Part I

Motor Basics

Chapter 1

Motor Principles

In order to obtain a clear concept of the principles on which the electric motor operates, it is necessary first to understand the fundamental laws of magnetism and magnetic induction. It is not necessary to have a great number of expensive laboratory instruments to obtain this knowledge. Instead, children's toy magnets, automobile accessories, and so on, will suffice. It is from these principles that the necessary knowledge about the behavior of permanent magnets and the magnetic needle can be obtained.

In our early schooldays, we learned that the earth is a huge permanent magnet with its north magnetic pole somewhere in the Hudson Bay region, and that the compass needle points toward the magnetic pole. The compass is thus an instrument that can give an indication of magnetism.

The two spots on the magnet that point one to the north and the other to the south are called the poles: one is called the north-seeking pole (N) and the other the south-seeking pole (S).

Magnetic Attraction and Repulsion

If the south-seeking, or S, pole of a magnet is brought near the S pole of a suspended magnet, as in Figure 1-1, the poles repel each other. If the two N poles are brought together, they also repel each other. But if an N pole is brought near the S pole of the moving

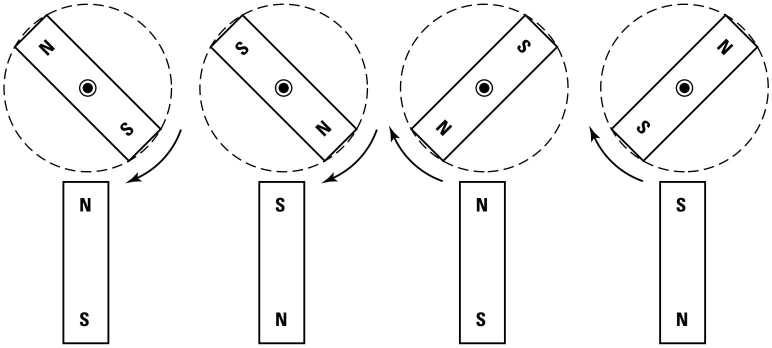

Figure 1-1 Illustrating that like poles of permanent magnets repel each other and unlike poles attract each other.

magnet, or an S pole toward the N pole, the two unlike poles attract each other. In other words, *like poles repel each other,* and *unlike poles attract each other.* It can also be shown by experiment that these attractive or repulsive forces between magnetic poles vary inversely as the square of the distance between the poles.

Effects of an Electric Current

As a further experiment, connect a coil to a battery, as shown in Figure 1-2. The compass points to one end of the coil, but if the battery connections are reversed, the compass points away from that end. Thus, the direction of the current through the coil affects the compass in a manner similar to the permanent magnet in the previous experiment.

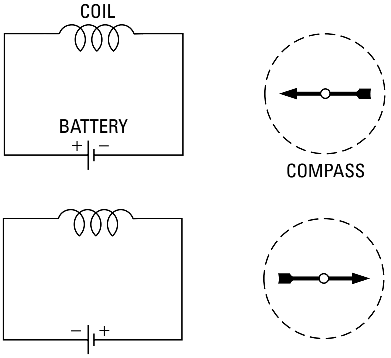

Figure 1-2 A demonstration showing that the direction of current flow through a coil affects a compass needle.

In the early part of the nineteenth century, Oersted discovered the relationship between magnetism and electricity. He observed that when a wire connecting the poles of a battery was held *over* a compass needle, the north pole of the needle was deflected as shown in Figure 1-3. A wire placed *under* the compass needle caused the north pole of the needle to be deflected in the opposite direction.

Magnetic Field of an Electric Current

Inasmuch as the compass needle indicates the direction of magnetic lines of force, it is evident from Oersted's experiment that an electric current sets up a magnetic field at right angles to the conductor. This can be shown by the experiment illustrated in Figure 1-4. If a strong current is sent through a vertical wire that passes through a horizontal piece of cardboard on which iron filings are placed, a gentle tap of the board causes the iron filings to arrange themselves

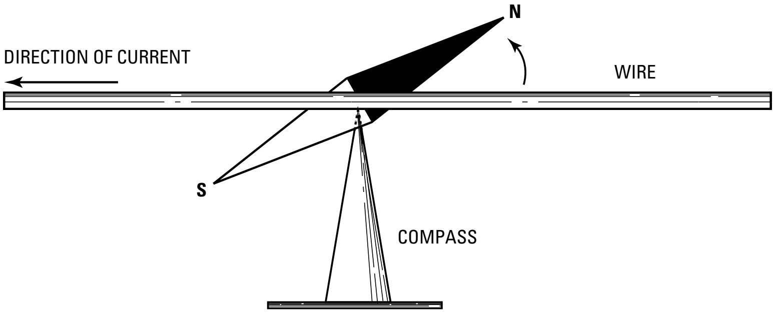

Figure 1-3 A demonstration showing that current flowing through a wire will cause a compass needle to deflect.

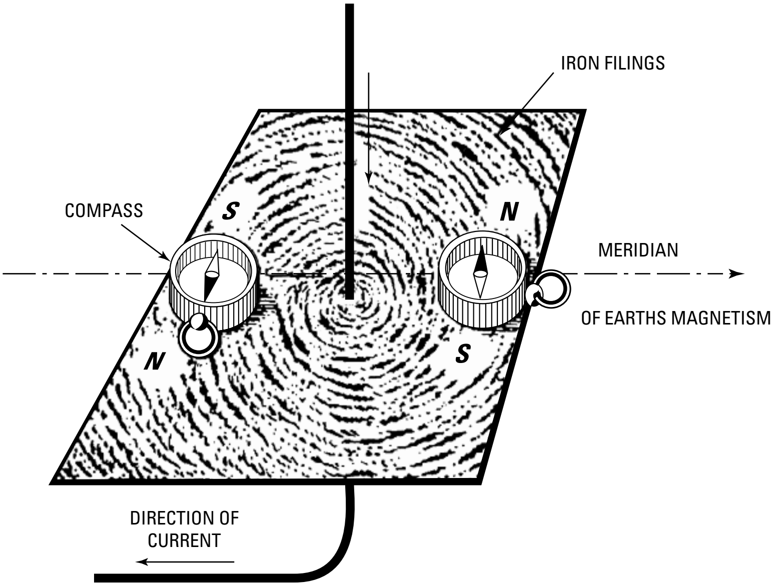

Figure 1-4 An experiment to show the direction of lines of force that surround a conductor carrying current.

in concentric rings about the wire. A compass placed at various positions on the board will indicate the direction of these lines of force, as shown in Figure 1-4.

