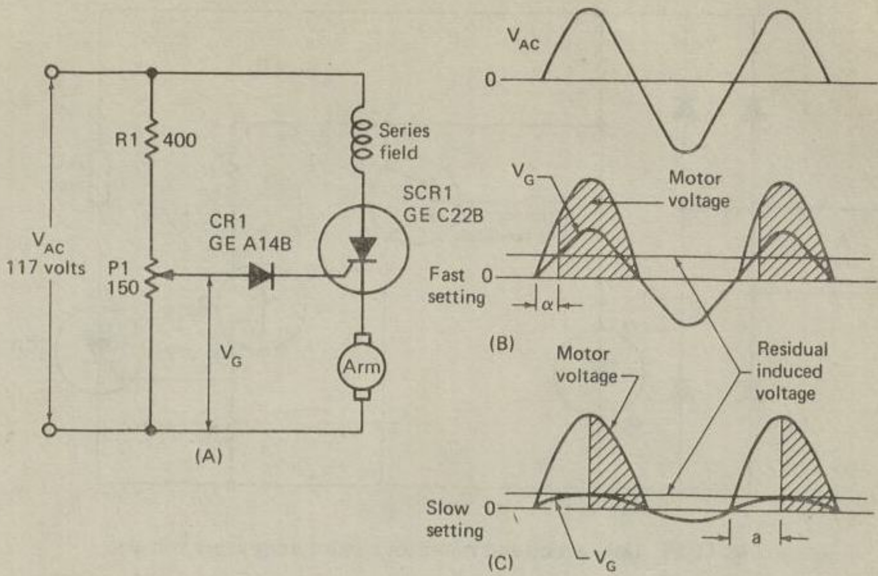


Fig. 11-61. Half wave control with feedback.
(General Electric Co., Semiconductor Products Department)

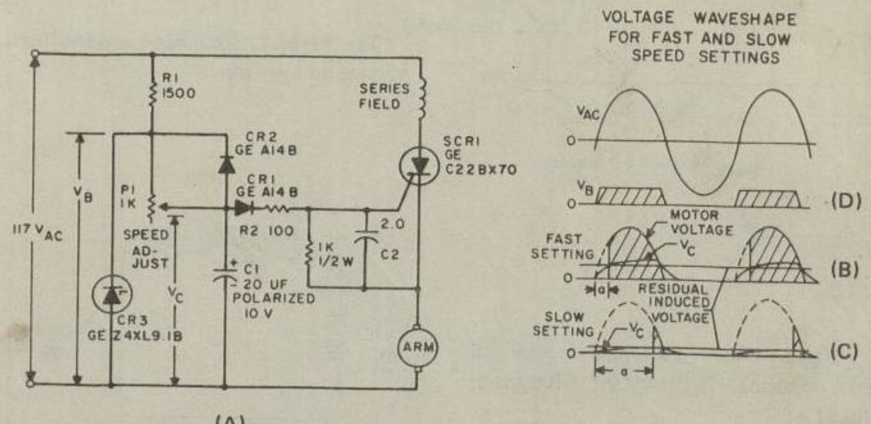
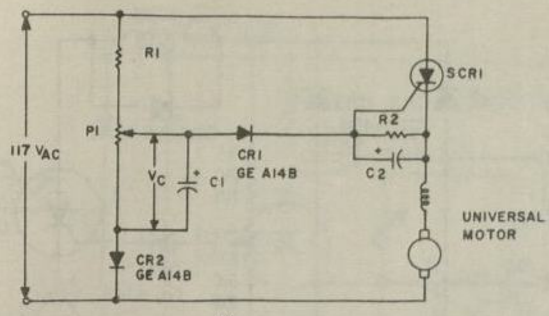
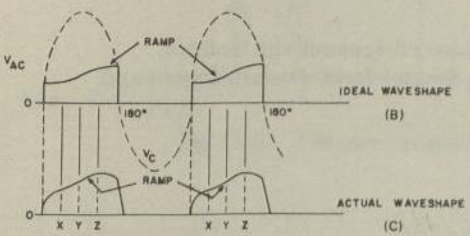


Fig. 11-62. Half wave improved performance.
(General Electric Co., Semiconductor Products Department)



