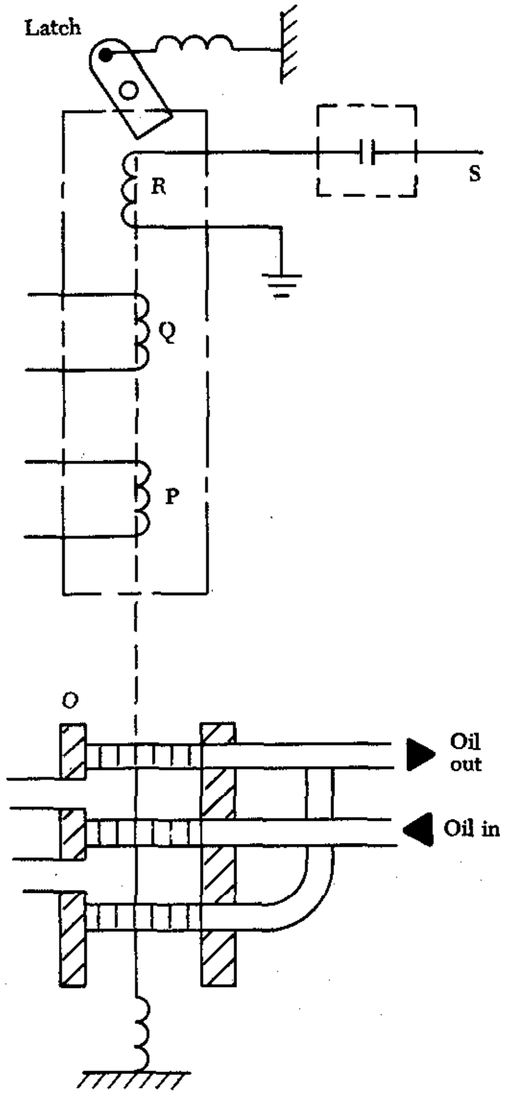


FIGURE 9–52. Overspeed circuit.

upon the amount of current flowing in the line of one phase. In this way, it measures the real load of the generator. The output voltage of the current transformer is applied across resistor *H*. This voltage will be added vectorially to the voltage applied to the upper winding of transformer *J* by the output of transformer *F*. At the same time as it adds vectorially to the upper winding of transformer *J*, it subtracts vectorially from the voltage applied to the lower winding of *J*.

This voltage addition and subtraction depends on the real load of the generator. The amount of real load determines the phase angle and the amount of voltage impressed across resistor *H*. The greater the real load, the greater the voltage across *H*, and hence, the greater the difference between the voltages applied to the two primaries of transformer *J*. The unequal voltages applied to resistor *M* by the secondaries of transformer *J* cause a current flow through the control coil *P*.

The control coil is wound so that its voltage supplements the voltage for the control coil in the valve and solenoid assembly. The resulting increased voltage moves the valve and slows down the generator's speed. Why should the speed be decreased if the load has been increased? Actually, systems using only one generator would not have decreased speed, but for those having two or more generators, a decrease is necessary to equalize the loads.

The load division circuit is employed only when two or more generators supply power. In such systems, the control coils are connected in parallel. If the source voltage for one of these becomes higher than the others, it determines the direction of current flow throughout the entire load division circuit. As explained before, the real load on the generator determines the amount of voltage on the control coil; therefore, the generator with the highest real load has the highest voltage.

As shown in figure 9–54, current through No. 1 control coil, where the largest load exists, aids the control coil of the valve and solenoid, thereby slowing down the generator. (The source voltage of the control coils is represented by battery symbols in the illustration.) The current in the remaining control coils opposes the control coil of the valve and solenoid, in order to increase the speed of the other generators so the load will be more evenly distributed.

On some drives, instead of an electrically controlled governor, a flyweight-type governor is employed, which consists of a recess-type revolving valve driven by the output shaft of the drive, flyweights, two coil springs, and a nonrotating valve stem. Centrifugal force, acting on the governor flyweights, causes them to move outward, lifting the valve stem against the opposition of a coil spring.

The valve stem position controls the directing of oil to the two oil-out lines. If the output speed tends to exceed 6,000 r.p.m., the flyweights will lift the valve stem to direct more oil to the side of the control piston, causing the piston to move in a direction to reduce the pump wobble plate angle. If the speed drops below 6,000 r.p.m., oil is directed to the control piston so that it moves to increase the wobble plate angle. Overspeed

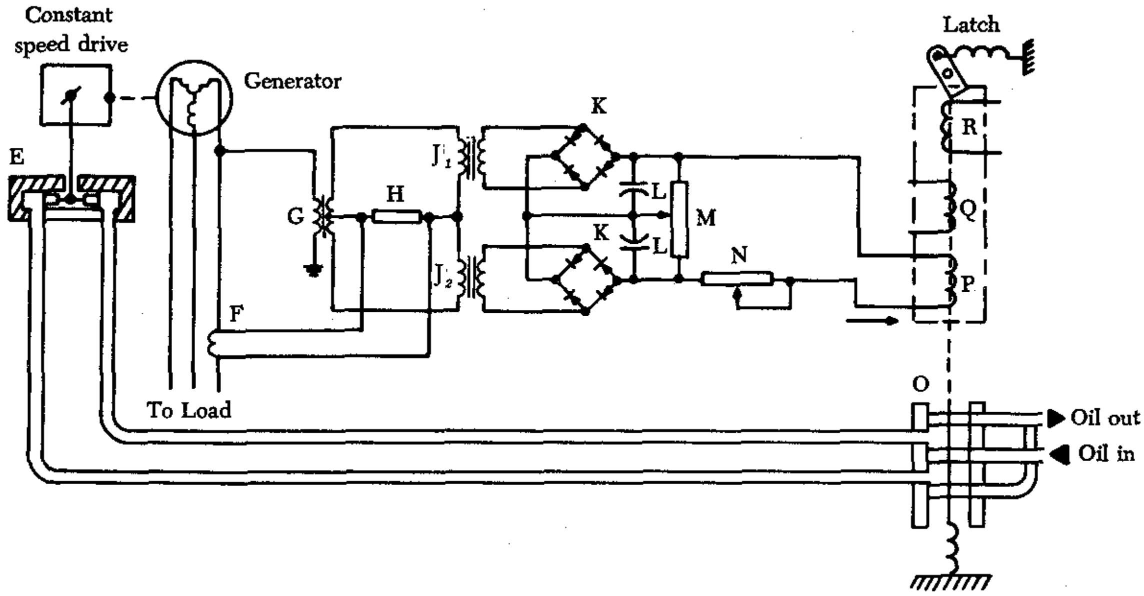


FIGURE 9–53. Droop circuit.

protection is installed in the governor. The drive starts in the underdrive position. The governor coil springs are fully extended and the valve stem is held at the limit of its downward travel. In this condition, pressure is directed to the side of the control piston giving minimum wobble plate angle. The maximum angle side of the control piston is open to the hollow stem. As the input speed increases, the flyweights start to move outward to overcome the spring bias. This action lifts the valve stem and starts directing oil to the maximum side of the control piston, while the minimum side is opened to the hollow stem.

At about 6,000 r.p.m., the stem is positioned to stop drainage of either side, and the two pressures seek a balance point as the flyweight force is balanced against the spring bias. Thus, a mechanical failure in the governor will cause an underdrive condition. The flyweight's force is always tending to move the valve stem to the decrease speed position so that, if the coil spring breaks and the stem moves to the extreme position in that direction, output speed is reduced. If the input to the governor fails, the spring will force the stem all the way to the start position to obtain minimum output speed.

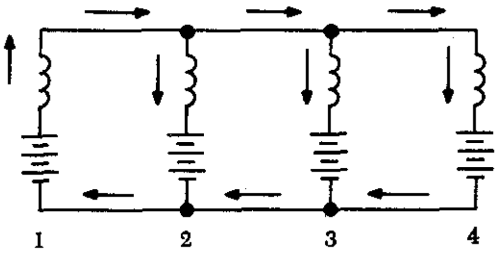


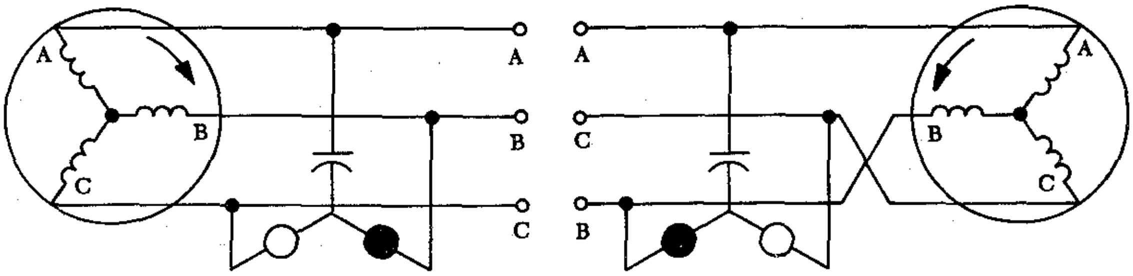
FIGURE 9–54. Relative direction of current in droop coil circuit with unequal loads.

The output speed of the constant-speed drive is regulated by an adjustment screw on the end of the governor. This adjustment increases or decreases the compression of a coil spring, opposing the action of the flyweights. The adjustment screws turn in an indented collar, which provides a means of making speed adjustments in known increments. Each "click" provides a small change in generator frequency.

SYNCHRONIZING ALTERNATORS

Two or more alternators may be operated in parallel, with each alternator carrying the same share of the load. However, certain precautions must be taken and various conditions complied with before connecting an alternator to a bus with another alternator.

Synchronizing, or paralleling, alternators is somewhat similar to paralleling d.c. generators, except that there are more steps with alternators. In order to synchronize (parallel) two or more alternators to the same bus, they must have the



Phase rotation ABC
left lamp lights

Phase rotation ABC
Right lamp lights
Two leads have been reversed

FIGURE 9–55. Phase sequence indicator.

same phase sequence as well as equal voltages and frequencies.

The following steps are a general guide in synchronizing an alternator and connecting it to a bus system on which one or more alternators are already operating.

1. *Phase sequence check.* The standard phase sequence for a.c., three-phase power circuits is *A*, *B*, *C*. The phase sequence can be determined by observing two small indicator lamps, connected as shown in figure 9–55. If one lamp lights, the phase sequence is *A*, *B*, *C*. If the other lamp lights, the phase sequence is *A*, *C*, *B*. If the light indicates the wrong phase sequence, reverse the two leads to the incoming alternator. To parallel or synchronize two alternators with the wrong phase sequence would be the same as short circuiting two leads and would set up dangerous circulating currents and magnetic disturbances within the alternator system, which could overheat the conductors and loosen the coil windings.
2. *Voltage check.* The voltage of the alternator to be connected to the bus must be equal to the bus voltage. It is adjusted by a control rheostat located on the switch panel. This rheostat controls the current in the voltage regulator coil and causes the alternator magnetic field to increase or decrease, controlling, in turn, the alternator voltage.
3. *Frequency check.* The frequency of an alternator is directly proportional to its speed. This means that the speed of the alternator being connected to the bus must equal the speed of the alternators already connected. By observing the frequency meter and by adjusting the rheostat on the switch panel, the frequency of the incoming alternator can be brought up to the correct value. By observing the synchronizing lamp, shown in figure 9–56, and by fine adjustment of the speed control rheostat, the frequencies may be brought to almost exact synchronization. The synchronizing lamp will blink as the two frequencies approach the same value; when they are very nearly the same, the lamp will blink slowly. When the blinking decreases to one blink or less per second, close the circuit breaker while the lamp is dark and connect alternator No. 2 to the bus. The dark lamp indicates no voltage between phase *A* of the bus and phase *A* of the incoming alternator. During the period when the lamp is lighted, there is a voltage difference between phase *A* of the bus and phase *A* of the alternator to be connected to the bus. To close the circuit breaker when the synchronizing lamp is lighted would be similar to short circuiting two leads and would cause serious voltage and magnetic disturbances within the alternators.

Alternator Protective Circuits

It is very important that operating alternators be disconnected from the system when harmful electrical faults occur. For an alternator to be removed from the bus when trouble occurs in the circuit, circuit breakers must open rapidly and automatically; otherwise, the alternator could burn up. To provide relays in the circuit breakers, there are a number of protective relays in the circuit. Most of these relays are d.c. energized, since similar a.c. equipment is usually much

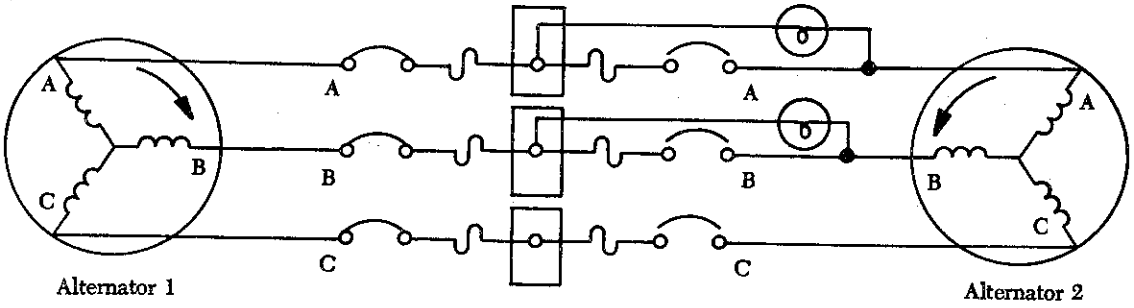


FIGURE 9–56. Synchronizing lamp circuit.

heavier and less efficient. Figure 9–57 contains a diagram showing an alternator control and protective circuit. Included in it are an alternator, circuit breakers, an exciter ceiling relay, and a differential current protection relay.

There are two circuit breakers in this type of airplane alternator control system: (1) The exciter control relay, which opens and closes the exciter field circuits, and (2) the main line circuit breaker, which connects or disconnects the alternator from the bus and also opens or closes the exciter field current.

The main line circuit breaker is latched by a d.c. electromagnet, called a "close" coil. This coil closes the circuit breakers. They are released by a second electromagnet, known as the trip coil, which opens the circuit. Only momentary contact of the closing and tripping circuits is necessary for operation. Once closed, a mechanical latch holds the contactors until the latch is released by the trip coil. The contacts are made of special alloys capable of breaking currents of several thousand amperes without damage to the contacts.

This main line triple-pole circuit breaker has an

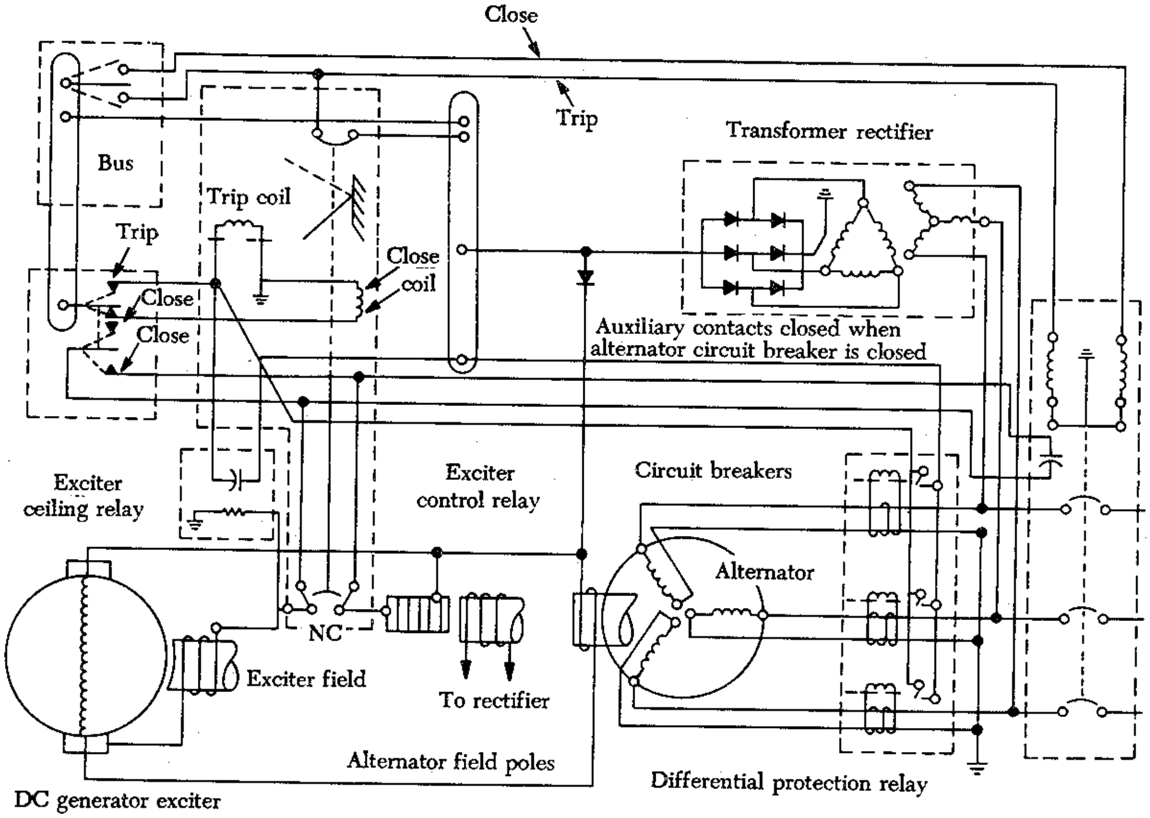


FIGURE 9–57. Alternator control and protective circuit.

auxiliary contact which closes the exciter field circuit whenever the main line circuit breakers close and opens it whenever the circuit breakers open. This is desirable because the alternator may be supplying load current when the circuit breakers open; in which case, the exciter field excitation should be decreased or removed. Also, the exciter field circuit is held closed until the main circuit breakers can open, in case the exciter control relay is opened first.