A convenient rule for remembering the direction of the magnetic flux around a straight wire carrying current is the so-called *left-hand*

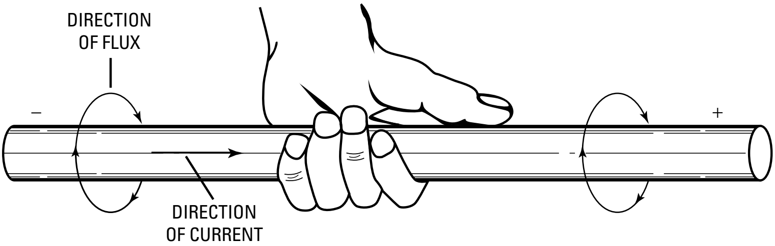

Figure 1-5 Using the left-hand rule to determine the direction of magnetic lines of force (flux) around a conductor through which current is flowing.

rule. With reference to Figure 1-5, it can be seen that if the wire is held by the left hand, with the thumb pointing in the direction of the current, the fingers will point in the direction of the magnetic field.

Conversely, if the direction of the magnetic field around a conductor is known, the direction of the current in the conductor can be found by applying this rule.

Electromagnets

A soft-iron core surrounded by a coil of wire is called an *electromagnet*. The electromagnet owes its utility not so much to its great strength as to its ability to change its magnetic strength with the amount of the current through it. An electromagnet is a magnet only when the current flows through its coil. When the current is interrupted, the iron core returns almost to its natural state. This loss of magnetism is not absolutely complete, however, since a very small amount, called *residual magnetism*, remains.

An electromagnet is a part of many electrical devices, including electric bells, telephones, motors, and generators.

The polarity of an electromagnet may be determined by means of the left-hand rule used for a straight wire as follows: Grasp the coil with the left hand so that the fingers point in the direction of the current in the coil, and the thumb will point to the north pole of the coil (see Figure 1-6).

The strength of an electromagnet depends on the strength of the current (in amperes) multiplied by the number of loops of wire (turns)—that is, the *ampere-turns* of the coil (Figure 1-7). In practical electromagnets, it is customary to make use of both poles by

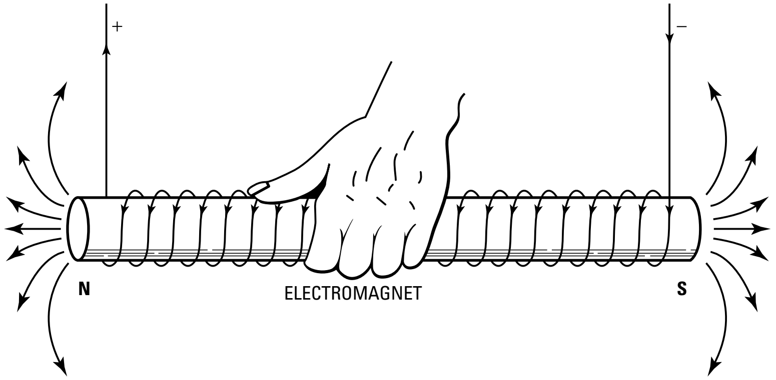

Figure 1-6 Using the left-hand rule to determine the polarity of an electromagnet.

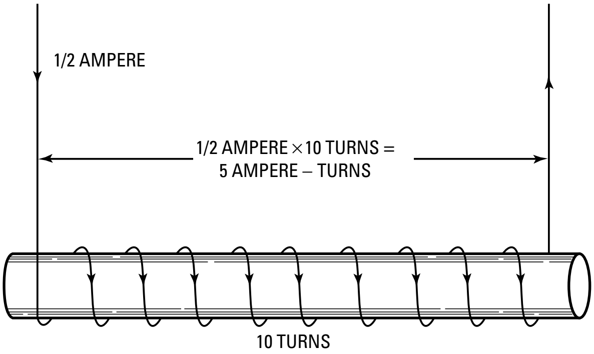

Figure 1-7 Ampere turns of a coil are equal to the product of the current (in amperes) flowing through the windings and the number of turns in the coil.

bending the iron core and the coil in the form of a horseshoe. It is from this form that the name *horseshoe magnet* is derived.

Induced Currents

If the ends of a coil of wire having many turns are connected to a sensitive galvanometer, as shown in Figure 1-8, and the coil is moved up and down over one pole of a horseshoe magnet, a deflection of the galvanometer pointer will be observed. It will also be noted that in lowering the coil, the deflection of the galvanometer

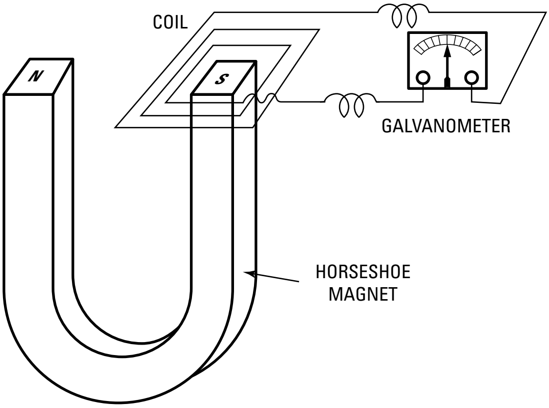

Figure 1-8 Demonstrating how the movement of a coil in a magnetic field generates an electric current.

pointer will be in a direction opposite that of the needle when the coil is raised. When the coil is lowered and held down, the galvanometer pointer returns to zero. This experiment shows that it is possible to produce a momentary electric current without an apparent electrical source.