(A)



COMPONENT VALUES FOR THE CIRCUIT

	LOW UP TO 1AMP NAMEPLATE	MEDIUM UP TO 3AMP NAMEPLATE	HIGH UP TO 5AMP NAMEPLATE
P1	10K 1W	1K 2W	1K 2W
R1	47K 1/2W	3.3K 2W	3.3K 2W
R2	1K 1/2W	150 1/2W OPTIONAL	150 1/2W OPTIONAL
C1	.5μf 10V	10μf 10V	10μf 10V
C2	1μf 10V	1μf 10V OPTIONAL	1μf 10V OPTIONAL
SCR1	GE C 106B	GE C 228X70	GE C 35B

(D)

Fig. 11-63. Universal motor control with feedback.
(General Electric Co., Semiconductor Products Department)

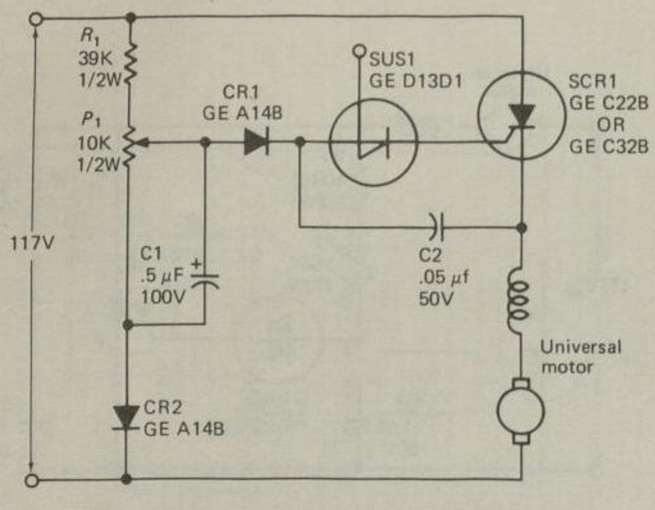


Fig. 11-64. SUS triggered universal motor speed control with feedback.
(General Electric Co., Semiconductor Products Department)

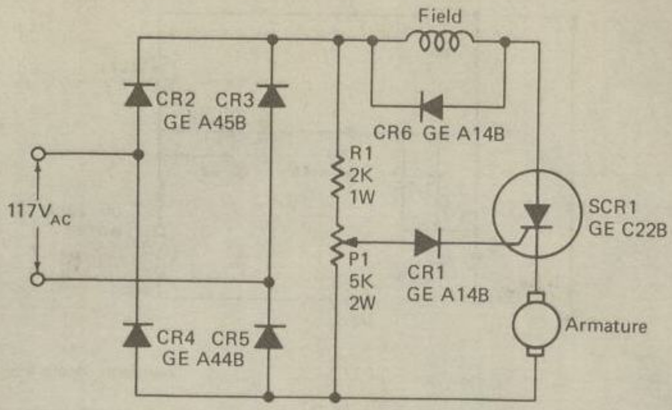


Fig. 11-65. Full-wave d-c control with feedback.
(General Electric Co., Semiconductor Products Department)

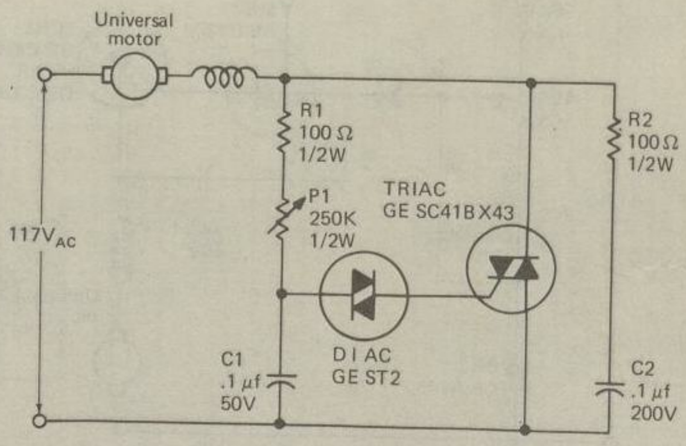


Fig. 11-66. Full-wave a-c control without feedback.
(General Electric Co., Semiconductor Products Department)