The exciter control relay opens and closes the exciter field circuit. Upon opening, it closes a contact furnishing d.c. power to the main line trip coil and causes the main line circuit breakers to open. The exciter control relay consists of two solenoids, one latching and one tripping. It needs only momentary closing of the switch for operation.

The exciter ceiling relay shown in the protective circuit diagram of figure 9–57 is a thermal-operated relay. It operates whenever the exciter field current increases enough to be dangerous to the operation of the alternator. If at any time the alternator becomes loaded too heavily, either by a short circuit on the line or by the alternator becoming inoperative, the exciter voltage increases to supply the heavy alternator load, and the thermal ceiling relay closes the contacts between the d.c. bus and the trip coil. This opens the exciter field and, at the same time, disconnects the alternator from the line.

The differential current protection relay is much simpler in operation than its name indicates. It is designed to protect the alternator from internal shorts between phases or to ground. As long as there is the same amount of current in each phase going into the alternator as coming out, the differential relay does not operate, no matter how heavy or light these currents may be. However, if a short occurs within the alternator in any one phase, there is a difference in current through the lines; the relay operates, closing the circuit to the exciter trip coil, which, in turn, closes the circuit to the trip coil of the main line circuit breakers. The location of components in a typical relay is shown in figure 9–58.

The two leads from each phase of the alternator are passed through the doughnut-like holes in the relay and act as the primaries of the current transformers. As the current flows in opposite directions in the two leads through each hole, their magnetic fields are cancelled and no current flows in the current-transformer secondary, which energizes the relay. The relay does not operate until a fault occurs that unbalances the currents in these two conductors and causes current to flow in the current-transformer secondary. Failure of the differential current relay would be backed up by the exciter protection relay. Fast clearing of internal faults reduces danger from fire and also reduces system disturbances when the alternators are paralleled improperly. A time-delay action in the exciter protection relay allows overexcitation for short intervals in order to supply d.c. voltage for clearing faults and for brief demands for current beyond the capacity of the alternator. It also opens the main breaker and drops the alternator excitation when other protective devices fail.

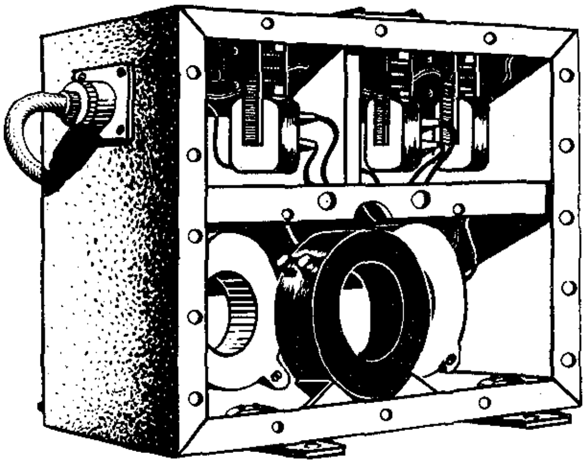


FIGURE 9–58. Differential current protection relay.

ALTERNATOR MAINTENANCE

Maintenance and inspection of alternator systems is similar to that of d.c. systems. Check the exciter brushes for wear and surfacing. On most large aircraft with two or four alternator systems, each power panel has three signal lights, one connected to each phase of the power bus, so the lamp will light when the panel power is on. The individual buses throughout the airplane can be checked by operating equipment from that particular bus. Consult the manufacturer's instructions on operation of equipment for the method of testing each bus.

Alternator test-stands are used for testing alternators and constant-speed drives in a repair facility. They are capable of supplying power to constant-speed drive units at input speeds varying from 2,400 r.p.m. to 9,000 r.p.m. A typical

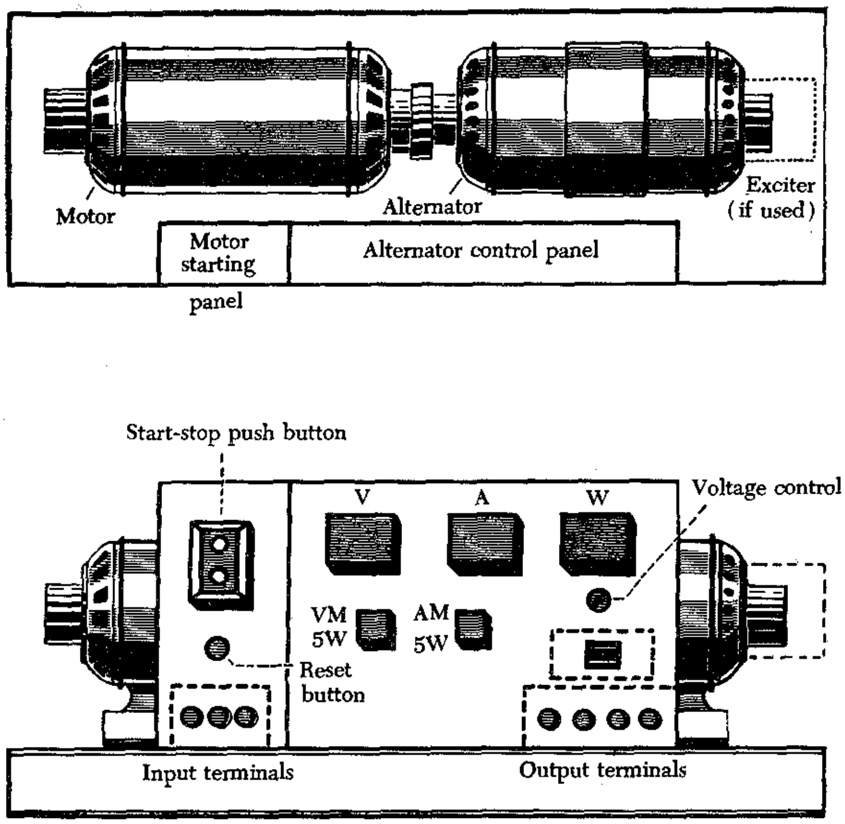


FIGURE 9–59. A.C. motor-generator set for ground testing.

test-stand motor uses 220/440-volt, 60-cycle, 3-phase power. Blowers for ventilation, oil coolers, and necessary meters and switches are integral parts of the test-stand. Test circuits are supplied by a load-bank. An a.c. motor-generator set for ground testing is shown in figure 9–59.

A typical, portable, a.c. electrical system test-set is an analyzer, consisting of a multirange ohmmeter, a multirange combination a.c.-d.c. voltmeter, an ammeter with a clip-on current transformer, a vibrating-reed type frequency meter, and an unmounted continuity light.

A portable load bank unit furnishes a load similar to that on the airplane for testing alternators, either while mounted in the airplane or on the shop test-stand. A complete unit consists of resistive and reactive loads controlled by selector switches and test meters mounted on a control panel. This load unit is compact and convenient, eliminating the difficulty of operating large loads on the airplane while testing and adjusting the alternators and control equipment.

Proper maintenance of an alternator requires that the unit be kept clean and that all electrical connections are tight and in good repair. If the alternator fails to build up voltage as designated by applicable manufacturer's technical instructions, test the voltmeter first by checking the voltages of other alternators, or by checking the voltage in the suspected alternator with another voltmeter and comparing the results. If the voltmeter is satisfactory, check the wiring, the brushes, and the drive unit for faults. If this inspection fails to reveal the trouble, the exciter may have lost its residual magnetism. Residual magnetism is restored to the exciter by flashing the field. Follow the applicable manufacturer's instructions when flashing the exciter field. If, after flashing the field, no voltage is indicated, replace the alternator, since it is probably faulty.

Clean the alternator exterior with an approved fluid; smooth a rough or pitted exciter commutator or slip ring with 000 sandpaper; then clean and polish with a clean, dry cloth. Check the brushes periodically for length and general condition. Consult the applicable manufacturer's instructions on the specific alternator to obtain information on the correct brushes.

Troubleshooting

Use the following table to assist in locating, diagnosing, and correcting alternator troubles:

Trouble	*Probable cause*	*Remedy*
Voltmeter registers no voltage.	Voltmeter defective.	Remove and replace voltmeter.
	Voltmeter regulator defective.	Replace regulator.
	Defective exciter.	Replace alternator.
Low voltage.	Improper regulator adjustment.	Adjust voltage regulator.
Erratic meter indication.	Loose connections.	Tighten connections.
	Defective meter.	Remove and replace meter.
Voltage falls off after a period of operation.	Voltage regulator not warmed up before adjustment.	Readjust voltage regulator.

INVERTERS

An inverter is used in some aircraft systems to convert a portion of the aircraft's d.c. power to a.c. This a.c. is used mainly for instruments, radio, radar, lighting, and other accessories. These inverters are usually built to supply current at a frequency of 400 c.p.s., but some are designed to provide more than one voltage; for example, 26-volt a.c. in one winding and 115 volts in another.

There are two basic types of inverters: the rotary and the static. Either type can be single-phase or multiphase. The multiphase inverter is lighter for the same power rating than the single-phase, but there are complications in distributing multiphase power and in keeping the loads balanced.

Rotary Inverters

There are many sizes, types, and configurations of rotary inverters. Such inverters are essentially a.c. generators and d.c. motors in one housing. The generator field, or armature, and the motor field, or armature, are mounted on a common shaft which will rotate within the housing. One common type of rotary inverter is the permanent magnet inverter.

Permanent Magnet Rotary Inverter

A permanent magnet inverter is composed of a d.c. motor and a permanent magnet a.c. generator assembly. Each has a separate stator mounted within a common housing. The motor armature is mounted on a rotor and connected to the d.c. supply through a commutator and brush assembly. The motor field windings are mounted on the housing and connected directly to the d.c. supply. A permanent magnet rotor is mounted at the opposite end of the same shaft as the motor armature, and the stator windings are mounted on the housing, allowing a.c. to be taken from the inverter without the use of brushes. Figure 9–60 shows an internal wiring diagram for this type of rotary inverter. The generator rotor has six poles, magnetized to provide alternate north and south poles about its circumference.

When the motor field and armature are excited, the rotor will begin to turn. As the rotor turns, the permanent magnet will rotate within the a.c. stator coils, and the magnetic flux developed by the permanent magnets will be cut by the conductors in the a.c. stator coils. An a.c. voltage will be produced in the windings whose polarity will change as each pole passes the windings.

This type inverter may be made multiphase by placing more a.c. stator coils in the housing in order to shift the phase the proper amount in each coil.

As the name of the rotary inverter indicates, it has a revolving armature in the a.c. generator section. The illustration in figure 9–61 shows the diagram of a revolving-armature, three-phase inverter.

The d.c. motor in this inverter is a four-pole, compound-wound motor. The four field coils consist of many turns of fine wire, with a few turns of heavy wire placed on top. The fine wire is the shunt field, connected to the d.c. source through a filter and to ground through a centrifugal governor. The heavy wire is the series field, which is connected in series with the motor armature. The centrifugal governor controls the speed by shunting a resistor which is in series with the shunt field when the motor reaches a certain speed.

The alternator is a three-phase, four-pole, star-connected a.c. generator. The d.c. input is supplied to the generator field coils and connected to ground through a carbon-pile voltage regulator. The output is taken off the armature through three slip rings to provide three-phase power.

The inverter would be a single-phase inverter if it had a single armature winding and one slip ring.

The frequency of this type unit is determined by the speed of the motor and the number of generator poles.

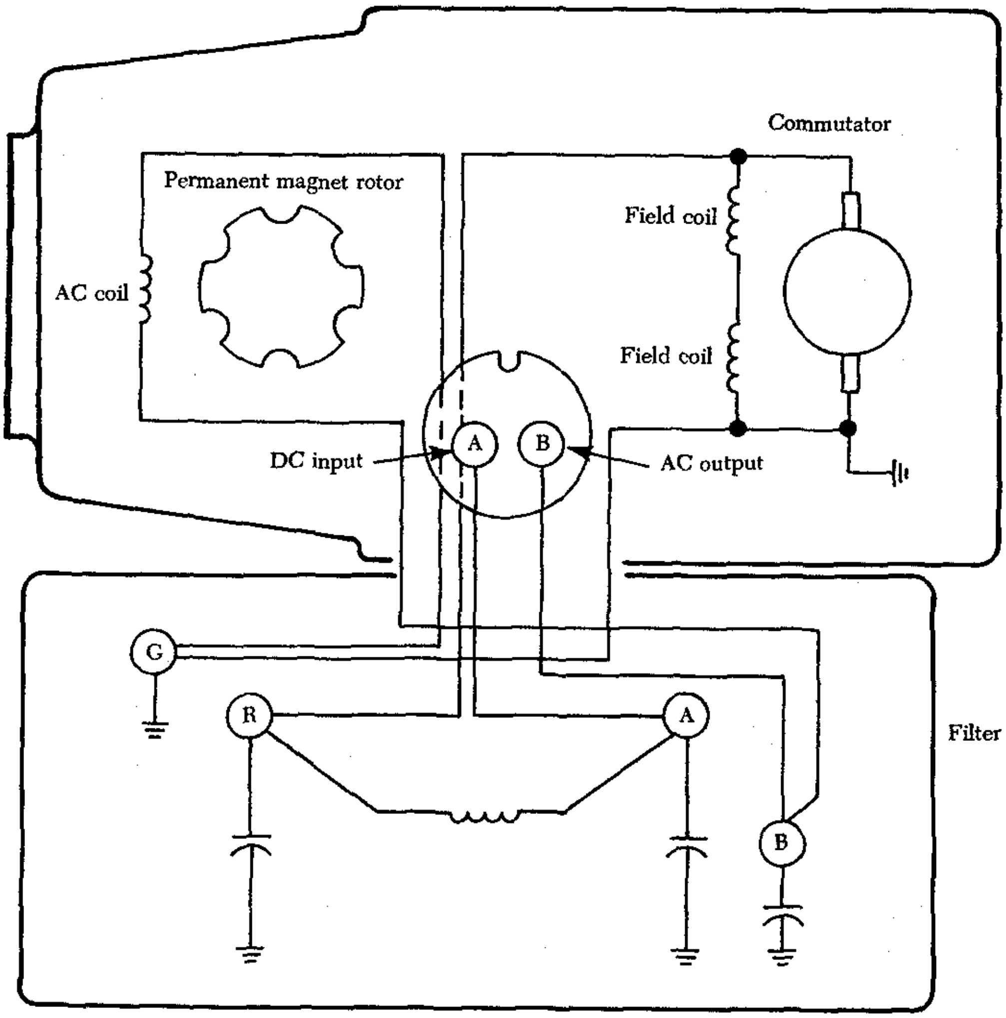


FIGURE 9-60. Internal wiring diagram of single-phase permanent magnet rotary inverter.

Inductor-Type Rotary Inverter

Inductor-type inverters use a rotor made of soft iron laminations with grooves cut laterally across the surface to provide poles that correspond to the number of stator poles, as illustrated in figure 9-62. The field coils are wound on one set of stationary poles and the a.c. armature coils on the other set of stationary poles. When d.c. is applied to the field coils, a magnetic field is produced. The rotor turns within the field coils and, as the poles on the rotor align with the stationary poles, a low reluctance path for flux is established from the field pole through the rotor poles to the a.c. armature pole and through the housing back to the field pole. In this circumstance, there will be a large amount of magnetic flux linking the a.c. coils.