The electrical current produced by moving the coil in a magnetic field is called an *induced current.* It is evident from the experiment that the current is induced only when the wire is moving, and that the direction of the current is reversed when the motion changes direction. Since an electric current is always made to flow by an electromotive force (*emf*), the motion of a coil in a magnetic field must generate and produce an induced electromotive force.

The direction of an induced current may be stated as follows: An induced current has such a direction that its magnetic action tends to resist the motion by which it is produced. This is known as Lenz's law.

The most useful application of induced currents is in the construction of electrical machinery of all sorts, the most common of which are the generator and motor.

A simple way to obtain a fundamental understanding of the generator is to think of the induced electromotive force produced in a single wire when it is moved across a magnetic field. Suppose wire *AB* in Figure 1-9 is pushed down through the magnetic field. An

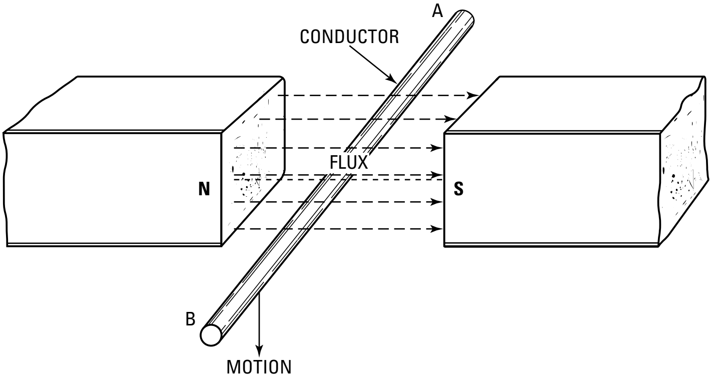

Figure 1-9 A voltage is induced when a wire cuts through magnetic lines of force.

induced emf is set up in *AB,* making point *B* at a higher potential than point *A*. This can be shown by connecting a voltmeter from *A* to *B*.

As long as the wire remains stationary, no current flows. In fact, even if the wire moves parallel to the lines of force, no current flows. Briefly, a wire must move so as to *cut lines of magnetic* force in order to have an emf induced in it.

Direct-Current (DC) Generators

A *generator* is a machine that converts mechanical energy into electrical energy. This is done by rotating an *armature,* which contains *conductors,* through a *magnetic field.* The movement of the conductors through a magnetic field produces an induced emf in the moving conductors. In any generator, a relative motion between the conductors and the magnetic field will always exist when the shaft is rotated.

Parts of a DC Generator

The principal parts of a DC generator are an armature, commutator, field poles, brushes and brush rigging, yoke or frame, and end bells or end frames (Figure 1-10). Figure 1-11 shows the parts of a DC generator.

Armature

The armature is the structure upon which the coils are mounted. These coils cut the magnetic lines of force. The armature is attached to a shaft. The shaft is suspended at each end of the machine by

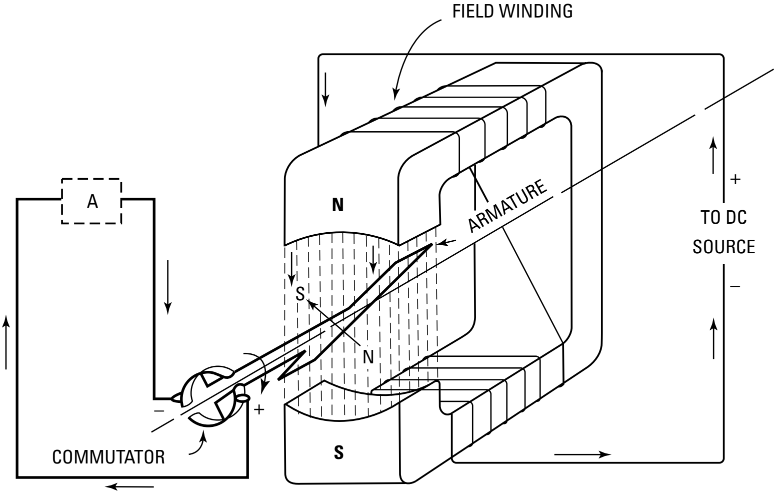

Figure 1-10 An elementary direct-current (DC) generator. A commutator keeps the current flowing in the same direction in the load circuit (A).

bearings set in the end bells, as shown in Figure 1-12. The armature core, which is circular in cross section, consists of many sheets of soft iron. The edge of the laminated core is slotted (Figure 1-13). Coil windings fit into these slots. The windings are held in place and in their slots by wooden or fiber wedges. Sometimes steel bands are also wrapped around the completed armature to provide extra support. On small generators, the laminations of the armature core are usually pressed onto the armature shaft.

Commutator

The commutator is that part of the generator that rectifies the generated alternating current to provide direct current output (Figure 1-12). It also connects the stationary output terminals to the rotating armature. A typical commutator consists of *commutator bars*. The bars are wedge-shaped segments of hard-drawn copper. These segments are insulated from each other by thin strips of mica. Commutator bars are held in place by steel V-rings or clamping flanges, as shown in Figure 1-14. These V-rings or clamping flanges are bolted to the commutator sleeve by hexagonal cap screws. The *commutator sleeve* is keyed to the shaft that rotates the armature. A mica collar or ring insulates the commutator bars from the commutator sleeve.