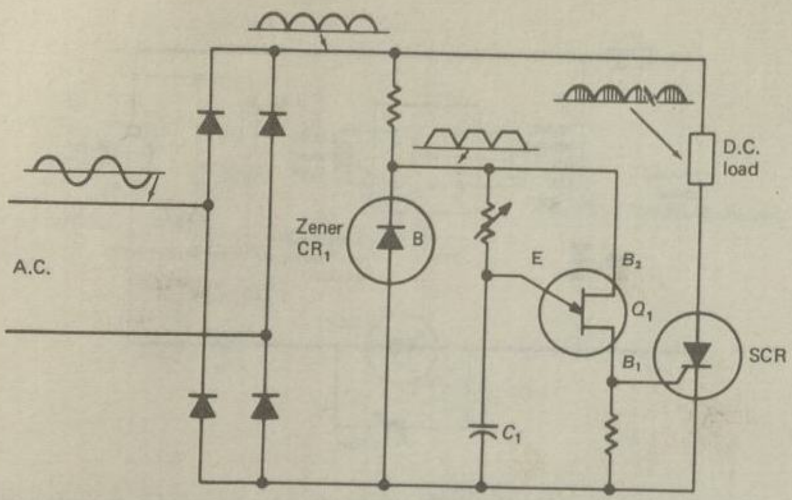


Fig. 11-67. Full-wave control with synchronization.

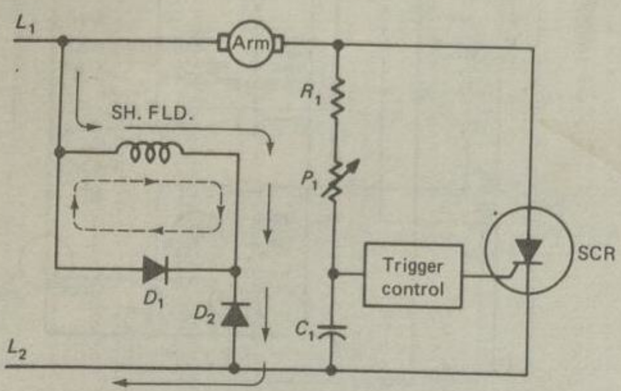


Fig. 11-68. Half-wave control for a shunt motor.

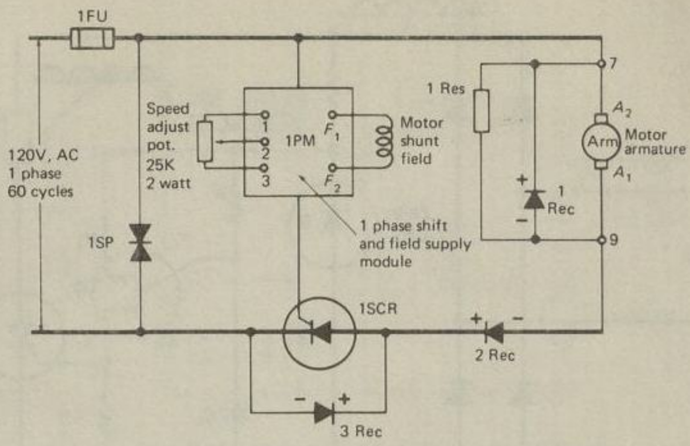


Fig. 11-69. Protecting the SCR by means of diodes, fuses and surge protectors. *(Square D Co.)*