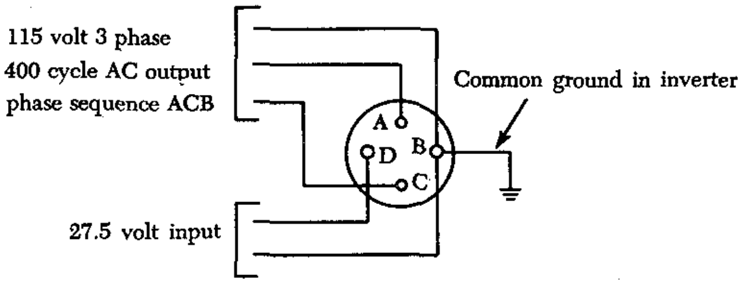
When the rotor poles are between the stationary poles, there is a high-reluctance path for flux, consisting mainly of air; then, there will be a small amount of magnetic flux linking the a.c. coils. This increase and decrease in flux density in the stator induces an alternating current in the a.c. coils.

The frequency of this type of inverter is determined by the number of poles and the speed of the motor. The voltage is controlled by the d.c. stator field current. A cutaway view of an inductor-type rotary inverter is shown in figure 9-63.

Figure 9-64 is a simplified diagram of a typical aircraft a.c. power distribution system, utilizing a main and a standby rotary inverter system.

Static Inverters

In many applications where continuous d.c. voltage must be converted to alternating voltage,



Plug rear view

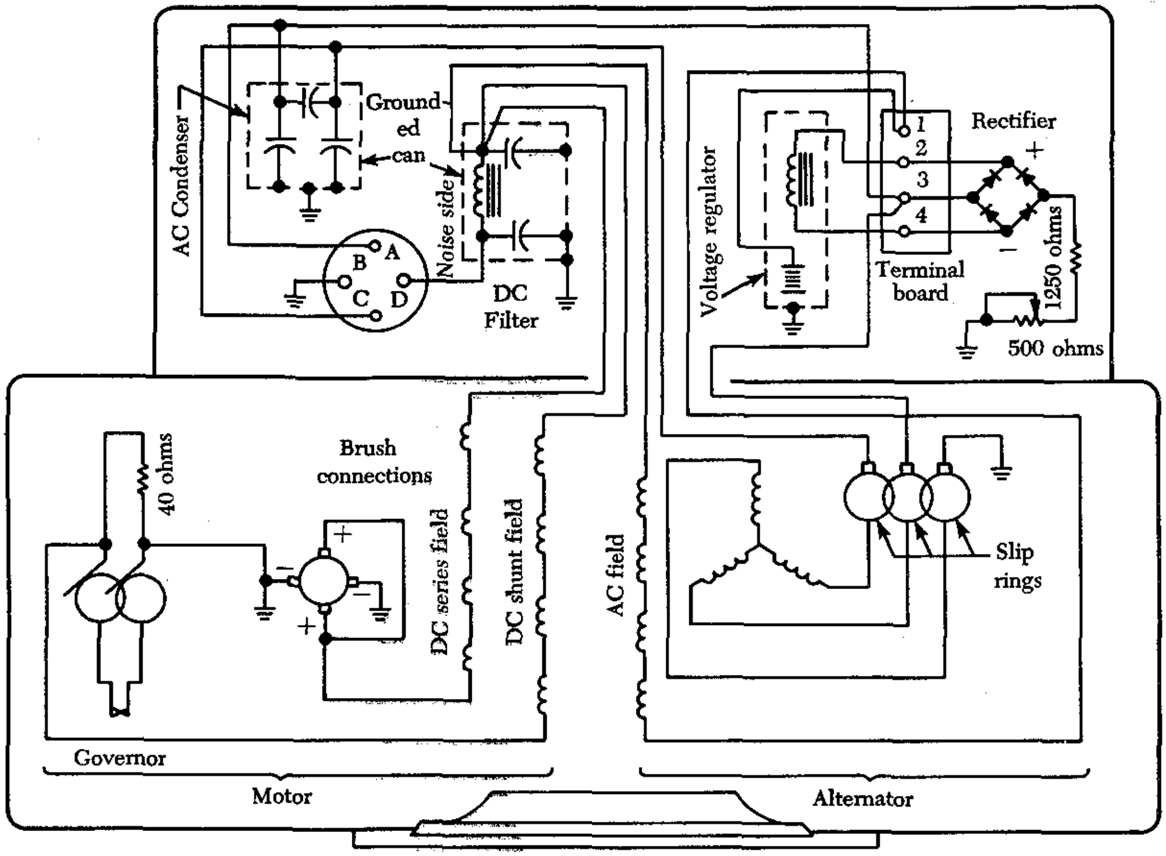


FIGURE 9–61. Internal wiring diagram of three-phase, revolving-armature inverter.

static inverters are used in place of rotary inverters or motor generator sets. The rapid progress being made by the semiconductor industry is extending the range of applications of such equipment into voltage and power ranges which would have been impractical a few years ago. Some such applications are power supplies for frequency-sensitive military and commercial a.c. equipment, aircraft emergency a.c. systems, and conversion of wide frequency range power to precise frequency power.

The use of static inverters in small aircraft also has increased rapidly in the last few years, and the technology has advanced to the point that static inverters are available for any requirement filled by rotary inverters. For example, 250 VA emergency a.c. supplies operated from aircraft batteries are in production, as are 2,500 VA main a.c. supplies operated from a varying frequency generator supply. This type of equipment has certain advantages for aircraft applications, particularly the absence of moving parts and the adaptability to conduction cooling.

Static inverters, referred to as solid-state inverters, are manufactured in a wide range of types and models, which can be classified by the shape of the a.c. output waveform and the power output capabilities. One of the most commonly used static inverters produces a regulated sine wave output. A block diagram of a typical regulated sine wave static inverter is shown in figure 9–65. This inverter converts a low d.c. voltage into higher a.c. voltage. The a.c. output voltage is held to a very small voltage tolerance, a typical variation of less than 1 percent with a full input load change. Output taps are normally provided to permit selection of various voltages; for example, taps may be provided for a 105-, 115-, and 125-volt a.c. outputs. Frequency regulation is typically within a range of one cycle for a 0–100 percent load change.

Variations of this type of static inverter are available, many of which provide a square wave output.

Since static inverters use solid-state components, they are considerably smaller, more compact, and much lighter in weight than rotary inverters. Depending on the output power rating required, static inverters that are no larger than a typical airspeed indicator can be used in aircraft systems. Some of the features of static inverters are:

1. High efficiency.
2. Low maintenance, long life.
3. No warmup period required.
4. Capable of starting under load.
5. Extremely quiet operation.
6. Fast response to load changes.

Static inverters are commonly used to provide power for such frequency-sensitive instruments as the attitude gyro and directional gyro. They also provide power for autosyn and magnesyn indicators and transmitters, rate gyros, radar, and other airborne applications. Figure 9–66 is a schematic of a typical small jet aircraft auxiliary battery system. It shows the battery as input to the inverter, and the output inverter circuits to various subsystems.

D. C. MOTORS

Most devices in an airplane, from the starter to the automatic pilot, depend upon mechanical energy furnished by direct-current motors. A direct-current motor is a rotating machine which transforms direct-current energy into mechanical energy. It consists of two principal parts—a field assembly and an armature assembly. The armature is the rotating part in which current-carrying wires are acted upon by the magnetic field.

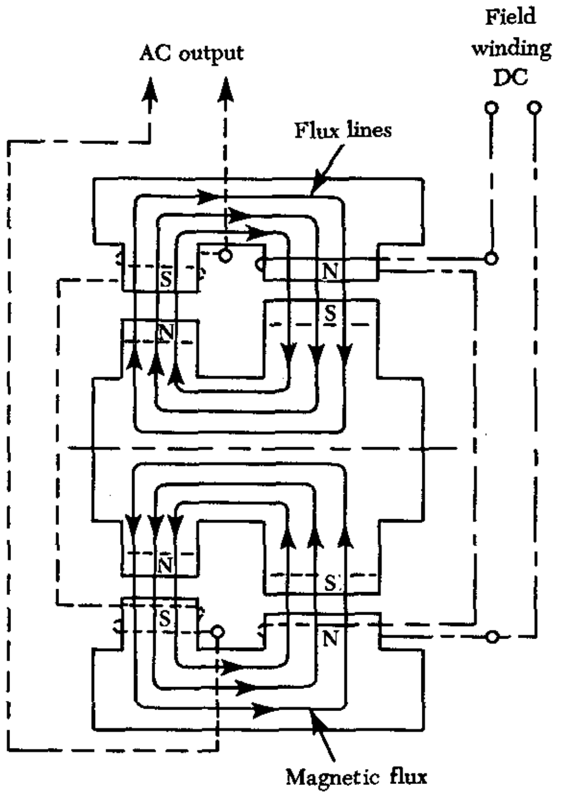


FIGURE 9–62. Diagram of basic inductor-type inverter.

Whenever a current-carrying wire is placed in the field of a magnet, a force acts on the wire. The force is not one of attraction or repulsion; however, it is at right angles to the wire and also at right angles to the magnetic field set up by the magnet.

The action of the force upon a current-carrying wire placed in a magnetic field is shown in figure 9–67. A wire is located between two permanent magnets. The lines of force in the magnetic field are from the north pole to the south pole. When no current flows, as in diagram *A*, no force is exerted on the wire, but when current flows through the wire, a magnetic field is set up about it, as shown in diagram *B*. The direction of the field depends on the direction of current flow. Current in one direction creates a clockwise field about the wire, and current in the other direction, a counterclockwise field.

Since the current-carrying wire produces a magnetic field, a reaction occurs between the field

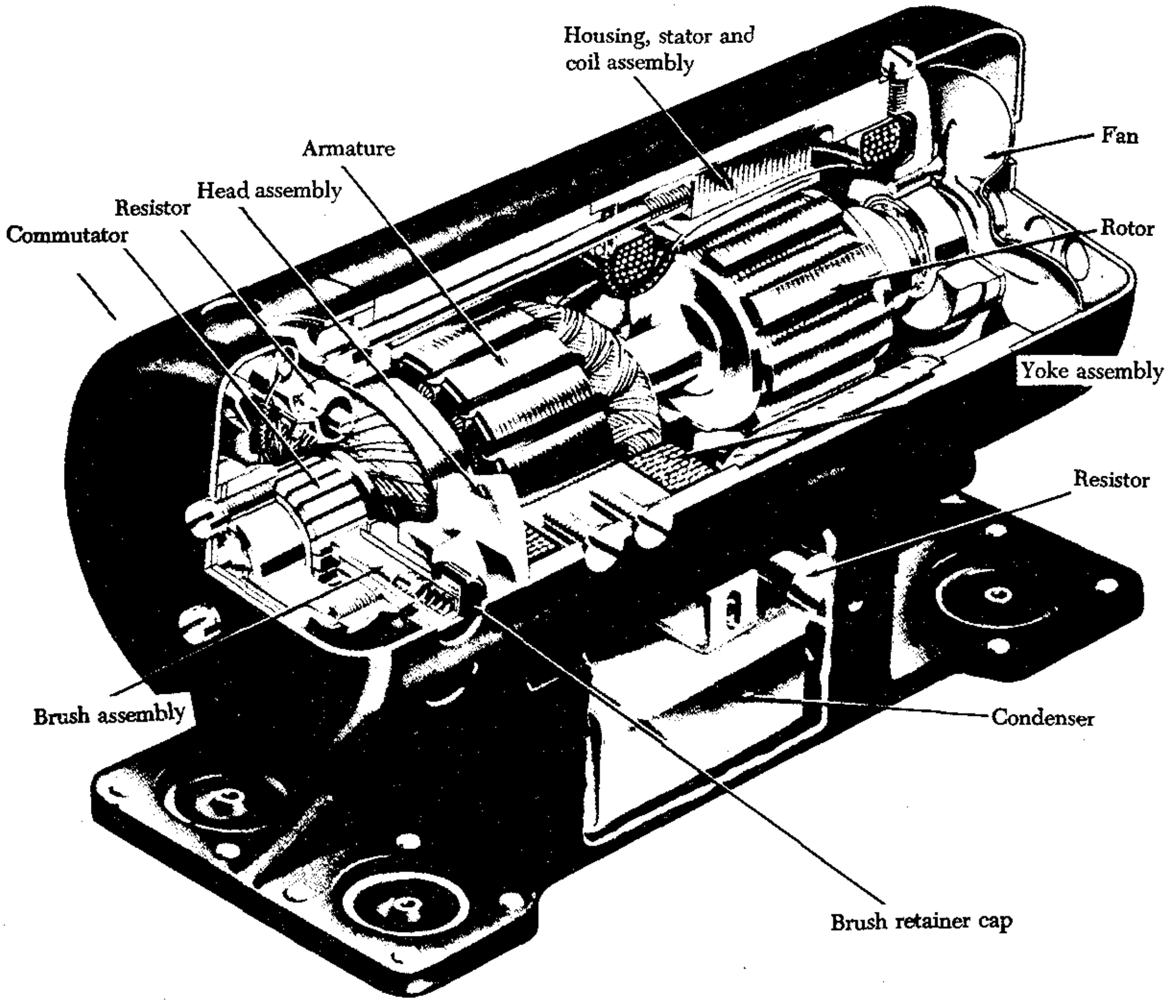


FIGURE 9–63. Cutaway view of inductor-type rotary inverter.

about the wire and the magnetic field between the magnets. When the current flows in a direction to create a counterclockwise magnetic field about the wire, this field and the field between the magnets add or reinforce at the bottom of the wire because the lines of force are in the same direction. At the top of the wire, they subtract or neutralize, since the lines of force in the two fields are opposite in direction. Thus, the resulting field at the bottom is strong and the one at the top is weak. Consequently, the wire is pushed upward as shown in diagram *C* of figure 9–67. The wire is always pushed away from the side where the field is strongest.

If current flow through the wire were reversed in direction, the two fields would add at the top and subtract at the bottom. Since a wire is always pushed away from the strong field, the wire would be pushed down.

Force Between Parallel Conductors

Two wires carrying current in the vicinity of one another exert a force on each other because of their magnetic fields. An end view of two conductors is shown in figure 9–68. In *A*, electron flow in both conductors is toward the reader, and the magnetic fields are clockwise around the conductors. Between the wires, the fields cancel because the directions of the two fields oppose each other. The wires are forced in the direction of the weaker field, toward each other. This force is one of attraction.

In *B*, the electron flow in the two wires is in opposite directions. The magnetic fields are,

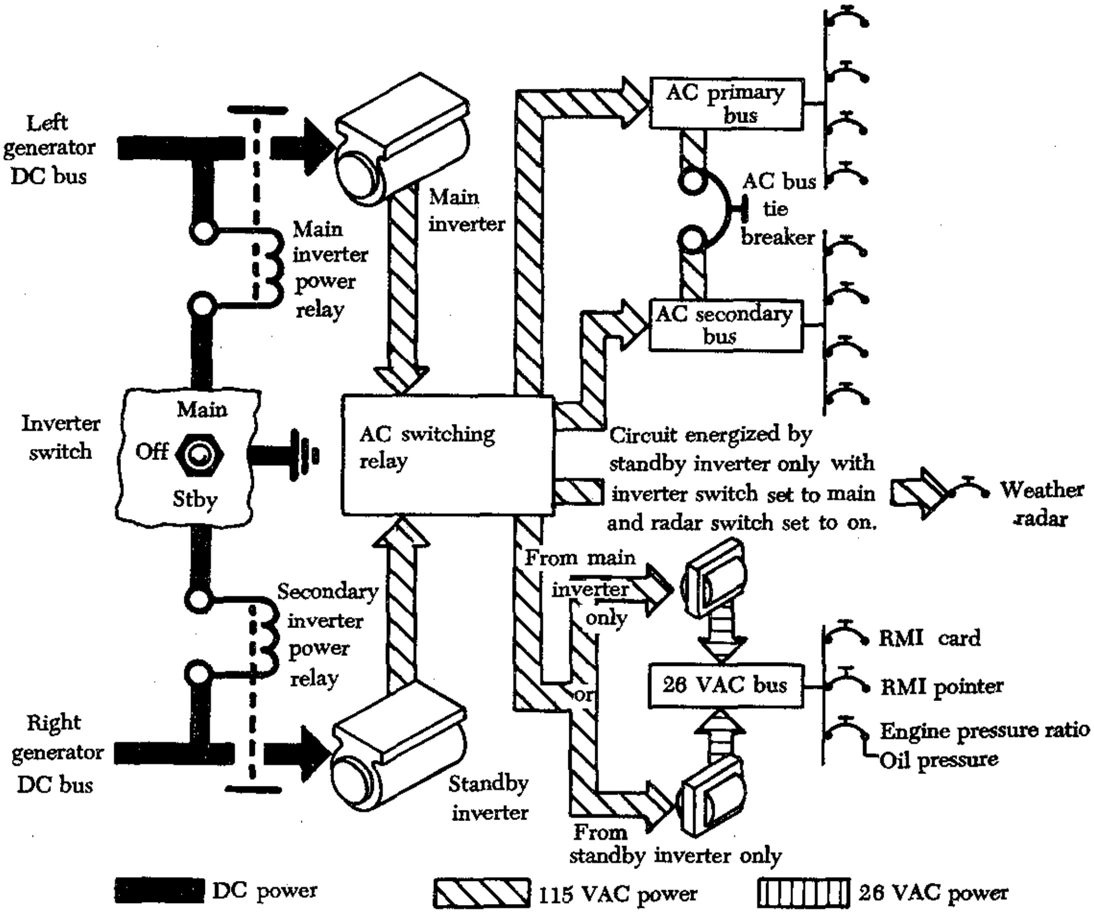


FIGURE 9–64. A typical aircraft a.c. power distribution system using main and standby rotary inverters.

therefore, clockwise in one and counterclockwise in the other, as shown. The fields reinforce each other between the wires, and the wires are forced in the direction of the weaker field, away from each other. This force is one of repulsion.