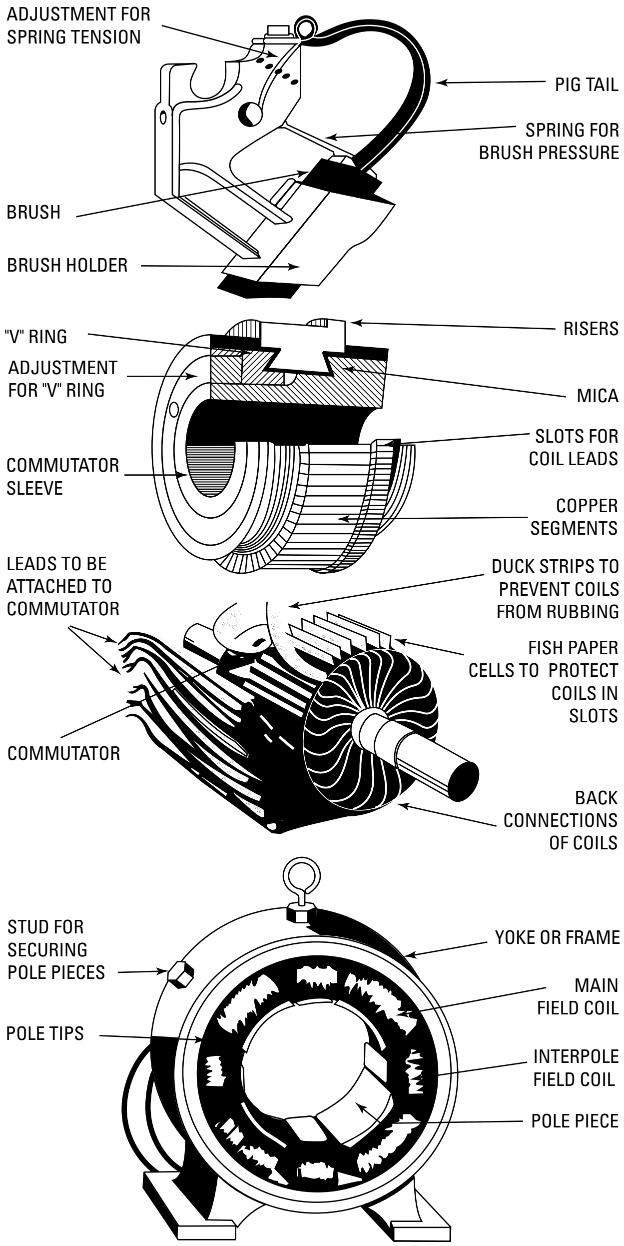

Figure 1-11 Parts of a DC generator, stationary type.

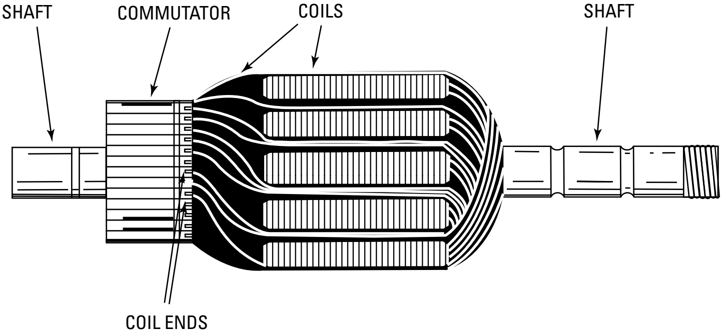

Figure 1-12 Armature of a DC generator.

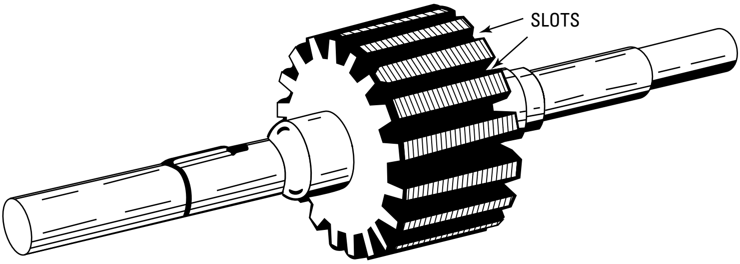

Figure 1-13 Unwound armature core on a shaft.

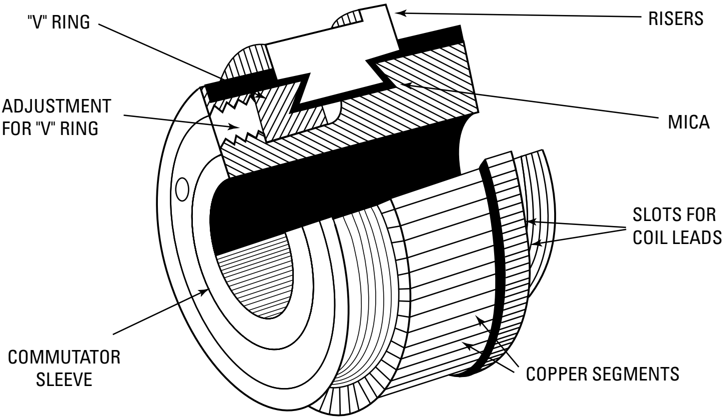

Figure 1-14 Commutator construction.

The commutator bars usually have risers or flanges to which the leads from the associated armature coils are soldered. These risers serve as a shield for the soldered connections when the commutator bars become worn. When risers are not provided, it is necessary to solder the leads from the armature coils to short slits in the ends of the commutator bars. The brushes contact the commutator bars.

The brushes collect the current generated by the armature coils. The brush holders transfer the current to the main terminals. The commutator bars are insulated from each other. Thus, each set of brushes, as it contacts the commutator bars, collects current of the same polarity. This results in a continuous flow of direct current. The finer the division of the commutator bars, the less the ripple that appears in the current, and therefore, the smoother the flow of the DC output.

Field Pole and Frame

The frame or yoke of a generator serves two purposes. It provides mechanical support for the machine. It is also a path for the completion of the magnetic circuit. The lines of force that pass from the north to the south pole through the armature are returned to the north pole through the frame. Frames are made of electrical-grade steel. The method of construction of field poles and frames varies with the manufacturer. Figure 1-15 shows the magnetic circuit of a two-pole generator.

Field Windings

The field windings are connected so that they produce alternate north and south poles, as shown in Figure 1-16. Connection is done that way to obtain the correct direction of emf in the armature conductors. The field windings form an electromagnet that establishes the generator field flux. These field windings may receive current from an external DC source, or they may be connected directly across the armature, which then becomes the source of voltage. When the windings are energized, they establish magnetic flux in the field yoke, pole pieces, air gap, and armature core (Figure 1-15).