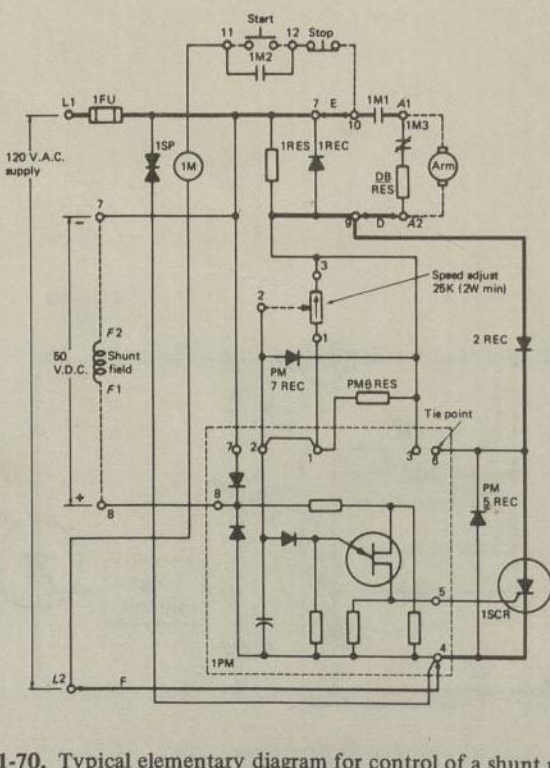
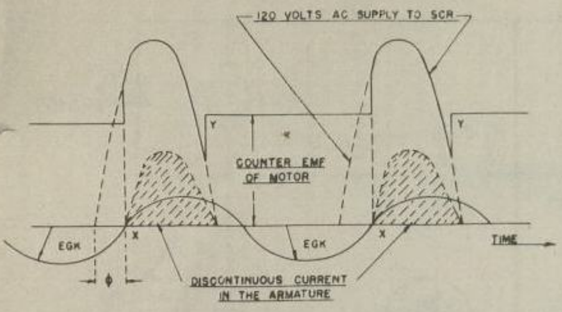


Fig. 11-70. Typical elementary diagram for control of a shunt motor. *(Square D Co.)*



(A)

Fig. 11-71A. Wave forms.

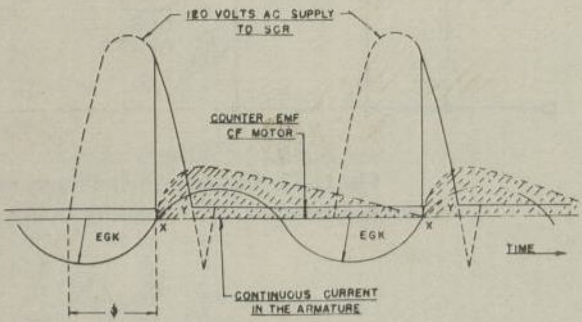


Fig. 11-71B. Wave forms. *(Square D Co.)* (B)

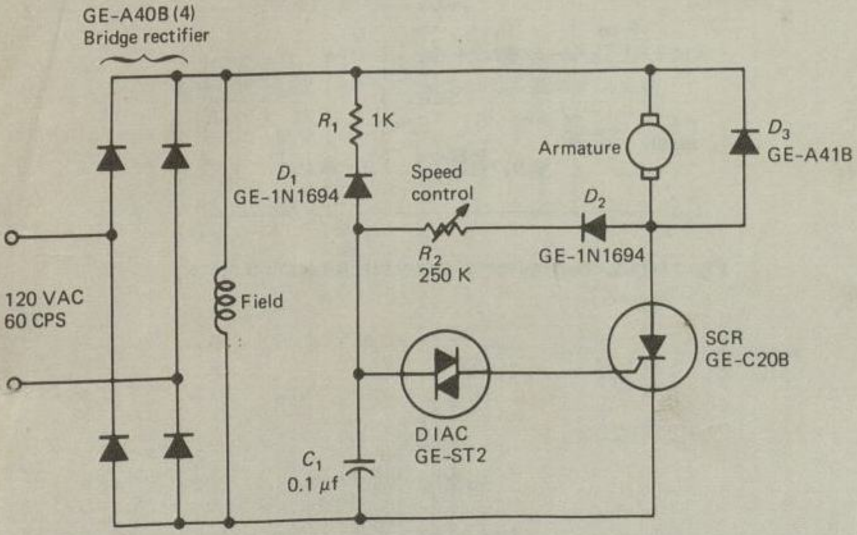


Fig. 11-72. Speed control for shunt-wound d-c motor.
(General Electric Co., Semiconductor Products Department)