To summarize: Conductors carrying current in the same direction tend to be drawn together; conductors carrying current in opposite directions tend to be repelled from each other.

Developing Torque

If a coil in which current is flowing is placed in a magnetic field, a force is produced which will cause

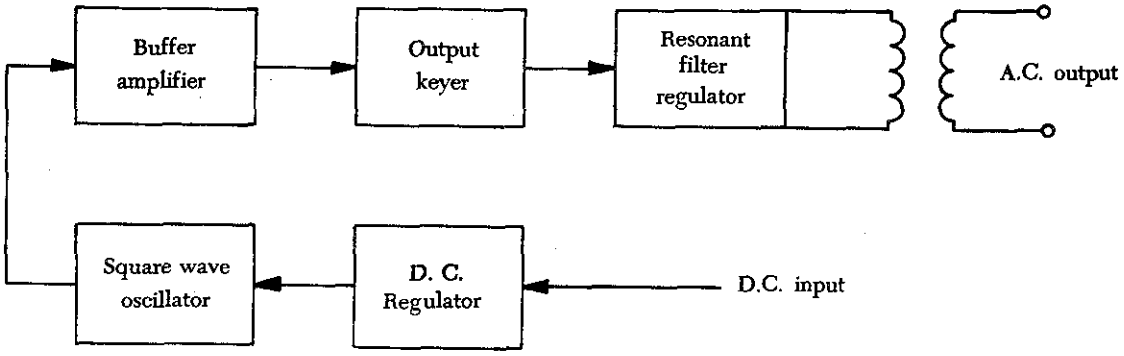


FIGURE 9–65. Regulated sine wave static inverter.

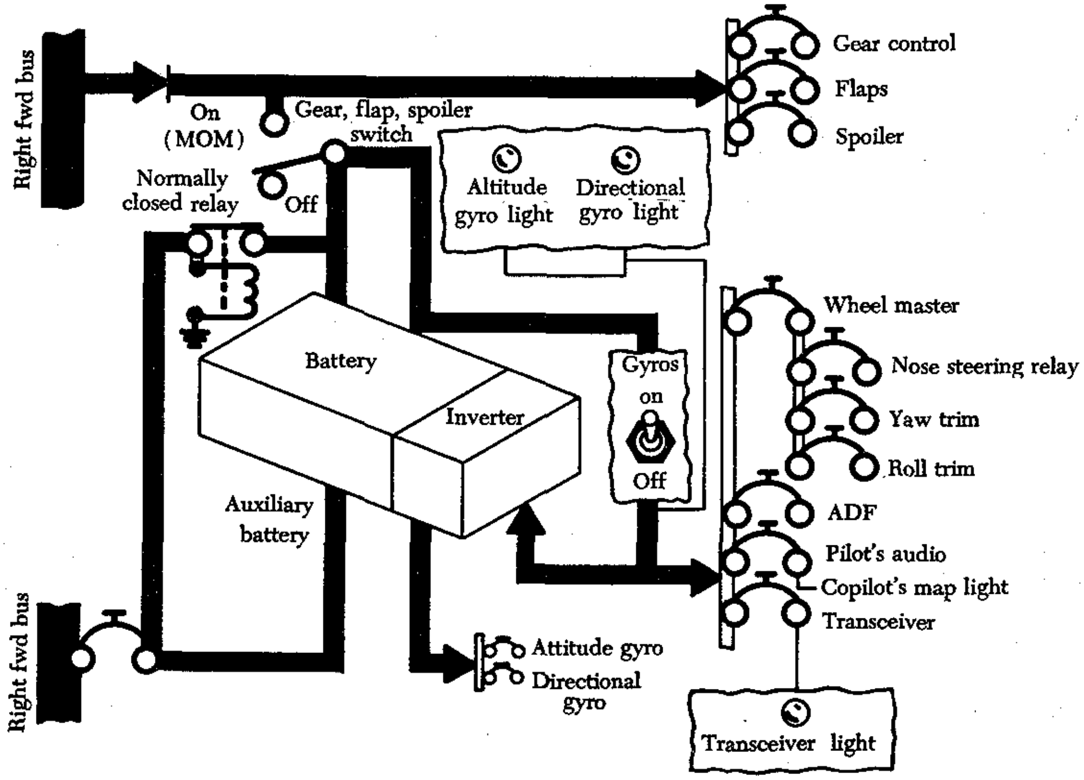
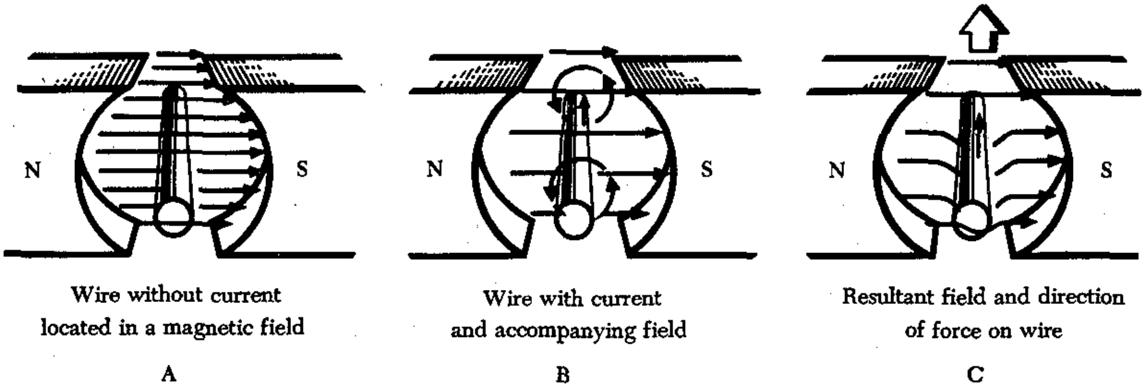


FIGURE 9–66. Auxiliary battery system using static inverter.

the coil to rotate. In the coil shown in figure 9–69, current flows inward on side *A* and outward on side *B*. The magnetic field about *B* is clockwise and that about *A*, counterclockwise. As previously explained, a force will develop which pushes side *B* downward. At the same time, the field of the magnets and the field about *A*, in which the current is inward, will add at the bottom and subtract at the top. Therefore, *A* will move upward. The coil will thus rotate until its plane is perpendicular to the magnetic lines between the north and south poles of the magnet, as indicated in figure 9–69 by the white coil at right angles to the black coil.

The tendency of a force to produce rotation is called torque. When the steering wheel of a car is



Wire without current located in a magnetic field

A

Wire with current and accompanying field

B

Resultant field and direction of force on wire

C

FIGURE 9–67. Force on a current-carrying wire

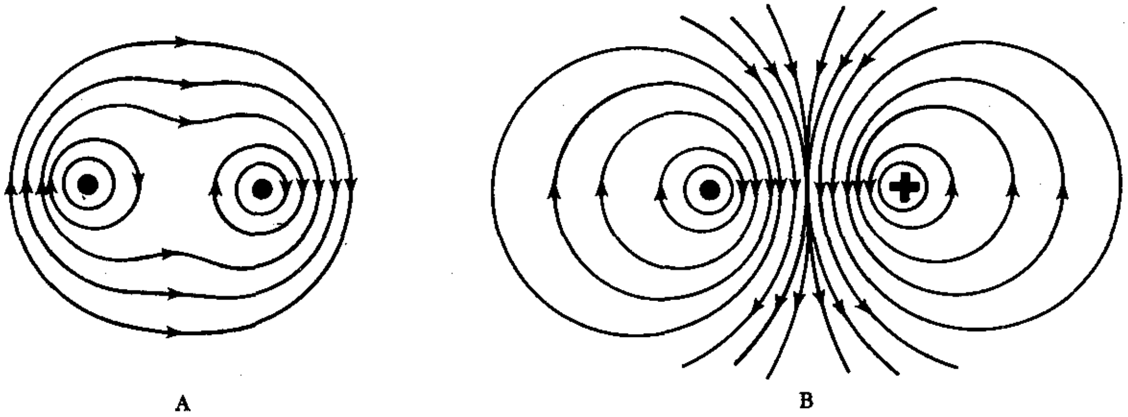


FIGURE 9-68. Fields surrounding parallel conductors.

turned, torque is applied. The engine of an airplane gives torque to the propeller. Torque is developed also by the reacting magnetic fields about the current-carrying coil just described. This is the torque which turns the coil.

The right-hand motor rule can be used to determine the direction a current-carrying wire will move in a magnetic field. As illustrated in figure 9-70, if the index finger of the right hand is pointed in the direction of the magnetic field and the second finger in the direction of current flow, the thumb will indicate the direction the current-carrying wire will move.

The amount of torque developed in a coil depends upon several factors: the strength of the magnetic field, the number of turns in the coil, and the position of the coil in the field. Magnets are made of special steel which produces a strong field. Since there is a torque acting on each turn, the greater the number of turns on the coil, the greater the torque. In a coil carrying a steady current located in a uniform magnetic field, the torque will vary at successive positions of rotation, as shown in figure 9-71. When the plane of the coil is parallel to the lines of force, the torque is zero. When its plane cuts the lines of force at right angles, the torque is 100 percent. At intermediate positions, the torque ranges between zero and 100 percent.

Basic D. C. Motor

A coil of wire through which the current flows will rotate when placed in a magnetic field. This is the technical basis governing the construction of a d.c. motor. Figure 9-72 shows a coil mounted in a magnetic field in which it can rotate. However, if the connecting wires from the battery were permanently fastened to the terminals of the coil and there was a flow of current, the coil would rotate only until it lined itself up with the magnetic field. Then, it would stop, because the torque at that point would be zero. A motor, of course,

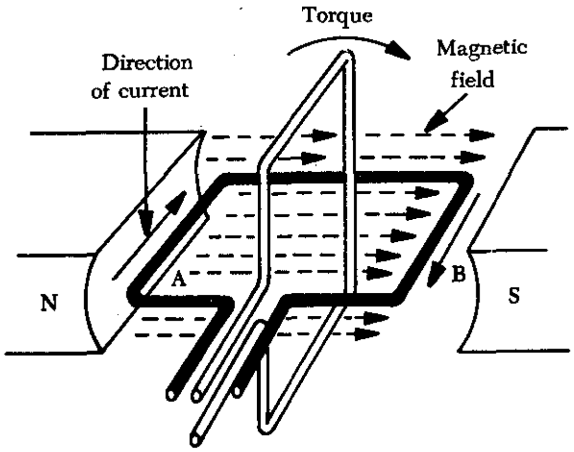


FIGURE 9-69. Developing a torque.

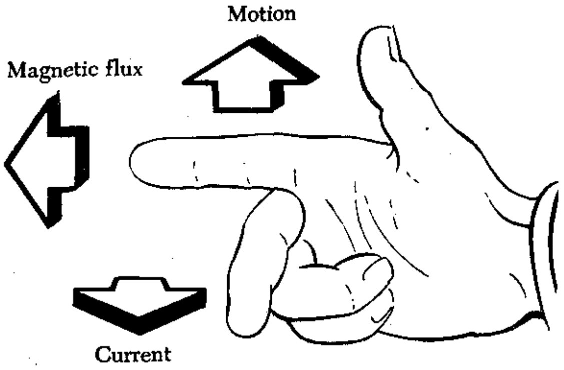


FIGURE 9-70. Right-hand motor rule.

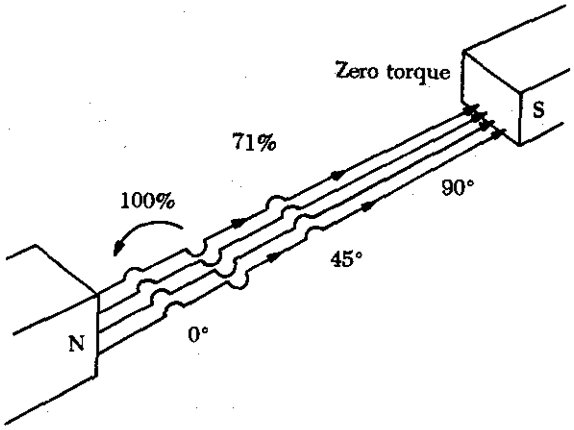


FIGURE 9–71. Torque on a coil at various angles of rotation.

must continue rotating. It is necessary, therefore, to design a device that will reverse the current in the coil just at the time the coil becomes parallel to the lines of force. This will create torque again and cause the coil to rotate. If the current-reversing device is set up to reverse the current each time the coil is about to stop, the coil can be made to continue rotating as long as desired.

One method of doing this is to connect the circuit so that, as the coil rotates, each contact slides off the terminal to which it connects and slides onto the terminal of opposite polarity. In other words, the coil contacts switch terminals continuously as the coil rotates, preserving the torque and keeping the coil rotating. In figure 9–72, the coil terminal segments are labeled *A* and *B*. As the coil rotates, the segments slide onto and past the fixed terminals or brushes. With this arrangement, the direction of current in the side of the coil next to the north seeking pole flows toward the reader, and the force acting on that side of the coil turns it downward. The part of the motor which changes the current from one wire to another is called the commutator.

When the coil is positioned as shown in *A* of figure 9–72, current will flow from the negative terminal of the battery to the negative (−) brush, to segment *B* of the commutator, through the loop to segment *A* of the commutator, to the positive (+) brush, and then, back to the positive terminal of the battery. By using the right-hand motor rule, it is seen that the coil will rotate counterclockwise. The torque at this position of the coil is maximum, since the greatest number of lines of force are being cut by the coil.

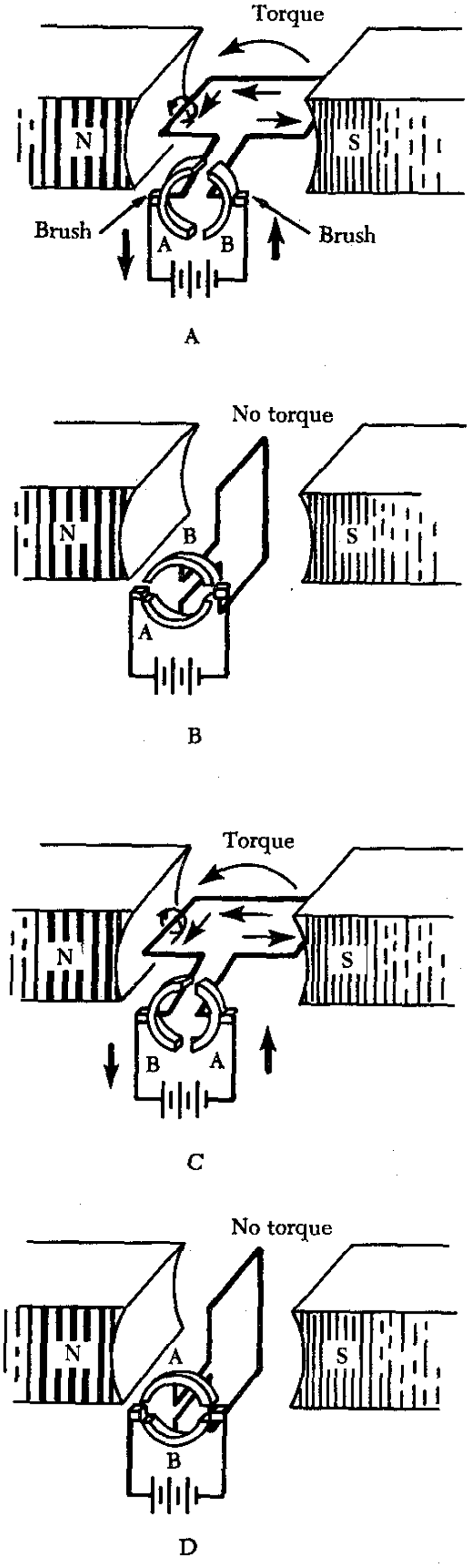


FIGURE 9–72. Basic d.c. motor operation.