Brushes and Brush Holders

The brushes carry the current from the commutator to an external circuit. Usually they are a mixture of graphite and metallic powder. Brushes are designed to slide freely in their holders because the commutator surface is usually uneven, and the brushes and commutator wear. The freedom thus allows the brushes to have good contact with the commutator despite wear or uneven surfaces.

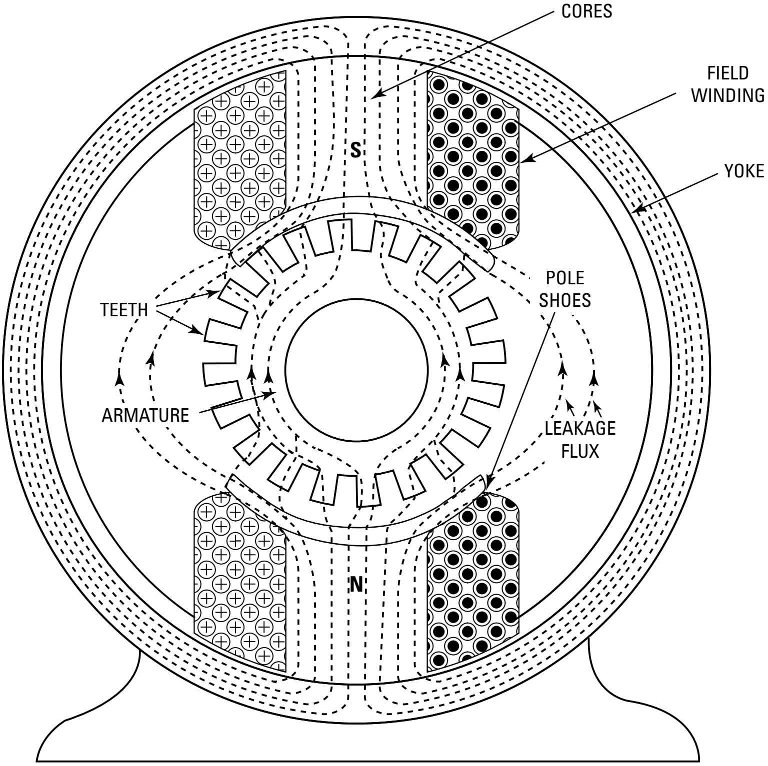

Figure 1-15 Magnetic circuit of a two-pole generator.

Proper pressure of the brushes against the commutator is maintained by means of springs. This pressure is usually about 1½ to 2 pounds per square inch of brush contact area. A low resistance connection—usually braided copper wire—is provided between the brushes and brush holders.

Armature Windings

The simplest generator armature winding is a *loop* or *single coil.* Rotating this loop in a magnetic field induces an emf. The strength of the magnetic field and the speed of rotation of the conductor determine the emf produced.

A *single-coil generator* is shown in Figure 1-17. Each coil terminal is connected to a bar of a two-segment metal ring. The two segments of the split rings are insulated from each other and the shaft. This forms a simple commutator. The commutator mechanically

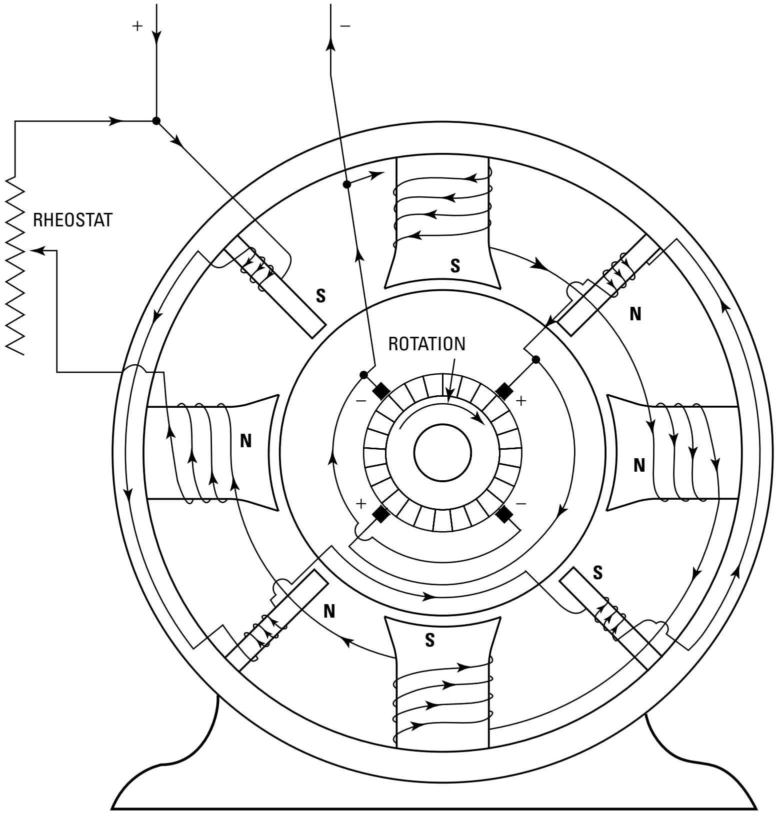

Figure 1-16 Schematic wiring diagram of a shunt generator.

reverses the armature coil connections to the external circuit at the same instant that the direction of the generated voltage reverses the armature coil. This process is known as *commutation*.

Figure 1-18 is a graph of a *pulsating current* (DC) for one rotation of a single-loop, two-pole armature. A pulsating current or *direct voltage* has ripple. In most cases, this current is not usable. More coils have to be added.

The heavy black line in Figure 1-19 shows the DC output of a two-loop (coil) armature. A great reduction in voltage ripple is obtained by using two coils instead of one. Since there are now four commutator segments in the commutator and only two brushes, the voltage cannot fall lower than point *A*. Therefore, the ripple is limited to the rise and fall between points *A* and *B*. Adding more armature coils will reduce the ripple even more.