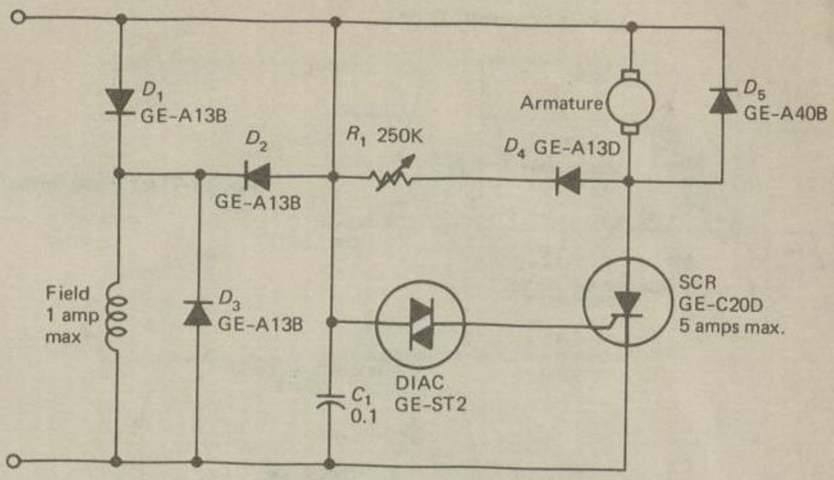


Fig. 11-73. Half-wave control for shunt motor.
(General Electric Co., Semiconductor Products Department)

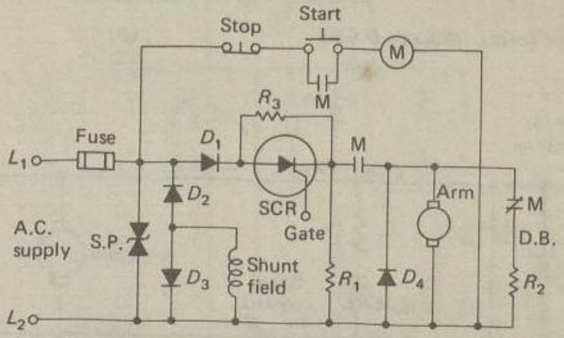


Fig. 11-74A. Half-wave power circuits for a shunt motor.

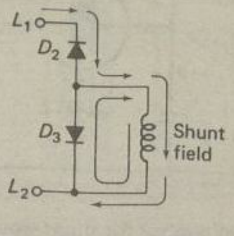


Fig. 11-74B. Shunt field excitation.

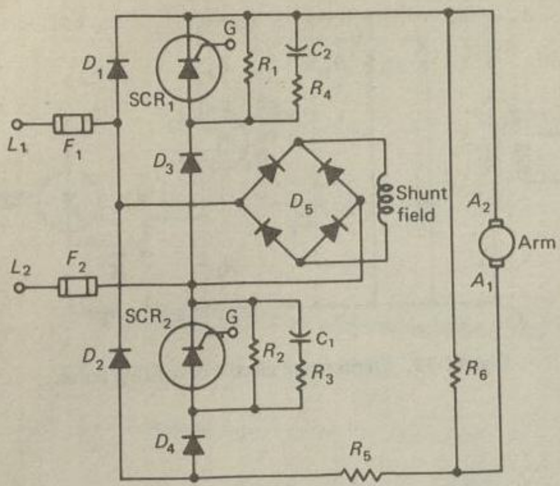


Fig. 11-75A. Full-wave power circuits for a shunt motor.

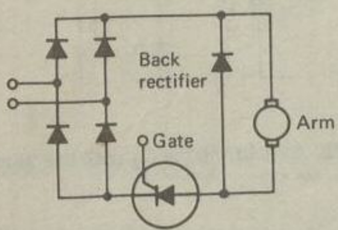


Fig. 11-75B. A back rectifier is necessary in this circuit.

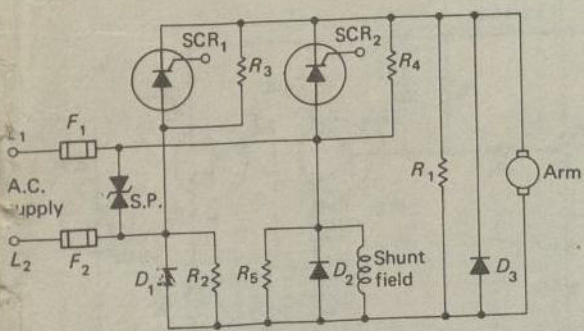
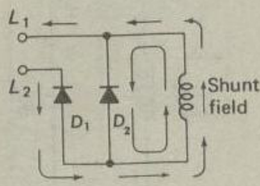


Fig. 11-76A. A full-wave power circuit for a shunt motor.