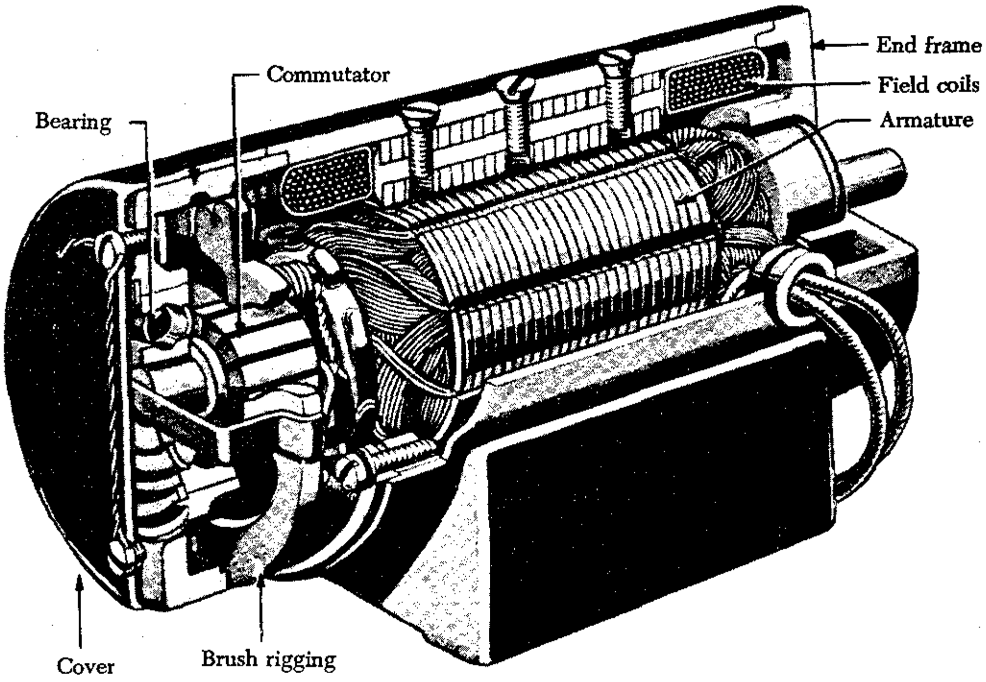


FIGURE 9–73. Cutaway view of practical d.c. motor.

When the coil has rotated 90° to the position shown in *B* of figure 9–72, segments *A* and *B* of the commutator no longer make contact with the battery circuit and no current can flow through the coil. At this position, the torque has reached a minimum value, since a minimum number of lines of force are being cut. However, the momentum of the coil carries it beyond this position until the segments again make contact with the brushes, and current again enters the coil; this time, though, it enters through segment *A* and leaves through segment *B*. However, since the positions of segments *A* and *B* have also been reversed, the effect of the current is as before, the torque acts in the same direction, and the coil continues its counterclockwise rotation. On passing through the position shown in *C* of figure 9–72, the torque again reaches maximum. Continued rotation carries the coil again to a position of minimum torque, as in *D* of figure 9–72. At this position, the brushes no longer carry current, but once more the momentum rotates the coil to the point where current enters through segment *B* and leaves through *A*. Further rotation brings the coil to the starting point and, thus, one revolution is completed.

The switching of the coil terminals from the positive to the negative brushes occurs twice per revolution of the coil.

The torque in a motor containing only a single coil is neither continuous nor very effective, for there are two positions where there is actually no torque at all. To overcome this, a practical d.c. motor contains a large number of coils wound on the armature. These coils are so spaced that, for any position of the armature, there will be coils near the poles of the magnet. This makes the torque both continuous and strong. The commutator, likewise, contains a large number of segments instead of only two.

The armature in a practical motor is not placed between the poles of a permanent magnet but between those of an electromagnet, since a much stronger magnetic field can be furnished. The core is usually made of a mild or annealed steel, which can be magnetized strongly by induction. The current magnetizing the electromagnet is from the same source that supplies the current to the armature.

D. C. Motor Construction

The major parts in a practical motor are the armature assembly, the field assembly, the brush assembly, and the end frame. (See figure 9–73.)

Armature Assembly

The armature assembly contains a laminated, soft-iron core, coils, and a commutator, all

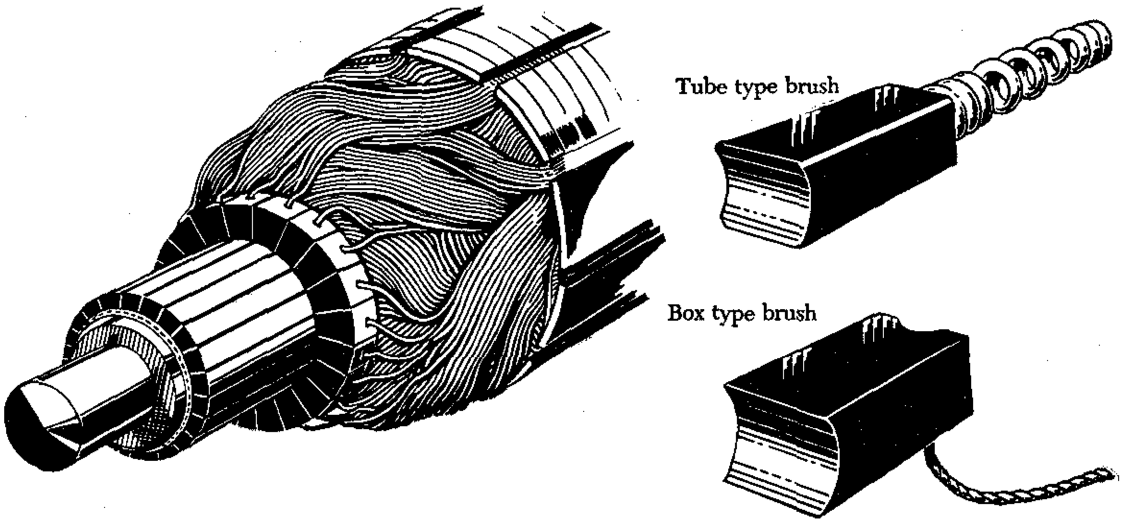


FIGURE 9–74. Commutator and brushes.

mounted on a rotatable steel shaft. Laminations made of stacks of soft iron, insulated from each other, form the armature core. Solid iron is not used, since a solid-iron core revolving in the magnetic field would heat and use energy needlessly. The armature windings are insulated copper wire, which are inserted in slots insulated with fiber paper (fish paper) to protect the windings. The ends of the windings are connected to the commutator segments. Wedges or steel bands hold the windings in place to prevent them from flying out of the slots when the armature is rotating at high speeds. The commutator consists of a large number of copper segments insulated from each other and the armature shaft by pieces of mica. Insulated wedge rings hold the segments in place.

Field Assembly

The field assembly consists of the field frame, the pole pieces, and the field coils. The field frame is located along the inner wall of the motor housing. It contains laminated soft steel pole pieces on which the field coils are wound. A coil, consisting of several turns of insulated wire, fits over each pole piece and, together with the pole, constitutes a field pole. Some motors have as few as two poles, others as many as eight.

Brush Assembly

The brush assembly consists of the brushes and their holders. The brushes are usually small blocks of graphitic carbon, since this material has a long service life and also causes minimum wear to the commutator. The holders permit some play in the brushes so they can follow any irregularities in the surface of the commutator and make good contact. Springs hold the brushes firmly against the commutator. A commutator and two types of brushes are shown in figure 9–74.

End Frame

The end frame is the part of the motor opposite the commutator. Usually, the end frame is designed so that it can be connected to the unit to be driven. The bearing for the drive end is also located in the end frame. Sometimes the end frame is made a part of the unit driven by the motor. When this is done, the bearing on the drive end may be located in any one of a number of places.

TYPES OF D. C. MOTORS

There are three basic types of d.c. motors: (1) Series motors, (2) shunt motors, and (3) compound motors. They differ largely in the method in which their field and armature coils are connected.

Series D. C. Motor

In the series motor, the field windings, consisting of a relatively few turns of heavy wire, are connected in series with the armature winding. Both a diagrammatic and a schematic illustration of a series motor is shown in figure 9–75. The same current flowing through the field winding also flows

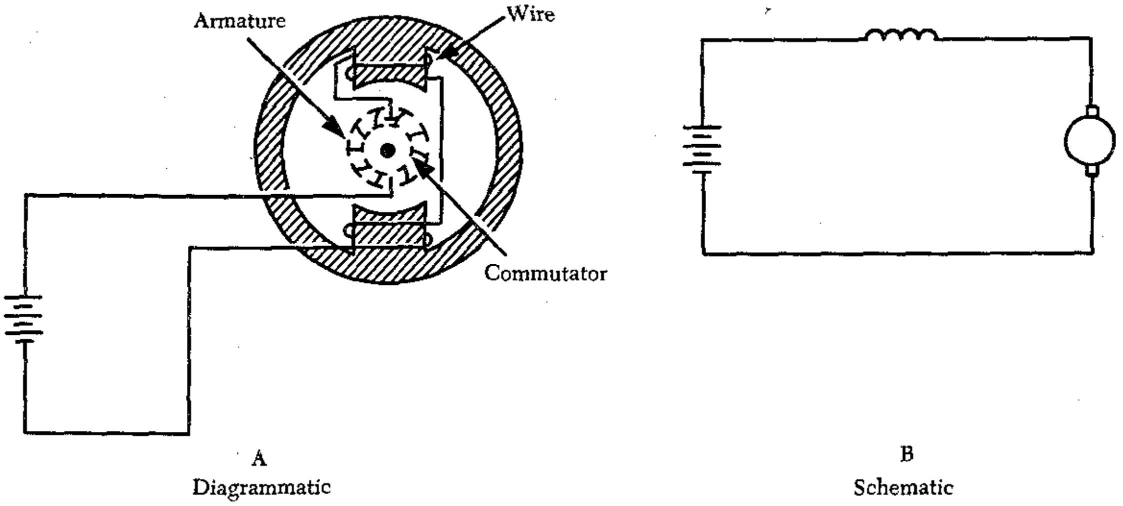


FIGURE 9–75. Series motor.

through the armature winding. Any increase in current, therefore, strengthens the magnetism of both the field and the armature.

Because of the low resistance in the windings, the series motor is able to draw a large current in starting. This starting current, in passing through both the field and armature windings, produces a high starting torque, which is the series motor's principal advantage.

The speed of a series motor is dependent upon the load. Any change in load is accompanied by a substantial change in speed. A series motor will run at high speed when it has a light load and at low speed with a heavy load. If the load is removed entirely, the motor may operate at such a high speed that the armature will fly apart. If high starting torque is needed under heavy load conditions, series motors have many applications. Series motors are often used in aircraft as engine starters and for raising and lowering landing gears, cowl flaps, and wing flaps.

Shunt D. C. Motor

In the shunt motor the field winding is connected in parallel or in shunt with the armature winding. (See figure 9–76) The resistance in the field winding is high. Since the field winding is connected directly across the power supply, the current through the field is constant. The field current does not vary with motor speed, as in the series motor and, therefore, the torque of the shunt motor will

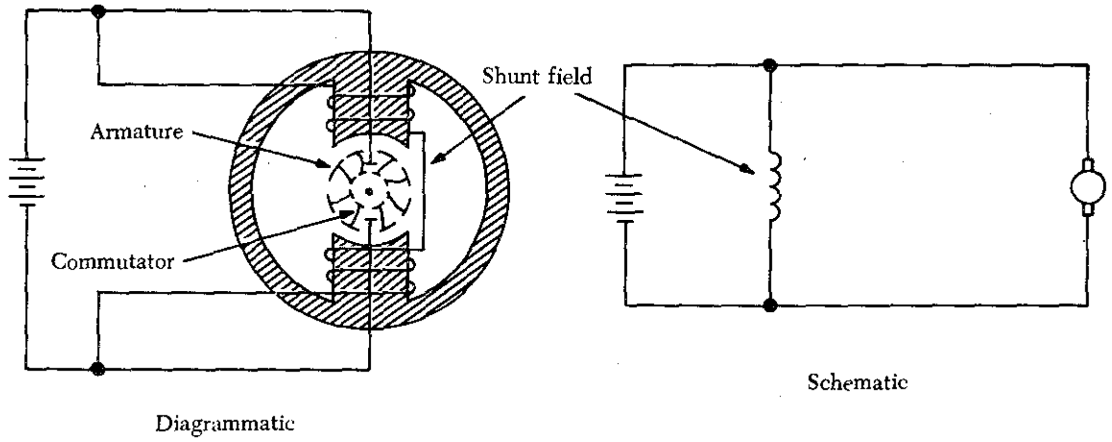


FIGURE 9–76. Shunt motor.

vary only with the current through the armature. The torque developed at starting is less than that developed by a series motor of equal size.

The speed of the shunt motor varies very little with changes in load. When all load is removed, it assumes a speed slightly higher than the loaded speed. This motor is particularly suitable for use when constant speed is desired and when high starting torque is not needed.

Compound D. C. Motor

The compound motor is a combination of the series and shunt motors. There are two windings in the field: a shunt winding and a series winding. A schematic of a compound motor is shown in figure 9–77. The shunt winding is composed of many turns of fine wire and is connected in parallel with the armature winding. The series winding consists of a few turns of large wire and is connected in series with the armature winding. The starting torque is higher than in the shunt motor but lower than in the series motor. Variation of speed with load is less than in a series-wound motor but greater than in a shunt motor. The compound motor is used whenever the combined characteristics of the series and shunt motors are desired.

Like the compound generator, the compound motor has both series and shunt field windings. The series winding may either aid the shunt wind (cumulative compound) or oppose the shunt winding (differential compound).

The starting and load characteristics of the cumulative-compound motor are somewhere between those of the series and those of the shunt motor.

Because of the series field, the cumulative-compound motor has a higher starting torque than a shunt motor. Cumulative-compound motors are used in driving machines which are subject to sudden changes in load. They are also used where a high starting torque is desired, but a series motor cannot be used easily.

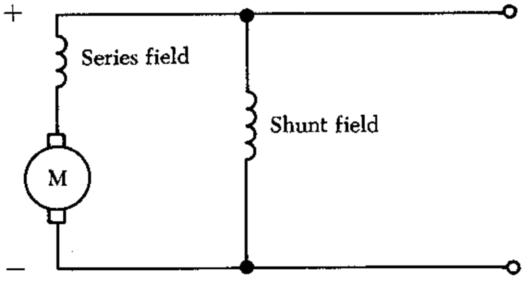


FIGURE 9–77. Compound motor.

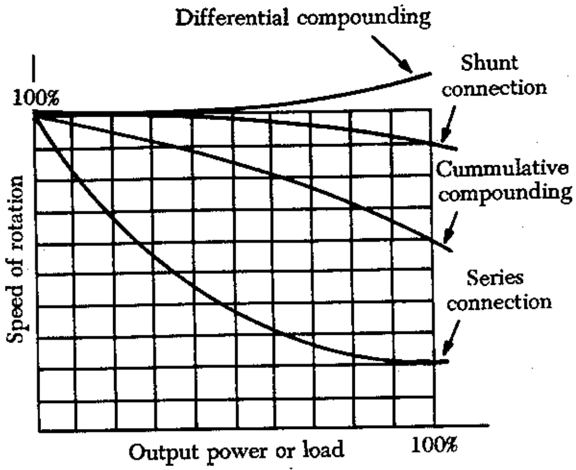


FIGURE 9–78. Load characteristics of d.c. motors.

In the differential compound motor, an increase in load creates an increase in current and a decrease in total flux in this type of motor. These two tend to offset each other and the result is a practically constant speed. However, since an increase in load tends to decrease the field strength, the speed characteristic becomes unstable. Rarely is this type of motor used in aircraft systems.

A graph of the variation in speed with changes of load of the various types of d.c. motors is shown in figure 9–78.

Counter E. M. F.