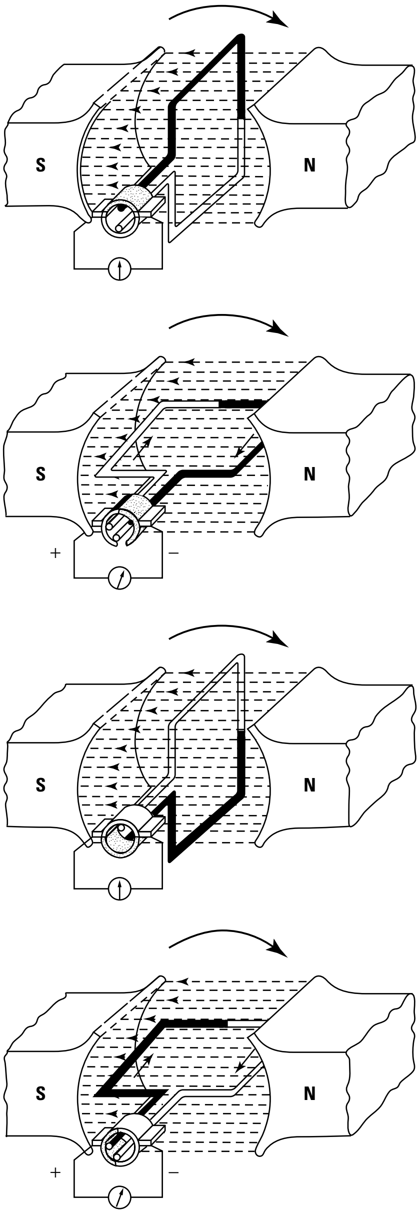

Figure 1-17 Single-coil generator with commutator.

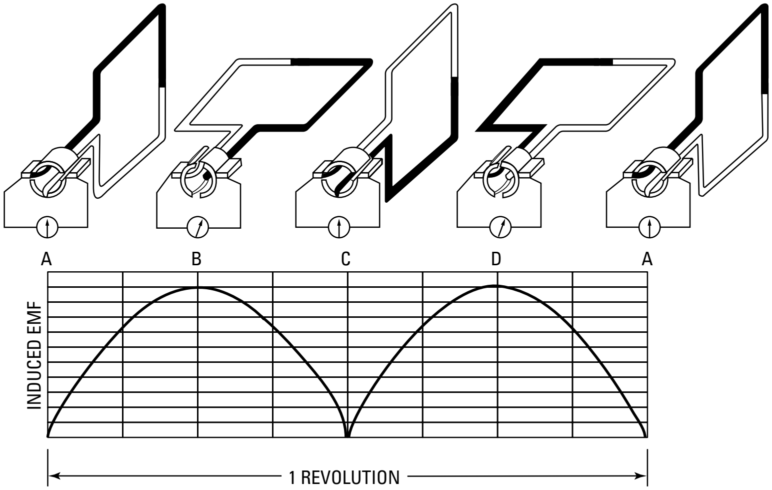

Figure 1-18 Output of a single-coil DC generator.

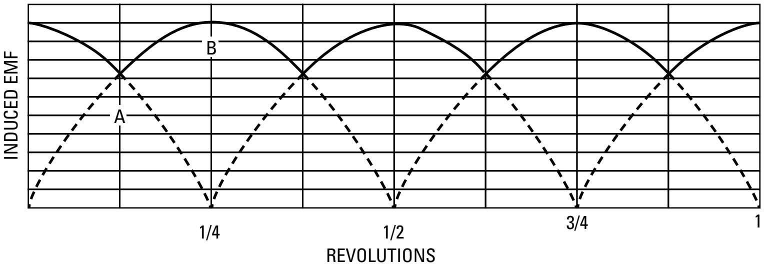

Figure 1-19 Output voltage from a two-coil armature.

Armature Losses

There are three losses in every DC generator armature. One is the *copper loss* in the winding. The second is the *eddy current loss* in the core. The third is the *hysteresis loss* caused by the friction of the revolving magnetic particles in the core.

Copper Losses

Copper loss is the power lost in heat in the windings due to the flow of current through the copper coils. This loss varies directly with the armature resistance and the square of the armature current. The armature resistance varies inversely with the cross-sectional area.

Armature copper loss varies mainly because of the variation of electrical load on the generator and not because of any loss occurring in the machine. This is because most generators are constant-potential machines supplying a current output that varies with the electrical load across the brushes. The limiting factor in load on a generator is the allowable current rating of the generator armature.

The armature circuit resistance includes the resistance of the windings between brushes of opposite polarity, the brush contact resistance, and the brush resistance.

Eddy Current Losses

If a DC generator armature core were made of solid iron and rotated rapidly in the field, as shown in Figure 1-20, part A, excessive heating would develop even with no-load current in the armature windings. This heat would be the result of a generated voltage in the core itself. As the core rotates, it cuts the lines of magnetic field flux at the same time the copper conductors of the armature cut them. Thus, induced currents alternate through the core, first in one direction and then in the other. These currents cause heat.

Such induced currents are called *eddy currents*. They can be minimized by sectionalizing *(laminating)* the armature core. For instance, a core is split into two equal parts, as shown in Figure 1-20, part B. These parts are insulated from each other. The voltage induced in each section of iron is thus one-half of what it would have been if it remained solid. The resistance of the eddy current paths is doubled. That is because resistance varies inversely with the cross-sectional area of the lamination.

If the armature core is subdivided into many sections or laminations, as in Figure 1-20, part C, the eddy current loss can be reduced to a negligible value. Reducing the thickness of the laminations reduces the magnitude of the induced emf in each section. It also increases the resistance of the eddy current paths. Laminations in small generator armatures are usually 1⁄64 in. thick. Often the laminations are insulated from each other by a thin coat of lacquer. Sometimes they are insulated simply by the oxidation of the surfaces caused by contact with the air while the laminations are being annealed. The voltages induced in laminations are small; thus the insulation need not be great.

All electrical rotating machines and transformers are laminated to reduce eddy current losses.