11-76B. Field excitation for Fig. 11-76A.

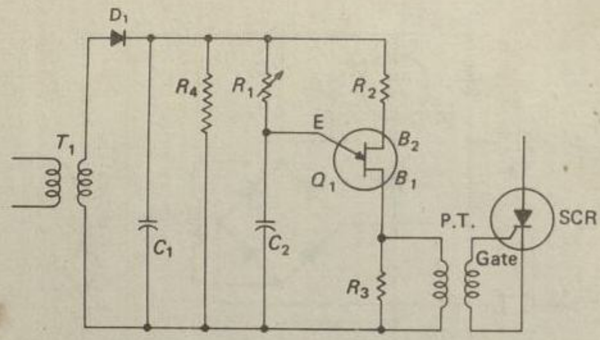


Fig. 11-77. Elementary circuit of a firing pulse.

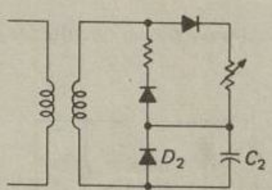


Fig. 11-78. Synchronizing C_2 with line alternations.

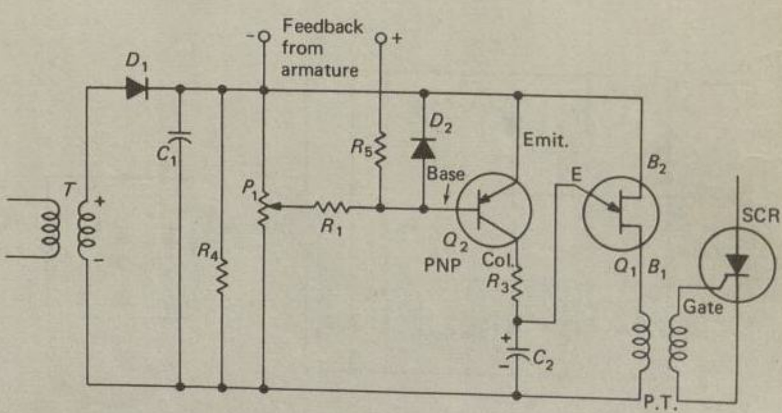


Fig. 11-79. Firing circuit using transistor Q_2 for amplifying the error signal.

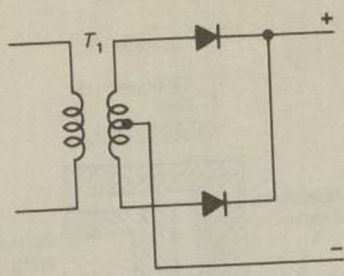


Fig. 11-80. Full-wave reference supply voltage.

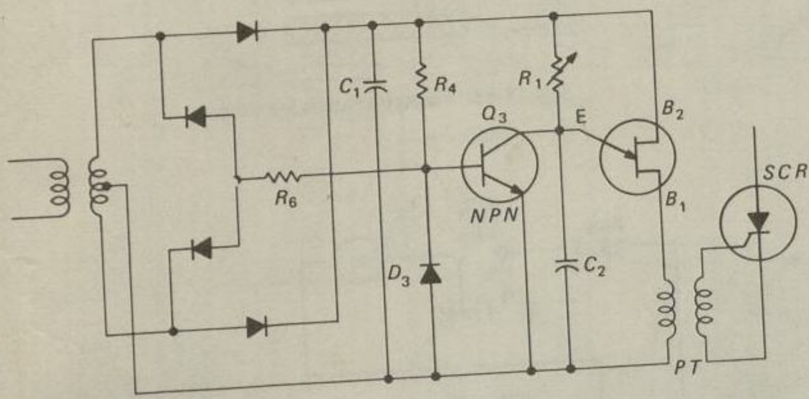


Fig. 11-81. Synchronizing by means of a transistor. R_1 may be replaced by a transistor as in Fig. 11-79.