The armature resistance of a small, 28-volt d.c. motor is extremely low, about 0.1 ohm. When the armature is connected across the 28-volt source, current through the armature will apparently be

$$I = \frac{E}{R} = \frac{28}{0.1} = 280 \text{ amperes.}$$

This high valve of current flow is not only impracticable but also unreasonable, especially when the current drain, during normal operation of a motor, is found to be about 4 amperes. This is because the current through a motor armature during operation is determined by more factors than ohmic resistance.

When the armature in a motor rotates in a magnetic field, a voltage is induced in its windings. This voltage is called the back or counter e.m.f. (electromotive force) and is opposite in direction to the voltage applied to the motor from the external source. Counter e.m.f. opposes the current which causes the armature to rotate. The current flowing through the armature, therefore, decreases as the counter e.m.f. increases. The faster the armature rotates, the greater the counter e.m.f. For this reason, a motor connected to a battery may draw a fairly high current on starting, but as the armature speed increases, the current flowing through the armature decreases. At rated speed, the counter e.m.f. may be only a few volts less than the battery voltage. Then, if the load on the motor is increased, the motor will slow down, less counter e.m.f. will be generated, and the current drawn from the external source will increase. In a shunt motor, the counter e.m.f. affects only the current in the armature, since the field is connected in parallel across the power source. As the motor slows down and the counter e.m.f. decreases, more current flows through the armature, but the magnetism in the field is unchanged. When the series motor slows down, the counter e.m.f. decreases and more current flows through the field and the armature, thereby strengthening their magnetic fields. Because of these characteristics, it is more difficult to stall a series motor than a shunt motor.

Types of Duty

Electric motors are called upon to operate under various conditions. Some motors are used for intermittent operation; others operate continuously. Motors built for intermittent duty can be operated for short periods only and, then, must be allowed to cool before being operated again. If such a motor is operated for long periods under full load, the motor will be overheated. Motors built for continuous duty may be operated at rated power for long periods.

Reversing Motor Direction

By reversing the direction of current flow in either the armature or the field windings, the direction of a motor's rotation may be reversed. This will reverse the magnetism of either the armature or the magnetic field in which the armature rotates. If the wires connecting the motor to an external source are interchanged, the direction of rotation will not be reversed, since changing these wires reverses the magnetism of both field and armature and leaves the torque in the same direction as before.

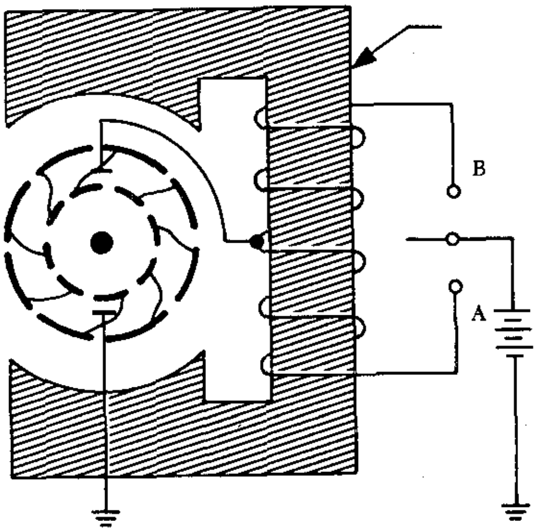


FIGURE 9–79. Split field series motor.

One method for reversing direction of rotation employs two field windings wound in opposite directions on the same pole. This type of motor is called a split field motor. Figure 9–79 shows a series motor with a split field winding. The single-pole, double-throw switch makes it possible to direct current through either of the two windings. When the switch is placed in the lower position, current flows through the lower field winding, creating a north pole at the lower field winding and at the lower pole piece, and a south pole at the upper pole piece. When the switch is placed in the upper position, current flows through the upper field winding, the magnetism of the field is reversed, and the armature rotates in the opposite direction. Some split field motors are built with two separate field windings wound on alternate poles. The armature in such a motor, a four-pole reversible motor, rotates in one direction when current flows through the windings of one set of opposite pole pieces, and in the opposite direction when current flows through the other set of windings.

Another method of direction reversal, called the switch method, employs a double-pole, double-throw switch which changes the direction of current flow in either the armature or the field. In the illustration of the switch method shown in figure 9–80, current direction may be reversed through the field but not through the armature.

When the switch is thrown to the "up" position, current flows through the field winding to establish a north pole at the right side of the motor and a

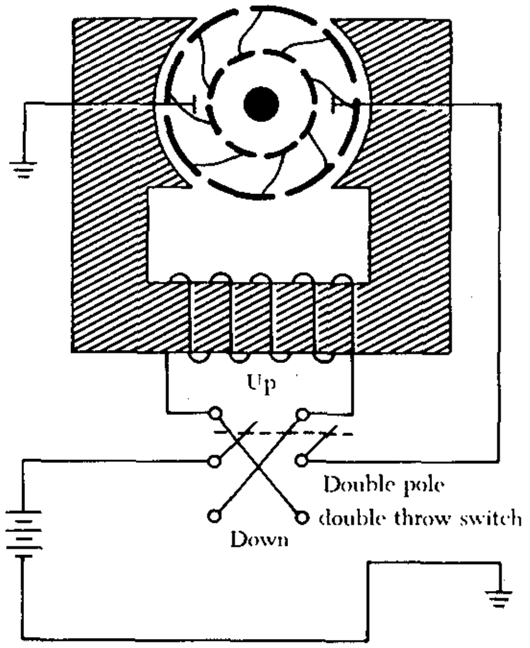


FIGURE 9–80. Switch method of reversing motor direction.

south pole at the left side of the motor. When the switch is thrown to the "down" position, this polarity is reversed and the armature rotates in the opposite direction.

Motor Speed

Motor speed can be controlled by varying the current in the field windings. When the amount of current flowing through the field windings is increased, the field strength increases, but the motor slows down since a greater amount of counter e.m.f. is generated in the armature windings. When the field current is decreased, the field strength decreases, and the motor speeds up because the counter e.m.f. is reduced. A motor in which speed can be controlled is called a variable-speed motor. It may be either a shunt or series motor.

In the shunt motor, speed is controlled by a rheostat in series with the field windings (figure 9–81). The speed depends on the amount of current which flows through the rheostat to the field windings. To increase the motor speed, the resistance in the rheostat is increased, which decreases the field current. As a result, there is a decrease in the strength of the magnetic field and in the counter e.m.f. This momentarily increases the armature current and the torque. The motor will then automatically speed up until the counter e.m.f. increases and causes the armature current to decrease to its former value. When this occurs, the motor will operate at a higher fixed speed than before.

To decrease the motor speed, the resistance of the rheostat is decreased. More current flows through the field windings and increases the strength of the field; then, the counter e.m.f. increases momentarily and decreases the armature current. As a result, the torque decreases and the motor slows down until the counter e.m.f. decreases to its former value; then the motor operates at a lower fixed speed than before.

In the series motor (figure 9–82), the rheostat speed control is connected either in parallel or in series with the motor field, or in parallel with the armature. When the rheostat is set for maximum resistance, the motor speed is increased in the parallel armature connection by a decrease in current. When the rheostat resistance is maximum in the series connection, motor speed is reduced by a reduction in voltage across the motor. For above-normal speed operation, the rheostat is in parallel with the series field. Part of the series field current is bypassed and the motor speeds up.

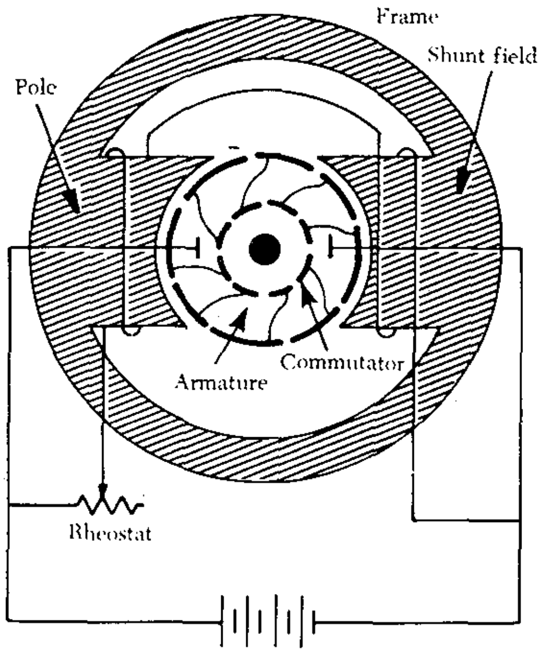


FIGURE 9–81. Shunt motor with variable speed control.

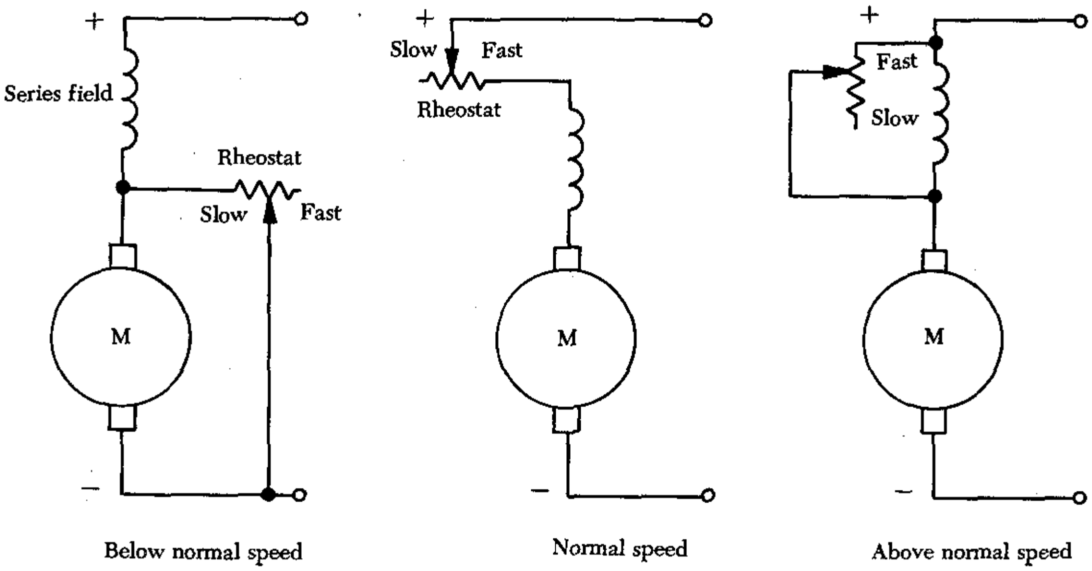


FIGURE 9–82. Controlling the speed of a series d.c. motor.

Energy Losses in D. C. Motors

Losses occur when electrical energy is converted to mechanical energy (in the motor), or mechanical energy is converted to electrical energy (in the generator). For the machine to be efficient, these losses must be kept to a minimum. Some losses are electrical, others are mechanical. Electrical losses are classified as copper losses and iron losses; mechanical losses occur in overcoming the friction of various parts of the machine.

Copper losses occur when electrons are forced through the copper windings of the armature and the field. These losses are proportional to the square of the current. They are sometimes called I^2R losses, since they are due to the power dissipated in the form of heat in the resistance of the field and armature windings.

Iron losses are subdivided in hysteresis and eddy current losses. Hysteresis losses are caused by the armature revolving in an alternating magnetic field. It, therefore, becomes magnetized first in one direction and then in the other. The residual magnetism of the iron or steel of which the armature is made causes these losses. Since the field magnets are always magnetized in one direction (d.c. field), they have no hysteresis losses.

Eddy current losses occur because the iron core of the armature is a conductor revolving in a magnetic field. This sets up an e.m.f. across portions of the core, causing currents to flow within the core. These currents heat the core and, if they become excessive, may damage the windings. As far as the output is concerned, the power consumed by eddy currents is a loss. To reduce eddy currents to a minimum, a laminated core usually is used. A laminated core is made of thin sheets of iron electrically insulated from each other. The insulation between laminations reduces eddy currents, because it is "transverse" to the direction in which these currents tend to flow. However, it has no effect on the magnetic circuit. The thinner the laminations, the more effectively this method reduces eddy current losses.

Inspection and Maintenance of D. C. Motors

Use the following procedures to make inspection and maintenance checks:

1. Check the operation of the unit driven by the motor in accordance with the instructions covering the specific installation.
2. Check all wiring, connections, terminals, fuses, and switches for general condition and security.
3. Keep motors clean and mounting bolts tight.
4. Check brushes for condition, length, and spring tension. Minimum brush lengths, correct spring tension, and procedures for replacing brushes are given in the applicable manufacturer's instructions.

5. Inspect commutator for cleanness, pitting, scoring, roughness, corrosion or burning. Check for high mica (if the copper wears down below the mica, the mica will insulate the brushes from the commutator). Clean dirty commutators with a cloth moistened with the recommended cleaning solvent. Polish rough or corroded commutators with fine sandpaper (000 or finer) and blow out with compressed air. Never use emery paper since it contains metallic particles which may cause shorts. Replace the motor if the commutator is burned, badly pitted, grooved, or worn to the extent that the mica insulation is flush with the commutator surface.
6. Inspect all exposed wiring for evidence of overheating. Replace the motor if the insulation on leads or windings is burned, cracked, or brittle.
7. Lubricate only if called for by the manufacturer's instructions covering the motor. Most motors used in today's airplanes require no lubrication between overhauls.
8. Adjust and lubricate the gearbox, or unit which the motor drives, in accordance with the applicable manufacturer's instructions covering the unit.

When trouble develops in a d.c. motor system, check first to determine the source of the trouble. Replace the motor only when the trouble is due to a defect in the motor itself. In most cases, the failure of a motor to operate is caused by a defect in the external electrical circuit, or by mechanical failure in the mechanism driven by the motor.

Check the external electrical circuit for loose or dirty connections and for improper connection of wiring. Look for open circuits, grounds, and shorts by following the applicable manufacturer's circuit-testing procedure. If the fuse is not blown, failure of the motor to operate is usually due to an open circuit. A blown fuse usually indicates an accidental ground or short circuit. The chattering of the relay switch which controls the motor is usually caused by a low battery. When the battery is low, the open-circuit voltage of the battery is sufficient to close the relay, but with the heavy current draw of the motor, the voltage drops below the level required to hold the relay closed. When the relay opens, the voltage in the battery increases enough to close the relay again. This cycle repeats and causes chattering, which is very harmful to the relay switch, due to the heavy current causing an arc which will burn the contacts.

Check the unit driven by the motor for failure of the unit or drive mechanism. If the motor has failed as a result of a failure in the driven unit, the fault must be corrected before installing a new motor.

If it has been determined that the fault is in the motor itself (by checking for correct voltage at the motor terminals and for failure of the driven unit), inspect the commutator and brushes. A dirty commutator or defective or binding brushes may result in poor contact between brushes and commutator. Clean the commutator, brushes, and brush holders with a cloth moistened with the recommended cleaning solvent. If brushes are damaged or worn to the specified minimum length, install new brushes in accordance with the applicable manufacturer's instructions covering the motor. If the motor still fails to operate, replace it with a serviceable motor.

A. C. MOTORS

Because of their advantages, many types of aircraft motors are designed to operate on alternating current. In general, a.c. motors are less expensive than comparable d.c. motors. In many instances, a.c. motors do not use brushes and commutators and, therefore, sparking at the brushes is avoided. They are very reliable and very little maintenance is needed. Also, they are well suited for constant-speed applications and certain types are manufactured that have, within limits, variable-speed characteristics. Alternating-current motors are designed to operate on polyphase or single-phase lines and at several voltage ratings.

The subject of a.c. motors is very extensive, and no attempt has been made to cover the entire field. Only the types of a.c. motors most common to aircraft systems are discussed in detail.

The speed of rotation of an a.c. motor depends upon the number of poles and the frequency of the electrical source of power:

$$\text{r.p.m.} = \frac{120 \times \text{Frequency}}{\text{Number of Poles}}.$$

Since airplane electrical systems typically operate at 400 cycles, an electric motor at this frequency operates at about seven times the speed of a 60-cycle commercial motor with the same number of poles. Because of this high speed of rotation, 400-cycle a.c. motors are suitable for operating small high-speed rotors, through reduction gears, in lifting and moving heavy loads, such as the wing flaps, the retractable landing gear, and the starting of engines. The 400-cycle induction type motor operates at speeds ranging from 6,000 r.p.m. to 24,000 r.p.m.

Alternating-current motors are rated in horsepower output, operating voltage, full load current, speed, number of phases, and frequency. Whether the motors operate continuously or intermittently (for short intervals) is also considered in the rating.