Eddy current loss is also influenced by speed and flux density. The induced voltage, which causes the eddy currents to flow, varies

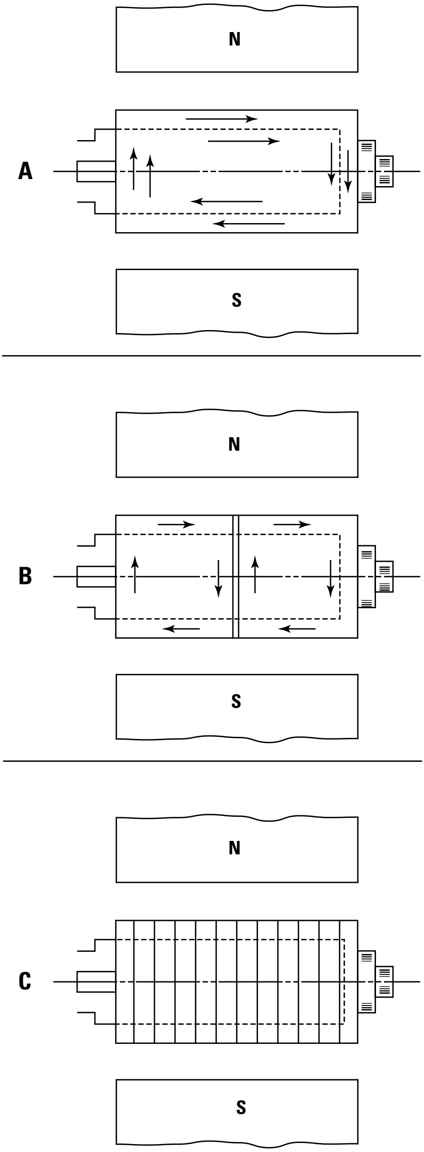

Figure 1-20 Eddy currents in a DC generator armature core.

with the speed and flux density. Therefore, the power loss,

$$P = \frac{E^2}{R}$$

varies as the square of the speed and the square of the flux density.

Hysteresis Losses

When an armature revolves in a stationary magnetic field, the number of magnetic particles of the armature that remain in alignment with the field depends on the strength of the field. If the field is that of a two-pole generator, these magnetic particles will rotate, with respect to the particles not held in alignment, one complete turn for each revolution of the armature. The rotating of the magnetic particles in the mass of iron produces friction and heat.

Heat produced this way is called *magnetic hysteresis loss*. The hysteresis loss varies with the speed of the armature and the volume of iron. The *flux density* varies from approximately 50,000 lines per square inch in the armature core to 130,000 lines per square inch in the iron between the bottom of adjacent armature slots (the *tooth root*). Heat-treated silicon steel having a low hysteresis loss is used in most DC generator armatures. The steel is formed to the proper shape. Then the laminations are heated to a dull red heat and allowed to cool. This annealing process reduces the hysteresis loss to a low value.

Armature Reaction

Armature reaction in a generator is the effect on the main field of the armature acting as an electromagnet. With no armature current, the field is undistorted (Figure 1-21, part A). This flux is produced entirely by the ampere-turns of the main field windings. The neutral plane *AB* is perpendicular to the direction of the main field flux. When an armature conductor moves through this plane, its path is parallel to the undistorted lines of force. Thus, the conductor does not cut through any flux, and no voltage is induced in the conductor. The brushes are placed on the commutator so that they short-circuit coils passing through the neutral plane. With no voltage generated in the coils, no current will flow through the local path formed momentarily between the coils and segments spanned by the brush. Therefore, no sparking at the brushes will result.

When a load is connected across the brushes, armature current flows through the armature conductors. The armature itself

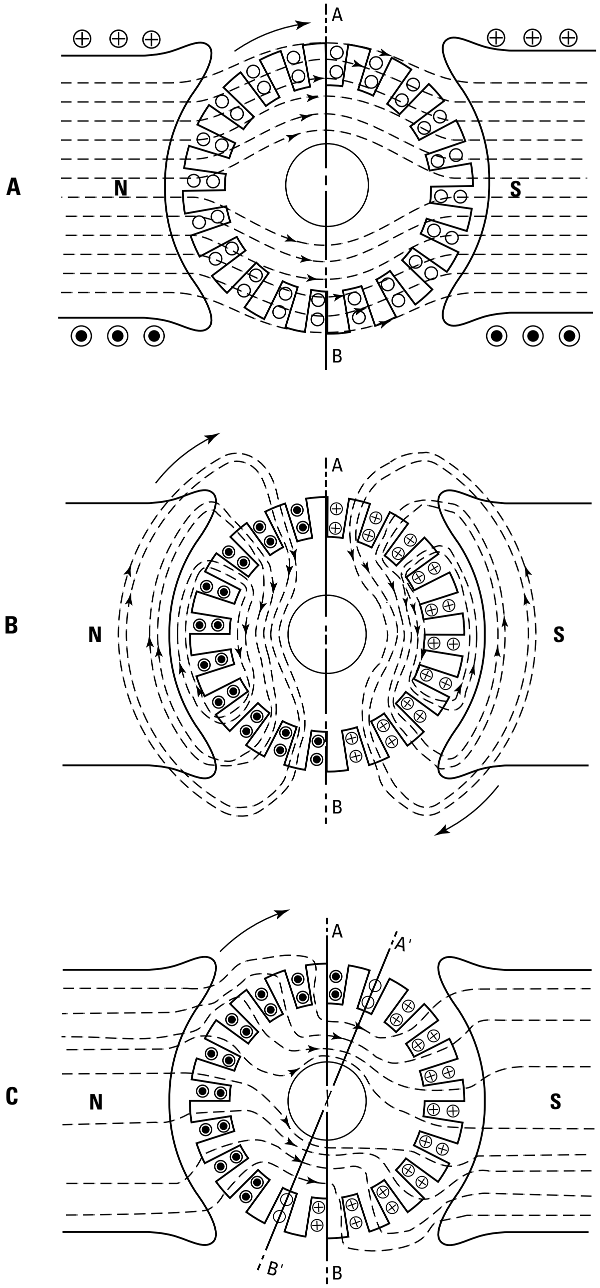

Figure 1-21 Flux distribution in a DC generator.

becomes a source of magnetomotive force. The effect of the armature acting as an electromagnet is shown in Figure 1-21, part B. The main field coils are de-energized, and full-load current is applied to the armature circuit from an external source. The conductors on the left of the neutral plane all carry current toward the observer. Those on the right carry current away from the observer. These directions are the same as those the current would follow under the influence of the normal emf generated in the armature with normal field excitation.