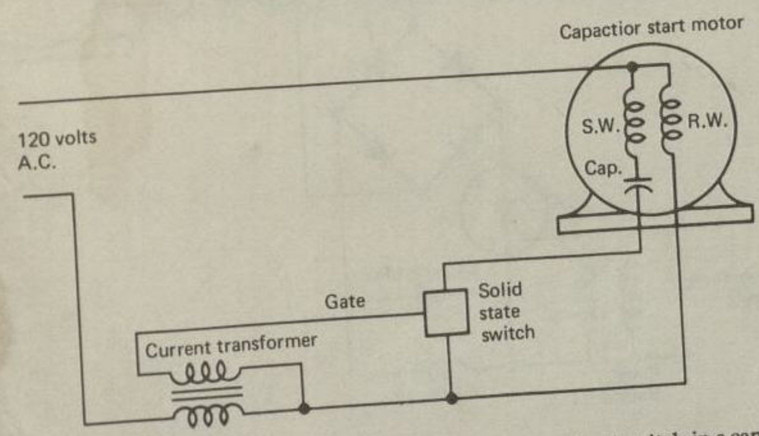


Fig. 11-82. A solid state switch is used to replace the centrifugal switch in a capacitor-start or split-phase motor.

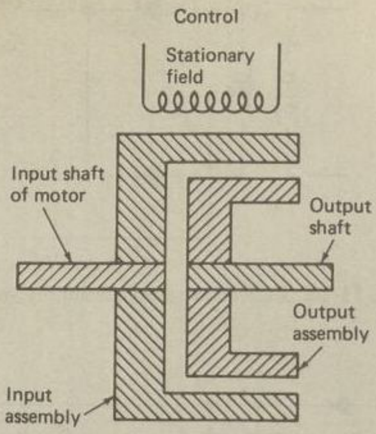


Fig. 11-83. Magnetic clutch assembly.

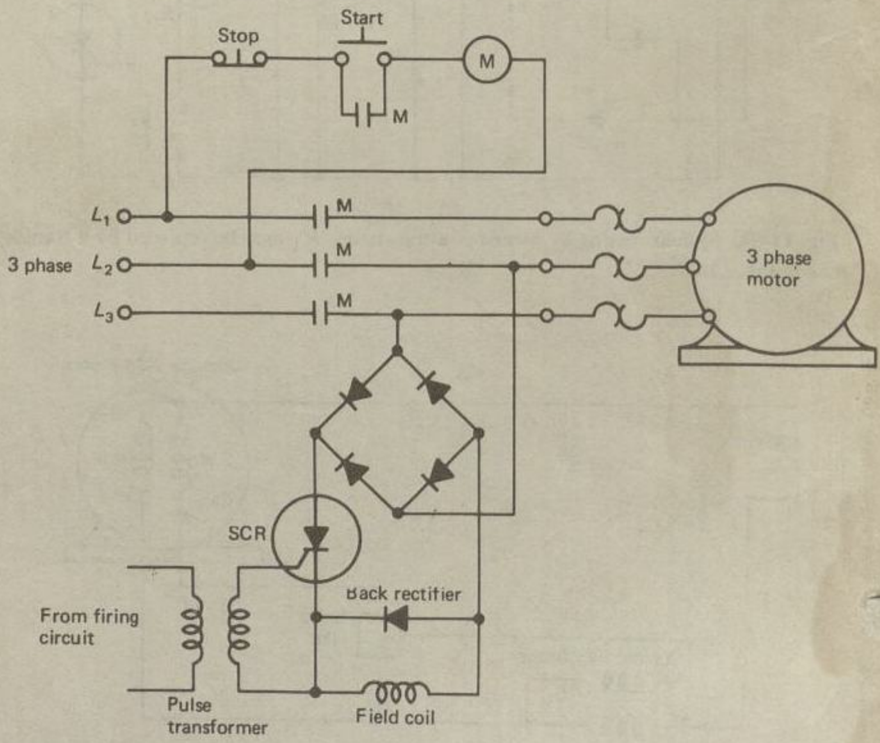


Fig. 11-84. Power circuit of a magnetic drive.