TYPES OF A. C. MOTORS

There are two general types of a.c. motors used in aircraft systems: induction motors and synchronous motors. Either type may be single-phase, two-phase, or three-phase.

Three-phase induction motors are used where large amounts of power are required. They operate such devices as starters, flaps, landing gears, and hydraulic pumps.

Single-phase induction motors are used to operate devices such as surface locks, intercooler shutters, and oil shutoff valves in which the power requirement is low.

Three-phase synchronous motors operate at constant synchronous speeds and are commonly used to operate flux gate compasses and propeller synchronizer systems.

Single-phase synchronous motors are common sources of power to operate electric clocks and other small precision equipment. They require some auxiliary method to bring them up to synchronous speeds; that is, to start them. Usually the starting winding consists of an auxiliary stator winding.

Three-Phase Induction Motor

The three-phase a.c. induction motor is also called a squirrel-cage motor. Both single-phase and three-phase motors operate on the principle of a rotating magnetic field. A horseshoe magnet held over a compass needle is a simple illustration of the principle of the rotating field. The needle will take a position parallel to the magnetic flux passing between the two poles of the magnet. If the magnet is rotated, the compass needle will follow. A rotating magnetic field can be produced by a two- or three-phase current flowing through two or more groups of coils wound on inwardly projecting poles of an iron frame. The coils on each group of poles are wound alternately in opposite directions to produce opposite polarity, and each group is connected to a separate phase of voltage. The operating principle depends on a revolving, or rotating, magnetic field to produce torque. The key to understanding the induction motor is a thorough understanding of the rotating magnetic field.

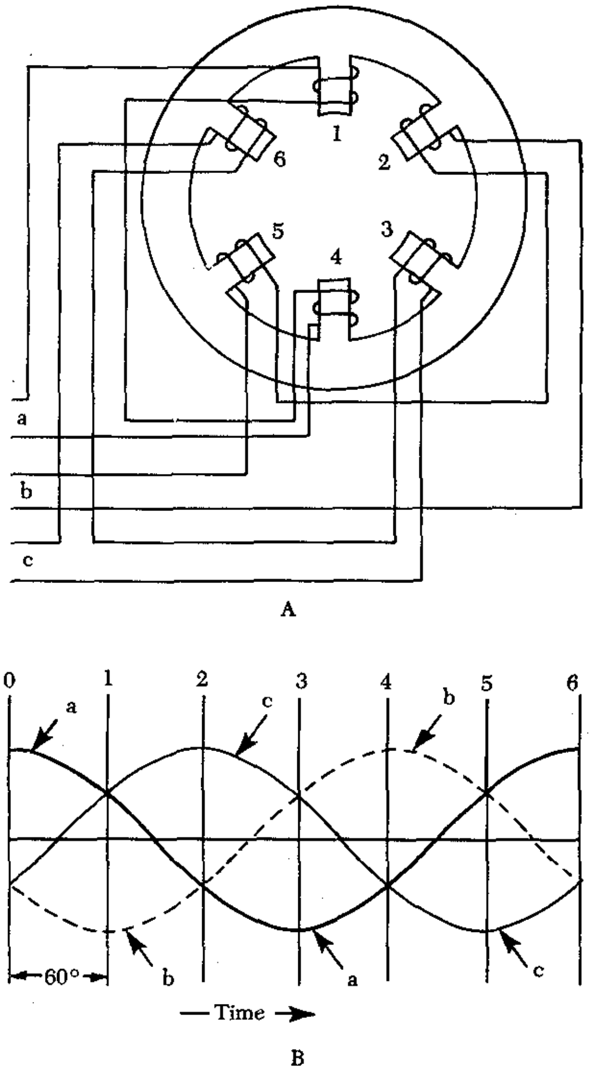


FIGURE 9–83. Rotating magnetic field developed by application of three-phase voltages.

Rotating Magnetic Field

The field structure shown in *A* of figure 9–83 has poles whose windings are energized by three a.c. voltages, *a*, *b*, and *c*. These voltages have equal magnitude but differ in phase, as shown in *B* of figure 9–83.

At the instant of time shown as 0 in *B* of figure 9–83, the resultant magnetic field produced by the application of the three voltages has its greatest intensity in a direction extending from pole 1 to pole 4. Under this condition, pole 1 can be considered as a north pole and pole 4 as a south pole.

At the instant of time shown as 1, the resultant magnetic field will have its greatest intensity in the direction extending from pole 2 to pole 5; in this case, pole 2 can be considered as a north pole and pole 5 as a south pole. Thus, between instant 0 and instant 1, the magnetic field has rotated clockwise.

At instant 2, the resultant magnetic field has its greatest intensity in the direction from pole 3 to pole 6, and the resultant magnetic field has continued to rotate clockwise.

At instant 3, poles 4 and 1 can be considered as north and south poles, respectively, and the field has rotated still farther.

At later instants of time, the resultant magnetic field rotates to other positions while traveling in a clockwise direction, a single revolution of the field occurring in one cycle. If the exciting voltages have a frequency of 60 c.p.s., the magnetic field makes 60 revolutions per second, or 3,600 r.p.m. This speed is known as the synchronous speed of the rotating field.

Construction of Induction Motor

The stationary portion of an induction motor is called a stator, and the rotating member is called a rotor. Instead of salient poles in the stator, as shown in *A* of figure 9–83, distributed windings are used; these windings are placed in slots around the periphery of the stator.

It is usually impossible to determine the number of poles in an induction motor by visual inspection, but the information can be obtained from the nameplate of the motor. The nameplate usually gives the number of poles and the speed at which the motor is designed to run. This rated, or nonsynchronous, speed is slightly less than the synchronous speed. To determine the number of poles per phase on the motor, divide 120 times the frequency by the rated speed; written as an equation:

$$P = \frac{120 \times f}{N}$$

where: P is the number of poles per phase, f is the frequency in c.p.s., N is the rated speed in r.p.m., and 120 is a constant.

The result will be very nearly equal to the number of poles per phase. For example, consider a 60-cycle, three-phase motor with a rated speed of 1,750 r.p.m. In this case:

$$P = \frac{120 \times 60}{1750} = \frac{7200}{1750} = 4.1.$$

Therefore, the motor has four poles per phase. If the number of poles per phase is given on the nameplate, the synchronous speed can be determined by dividing 120 times the frequency by the number of poles per phase. In the example used above, the synchronous speed is equal to 7,200 divided by 4, or 1,800 r.p.m.

The rotor of an induction motor consists of an iron core having longitudinal slots around its circumference in which heavy copper or aluminum bars are embedded. These bars are welded to a heavy ring of high conductivity on either end. The composite structure is sometimes called a squirrel cage, and motors containing such a rotor are called squirrel-cage induction motors. (See figure 9–84.)

Induction Motor Slip

When the rotor of an induction motor is subjected to the revolving magnetic field produced by the stator windings, a voltage is induced in the longitudinal bars. The induced voltage causes a current to flow through the bars. This current, in turn, produces its own magnetic field which combines with the revolving field so that the rotor assumes a position in which the induced voltage is minimized. As a result, the rotor revolves at very nearly the synchronous speed of the stator field, the difference in speed being just sufficient enough to induce the proper amount of current in the rotor to overcome the mechanical and electrical losses in the rotor. If the rotor were to turn at the same speed as the rotating field, the rotor conductors would not be cut by any magnetic lines of force, no e.m.f. would be induced in them, no current could flow, and there would be no torque. The rotor would then slow down. For this reason, there must always be a difference in speed between the rotor and the rotating field. This difference in speed is called slip and is expressed as a percentage of the synchronous speed. For example, if the rotor turns at 1,750 r.p.m. and the synchronous speed is

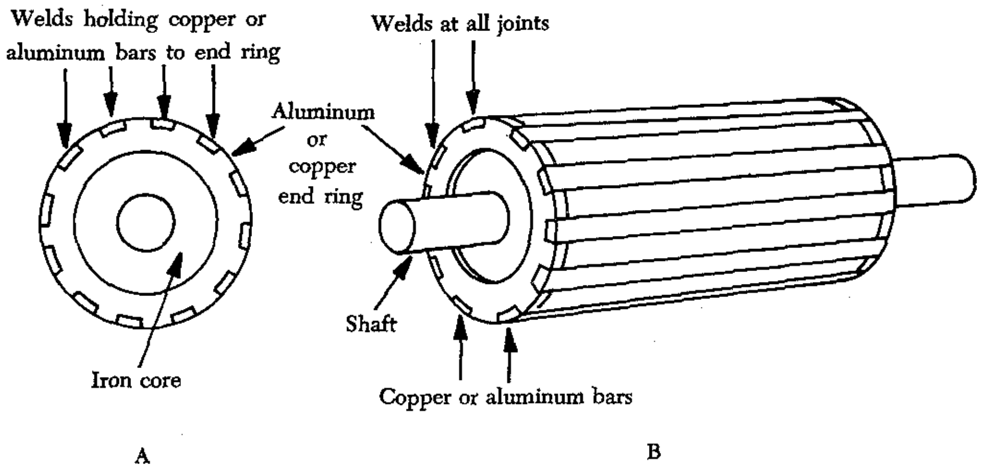


FIGURE 9–84. Squirrel-cage rotor for an a.c. induction motor.

1,800 r.p.m., the difference in speed is 50 r.p.m. The slip is then equal to 50/1,800 or 2.78 percent.

Single-Phase Induction Motor

The previous discussion has applied only to polyphase motors. A single-phase motor has only one stator winding. This winding generates a field which merely pulsates, instead of rotating. When the rotor is stationary, the expanding and collapsing stator field induces currents in the rotor. These currents generate a rotor field opposite in polarity to that of the stator. The opposition of the field exerts a turning force on the upper and lower parts of the rotor trying to turn it 180° from its position. Since these forces are exerted through the center of the rotor, the turning force is equal in each direction. As a result, the rotor does not turn. If the rotor is started turning, it will continue to rotate in the direction in which it is started, since the turning force in that direction is aided by the momentum of the rotor.

Shaded-Pole Induction Motor

The first effort in the development of a self-starting, single-phase motor was the shaded-pole induction motor (figure 9–85). This motor has salient poles, a portion of each pole being encircled by a heavy copper ring. The presence of the ring causes the magnetic field through the ringed portion of the pole face to lag appreciably behind that through the other part of the pole face. The net effect is the production of a slight component of rotation of the field, sufficient to cause the rotor to revolve. As the rotor accelerates, the torque increases until the rated speed is obtained. Such motors have low starting torque and find their greatest application in small fan motors where the initial torque required is low.

In figure 9–86, a diagram of a pole and the rotor is shown. The poles of the shaded-pole motor resemble those of a d.c. motor.

A low-resistance, short-circuited coil or copper band is placed across one tip of each small pole, from which, the motor gets the name of shaded

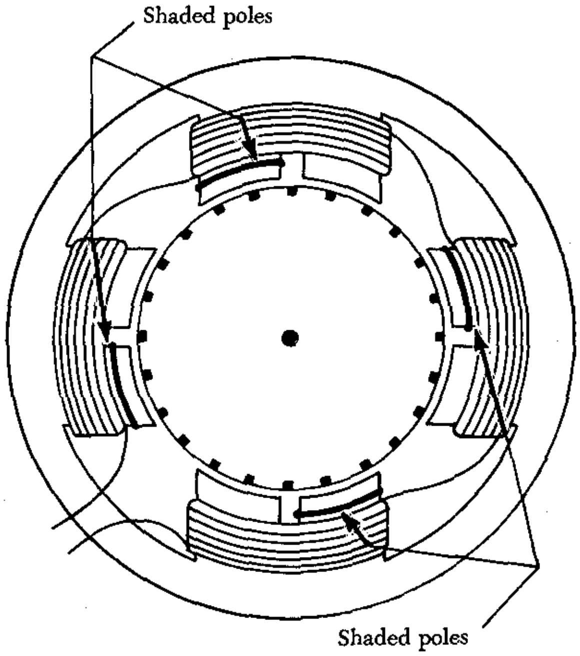


FIGURE 9–85. Shaded-pole induction motor.

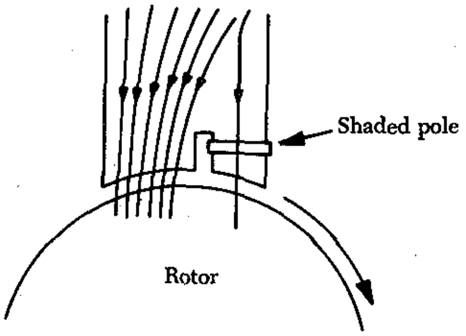


FIGURE 9–86. Diagram of a shaded-pole motor.

pole. The rotor of this motor is the squirrel-cage type.

As the current increases in the stator winding, the flux increases. A portion of this flux cuts the low resistance shading coil. This induces a current in the shading coil, and by Lenz's law, the current sets up a flux which opposes the flux inducing the current. Hence, most of the flux passes through the unshaded portion of the poles, as shown in figure 9–86.

When the current in the winding and the main flux reaches a maximum, the rate of change is zero; thus, no e.m.f. is induced in the shading coil. A little later, the shading coil current, which causes the induced e.m.f. to lag, reaches zero, and there is no opposing flux. Therefore, the main field flux passes through the shaded portion of the field pole.

The main field flux, which is now decreasing, induces a current in the shading coil. By Lenz's law, this current sets up a flux which opposes the decrease of the main field flux in the shaded portion of the pole. The effect is to concentrate the lines of force in the shaded portion of the pole face.

In effect, the shading coil retards, in time phase, the portion of the flux passing through the shaded part of the pole. This lag in time phase of the flux in the shaded tip causes the flux to produce the effect of sweeping across the face of the pole, from left to right in the direction of the shaded tip. This behaves like a very weak rotating magnetic field, and sufficient torque is produced to start a small motor.

The starting torque of the shaded-pole motor is exceedingly weak, and the power factor is low. Consequently, it is built in sizes suitable for driving such devices as small fans.

Split-Phase Motor

There are various types of self-starting motors, known as split-phase motors. Such motors have a starting winding displaced 90 electrical degrees from the main or running winding. In some types, the starting winding has a fairly high resistance, which causes the current in this winding to be out of phase with the current in the running winding. This condition produces, in effect, a rotating field and the rotor revolves. A centrifugal switch disconnects the starting winding automatically, after the rotor has attained approximately 25 percent of its rated speed.

Capacitor-Start Motor

With the development of high-capacity electrolytic capacitors, a variation of the split-phase motor, known as the capacitor-start motor, has been made. Nearly all fractional horsepower motors in use today on refrigerators, oil burners, and other similar appliances are of this type. (See figure 9–87.) In this adaptation, the starting winding and running winding have the same size and resistance value. The phase shift between currents of the two windings is obtained by using capacitors connected in series with the starting winding.

Capacitor-start motors have a starting torque comparable to their torque at rated speed and can be used in applications where the initial load is heavy. Again, a centrifugal switch is required for disconnecting the starting winding when the rotor speed is approximately 25 percent of the rated speed.

Although some single-phase induction motors are rated as high as 2 hp. (horsepower), the major field of application is 1 hp., or less, at a voltage rating of 115 volts for the smaller sizes and 110 to 220 volts for one-fourth hp. and up. For even larger power ratings, polyphase motors generally are used, since they have excellent starting torque characteristics.