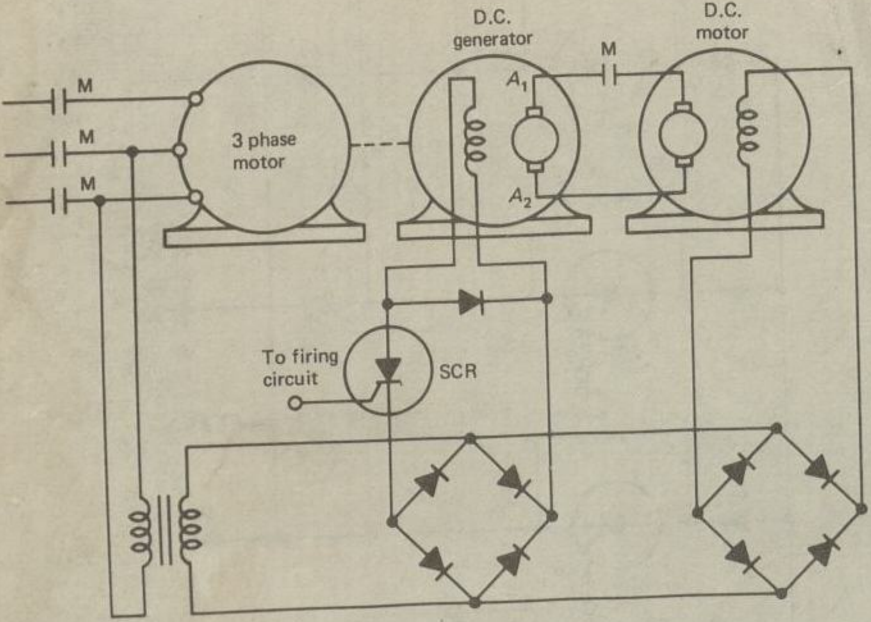


Fig. 11-85. Elementary diagram of motor generator drive.

Figure 11-85

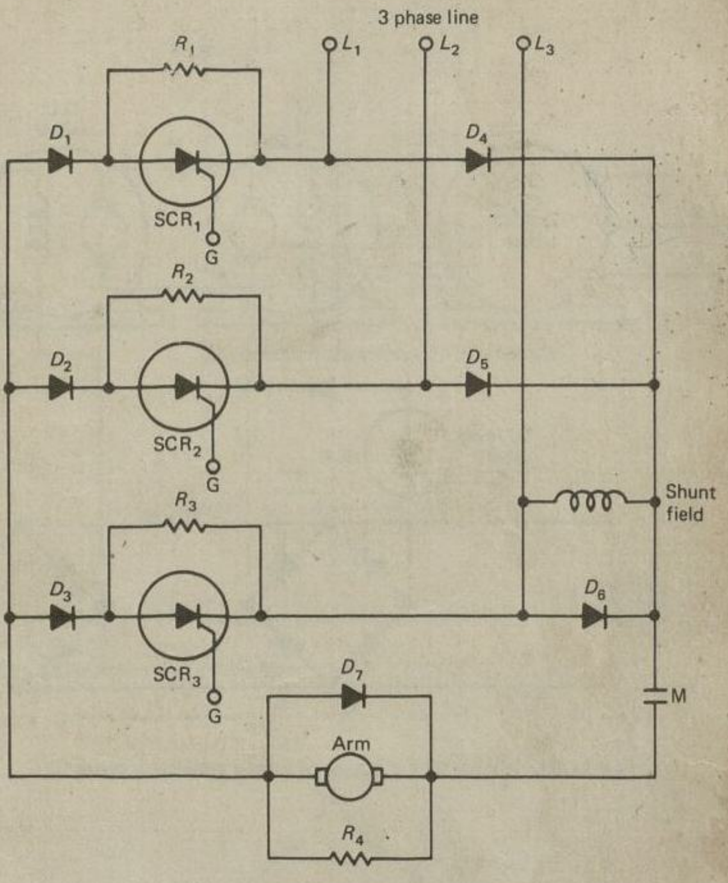


Fig. 11-86. Elementary diagram of the power circuit of a 3-phase static drive.

Figure 11-86