Direction of Rotation of Induction Motors

The direction of rotation of a three-phase induction motor can be changed by simply reversing two of the leads to the motor. The same effect can be obtained in a two-phase motor by reversing connections to one phase. In a single-phase motor, reversing connections to the starting winding will reverse the direction of rotation. Most

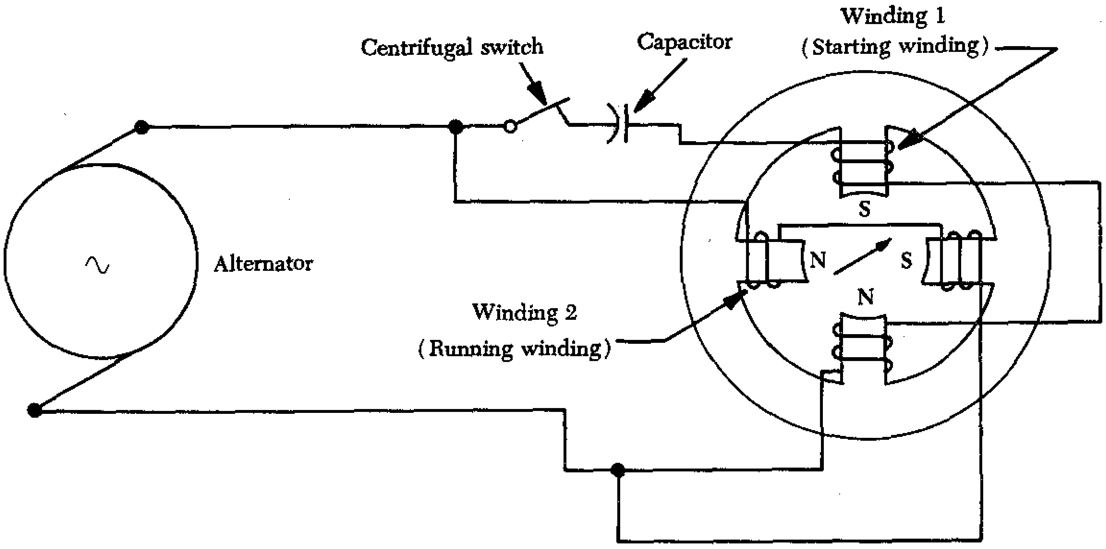


FIGURE 9–87. Single-phase motor with capacitor starting winding.

single-phase motors designed for general application have provision for readily reversing connections to the starting winding. Nothing can be done to a shaded-pole motor to reverse the direction of rotation because the direction is determined by the physical location of the copper shading ring.

If, after starting, one connection to a three-phase motor is broken, the motor will continue to run but will deliver only one-third the rated power. Also, a two-phase motor will run at one-half its rated power if one phase is disconnected. Neither motor will start under these abnormal conditions.

Synchronous Motor

The synchronous motor is one of the principal types of a.c. motors. Like the induction motor, the synchronous motor makes use of a rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction of currents in the rotor. Briefly, the principle of operation of the synchronous motor is as follows: A multiphase source of a.c. is applied to the stator windings, and a rotating magnetic field is produced. A direct current is applied to the rotor winding, and another magnetic field is produced. The synchronous motor is so designed and constructed that these two fields react to each other in such a manner that the rotor is dragged along and rotates at the same speed as the rotating magnetic field produced by the stator windings.

An understanding of the operation of the synchronous motor can be obtained by considering the simple motor of figure 9–88. Assume that poles *A* and *B* are being rotated clockwise by some mechanical means in order to produce a rotating magnetic field, they induce poles of opposite polarity in the soft-iron rotor, and forces of attraction exist between corresponding north and south poles. Consequently, as poles *A* and *B*

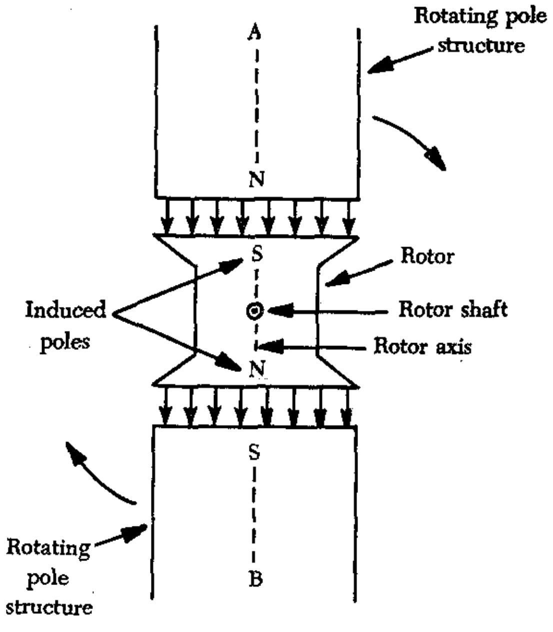


FIGURE 9–88. Illustrating the operation of a synchronous motor.

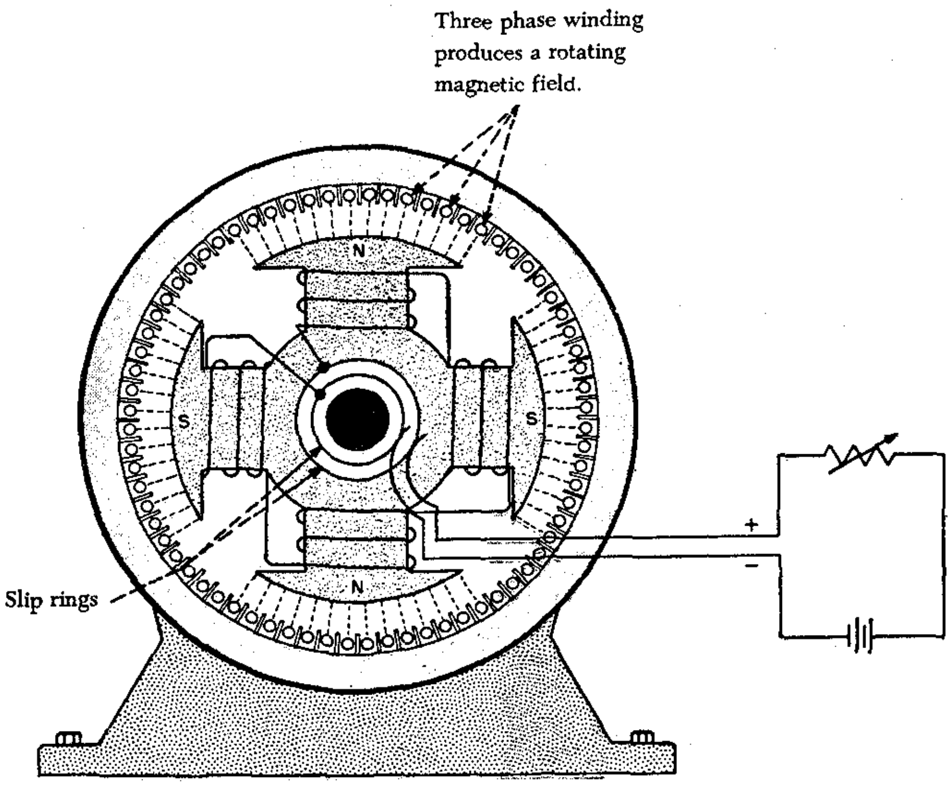


FIGURE 9–89. Synchronous motor.

rotate, the rotor is dragged along at the same speed. However, if a load is applied to the rotor shaft, the rotor axis will momentarily fall behind that of the rotating field but, thereafter, will continue to rotate with the field at the same speed, as long as the load remains constant. If the load is too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate with the field at the same speed. The motor is then said to be overloaded.

Such a simple motor as that shown in figure 9–88 is never used. The idea of using some mechanical means of rotating the poles is impractical because another motor would be required to perform this work. Also, such an arrangement is unnecessary because a rotating magnetic field can be produced electrically by using phased a.c. voltages. In this respect, the synchronous motor is similar to the induction motor.

The synchronous motor consists of a stator field winding similar to that of an induction motor. The stator winding produces a rotating magnetic field. The rotor may be a permanent magnet, as in small single-phase synchronous motors used for clocks and other small precision equipment, or it may be an electromagnet, energized from a d.c. source of power and fed through slip rings into the rotor field coils, as in an alternator. In fact, an alternator may be operated either as an alternator or a synchronous motor.

Since a synchronous motor has little starting torque, some means must be provided to bring it up to synchronous speed. The most common method is to start the motor at no load, allow it to reach full speed, and then energize the magnetic field. The magnetic field of the rotor locks with the magnetic field of the stator and the motor operates at synchronous speed.

The magnitude of the induced poles in the rotor shown in figure 9–89 is so small that sufficient torque cannot be developed for most practical loads. To avoid such a limitation on motor operation, a winding is placed on the rotor and energized with d.c. A rheostat placed in series with the d.c. source provides the operator of the machine with a means of varying the strength of the rotor poles, thus placing the motor under control for varying loads.

The synchronous motor is not a self-starting motor. The rotor is heavy and, from a dead stop, it is impossible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all synchronous motors have some kind of starting device. One type of simple starter is another motor, either a.c. or d.c., which brings the rotor up to approximately 90 percent of its synchronous speed. The starting motor is then disconnected, and the rotor locks in step with the rotating field. Another starting method is a second winding of the squirrel-cage type on the rotor. This induction winding brings the rotor almost to synchronous speed, and when the d.c. is connected to the rotor windings, the rotor pulls into step with the field. The latter method is the more commonly used.

A. C. Series Motor

An alternating-current series motor is a single-phase motor, but is not an induction or synchronous motor. It resembles a d.c. motor in that it has brushes and a commutator. The a.c. series motor will operate on either a.c. or d.c. circuits. It will be recalled that the direction of rotation of a d.c. series motor is independent of the polarity of the applied voltage, provided the field and armature connections remain unchanged. Hence, if a d.c. series motor is connected to an a.c. source, a torque will be developed which tends to rotate the armature in one direction. However, a d.c. series motor does not operate satisfactorily from an a.c. supply for the following reasons:

1. The alternating flux sets up large eddy-current and hysteresis losses in the unlaminated portions of the magnetic circuit and causes excessive heating and reduced efficiency.
2. The self-induction of the field and armature windings causes a low power factor.
3. The alternating field flux establishes large currents in the coils, which are short-circuited by the brushes; this action causes excessive sparking at the commutator.

To design a series motor for satisfactory operation on a.c., the following changes are made:

1. The eddy-current losses are reduced by laminating the field poles, frame and armature.
2. Hysteresis losses are minimized by using high-permeability, transformer-type, silicon-steel laminations.
3. The reactance of the field windings is kept satisfactorily low by using shallow pole pieces, few turns of wire, low frequency (usually 25 cycles for large motors), low flux density, and low reluctance (a short airgap).
4. The reactance of the armature is reduced by using a compensating winding embedded in the pole pieces. If the compensating winding is connected in series with the armature, as shown in figure 9–90, the armature is conductively compensated.

   If the compensating winding is designed as shown in figure 9–91, the armature is inductively compensated. If the motor is designed for operation on both d.c. and a.c. circuits, the compensating winding is connected in series with the armature. The axis of the compensating winding is displaced from the main field axis by an angle of 90°. This arrangement is similar to the compensating winding used in some d.c. motors and generators to overcome armature reaction. The compensating winding establishes a counter magnetomotive force, neutralizing the effect of the armature magnetomotive force, preventing distortion of the main field flux, and reducing the armature reactance. The inductively compensated armature acts like the primary of a transformer, the secondary of which is the shorted compensating winding. The shorted secondary receives an induced voltage by the action of the alternating armature flux, and the resulting current flowing through the turns of the compensating winding establishes the opposing magnetomotive force, neutralizing the armature reactance.
5. Sparking at the commutator is reduced by the use of preventive leads P_1, P_2, P_3, and so forth, as shown in figure 9–92, where a ring

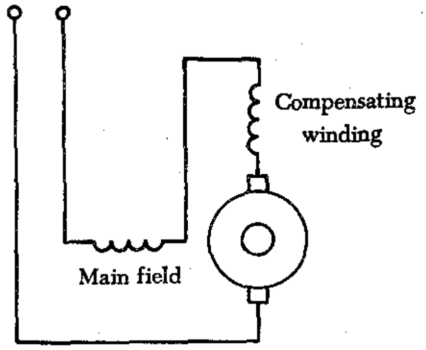


FIGURE 9–90. Conductively compensated armature of a.c. series motor.

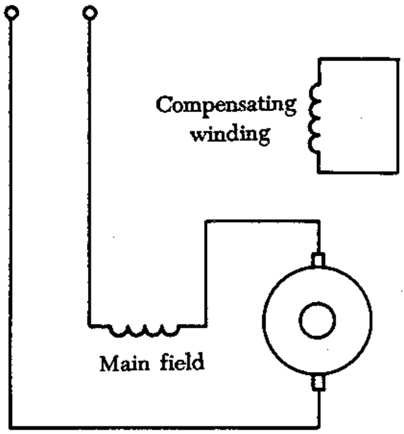


FIGURE 9–91. Inductively compensated armature of a.c. series motor.

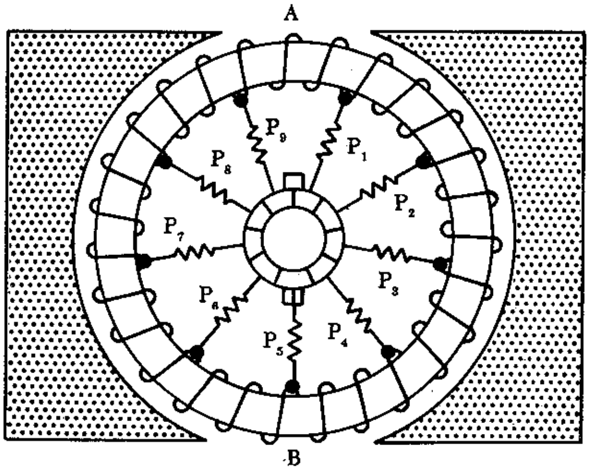


FIGURE 9–92. Preventive coils in a.c. series motor.

armature is shown for simplicity. When coils at *A* and *B* are shorted by the brushes, the induced current is limited by the relatively high resistance of the leads. Sparking at the brushes is also reduced by using armature coils having only a single turn and multipolar fields. High torque is obtained by having a large number of armature conductors and a large-diameter armature. Thus, the commutator has a large number of very thin commutator bars and the armature voltage is limited to about 250 volts.

Fractional horsepower a.c. series motors are called universal motors. They do not have compensating windings or preventive leads. They are used extensively to operate fans and portable tools, such as drills, grinders, and saws.

MAINTENANCE OF A. C. MOTORS

The inspection and maintenance of a.c. motors is very simple. The bearings may or may not need frequent lubrication. If they are the sealed type, lubricated at the factory, they require no further attention. Be sure the coils are kept dry and free from oil or other abuse.

The temperature of a motor is usually its only limiting operating factor. A good rule of thumb is that a temperature too hot for the hand is too high for safety.

Next to the temperature, the sound of a motor or generator is the best trouble indicator. When operating properly, it should hum evenly. If it is overloaded it will "grunt." A three-phase motor with one lead disconnected will refuse to turn and will "growl." A knocking sound generally indicates a loose armature coil, a shaft out of alignment, or armature dragging because of worn bearings.

The inspection and maintenance of all a.c. motors should be performed in accordance with the applicable manufacturer's instructions.

Troubleshooting

The following troubleshooting procedures are not applicable to a particular a.c. motor, but are included as examples of the general troubleshooting procedures provided by various manufacturers of a.c. motors.

Trouble	Possible cause	Correction
Motor speed slow.	No lubrication. Applied voltage low. Motor wiring defective.	Lubricate as necessary. Check motor source voltage. Perform voltage continuity test of motor wiring.
Motor speed fast.	Excessive supply voltage. Motor field windings shorted.	Check and adjust level of motor supply voltage. Repair shorted windings or replace or overhaul motor.

Trouble	Possible cause	Correction
Motor will not operate. No voltage applied to motor.	Loose or broken wiring inside motor.	Perform continuity test of motor circuit.
	Defective motor switch.	Check switch and switch wiring using a continuity tester.
	Armature or field winding open-circuited.	Repair open winding or replace motor.
	Brushes worn excessively.	Replace brushes.
	Brush springs broken or too weak,	Replace brush springs.
	Brushes sticking in brush holders.	Replace or clean and adjust brushes.
Motor vibrates.	Loose or broken motor mountings.	Repair or replace motor mountings.
	Motor shaft bent.	Replace shaft or overhaul or replace motor.
	Motor bearings worn excessively.	Replace bearings or overhaul motor.
Motor arcing excessively at brushes.	Brushes worn excessively.	Replace brushes.
	Brush springs weak.	Replace brush springs.
	Brushes sticking in holders.	Replace or clean brushes.
	Brushes incorrectly located.	Position brushes properly.
	Commutator dirty or excessively worn or pitted.	Clean or repair commutator as necessary.
	Open-circuited armature coil.	Repair open circuit or overhaul or replace motor.
Motor runs but overheats.	Motor bearings improperly lubricated.	Lubricate bearings.
	Excessive applied voltage.	Check voltage and adjust to proper level.
	Field windings short-circuited.	Repair short circuit or overhaul or replace.
	Excessive brush arcing.	Replace and adjust brushes.
Motor will not operate but draws high current.	Shorted circuit to motor.	Locate and repair short circuit.
	Open field winding in shunt motor.	Repair or overhaul or replace motor.
	Motor internal circuit shorted.	Repair short circuit or overhaul or replace motor.
	Mechanical stoppage.	Check for seized motor bearings or binding of mechanism driven by motor. Repair or replace seized components.
	Excessive load on motor.	Reduce load or install motor capable of carrying greater load.