These armature-current-carrying conductors establish magnetomotive force that is perpendicular to the axis of the main field. In Figure 1-21, part B the force acts downward. This magnetizing action of the armature current is called *cross magnetization.* It is present only when current flows through the armature circuit. The amount of cross magnetization produced is proportional to the armature current.

When current flows in both the field and armature circuits, the two resulting magnetomotive forces distort each other (Figure 1-21, part C). They twist in the direction of rotation of the armature. The mechanical (no-load) neutral plane, *AB,* is now advanced to the electrical (load) neutral plane *A'B'*. When the armature conductors move through plane *A'B'*, their paths are parallel to the distorted field. The conductors cut no flux. Thus, no voltage is induced in them. The brushes must, therefore, be moved on the commutator to the new neutral plane. They are moved in the direction of armature rotation. The absence of sparking at the commutator indicates the correct placement of the brushes. The amount that the neutral plane shifts is proportional to the load on the generator. That is because the amount of cross-magnetizing magnetomotive force is directly proportional to the armature current.

Effects of Brush Shift

When the brushes are shifted into the electrical neutral plane *A'B'*, the direction of the armature magnetomotive force is downward and to the left, instead of vertically downward (Figure 1-22, part A). The armature magnetomotive force may now be resolved into two components (Figure 1-22, part B).

The conductors at the top and bottom of the armature within sectors *BB* produce a magnetomotive force that is directly in opposition to the main field and weakens it. This component is called the *armature-demagnetizing mmf.* The conductors on the right and left sides of the armature within sector *AA* produce a *cross-magnetizing*

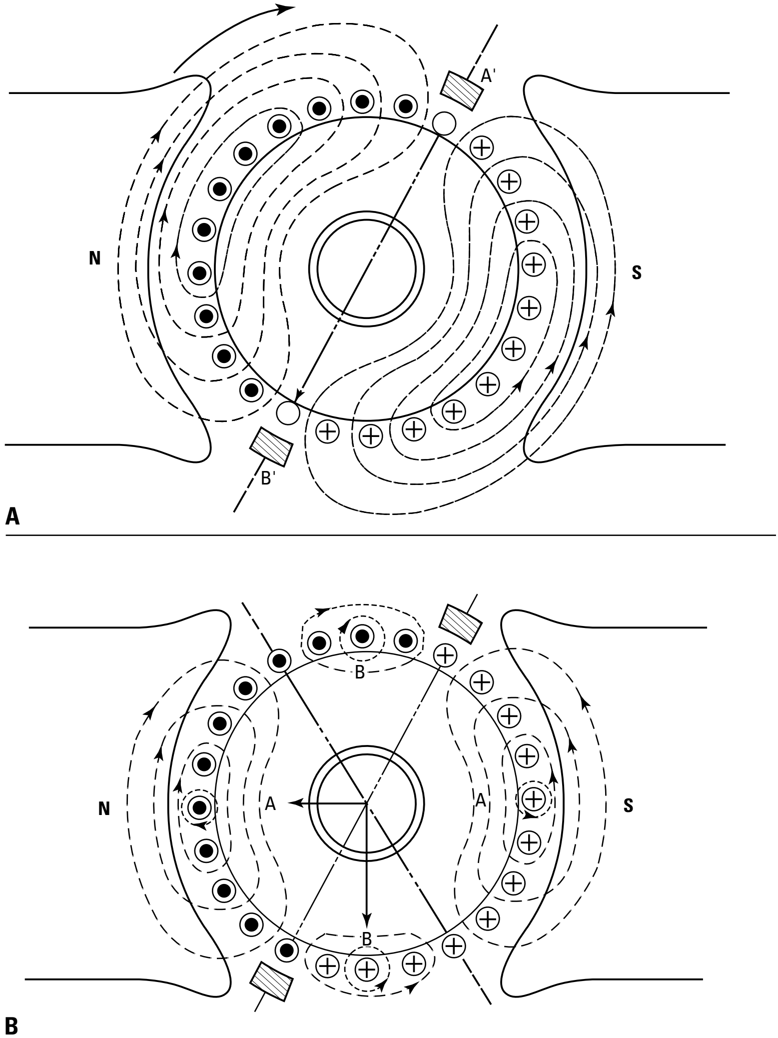

Figure 1-22 Effect of brush shift on armature reaction.

mmf at right angles to the main field axis. This cross-magnetizing force tends to distort the field in the direction of rotation. As mentioned, the distortion of the main field of the generator is the result of armature reaction. Armature reaction occurs in the same manner in multipolar generators.

Compensating for Armature Reaction

The effects of armature reaction are reduced in DC machines by the use of *high-flux density pole tips*, a *compensating winding*, and *commutation poles*.

The cross-sectional area of the pole tips is reduced by building field poles with laminations having only one tip. These laminations are alternately reversed when the pole core is stacked so that a space exists between alternate laminations at the pole tips. The reduced cross section of iron at the pole tips increases the flux density. Thus, they become saturated. Cross-magnetizing and demagnetizing forces of the armature do not affect the flux distribution in the pole face as much as they would reduced flux densities.

The compensating winding consists of conductors embedded in the pole faces parallel to the armature conductors. The winding is connected in series with the armature. It is arranged so that the ampere-turns are equal in magnitude and opposite in direction to those of the armature. The magnetomotive force of the compensating winding, therefore, neutralizes the armature magnetomotive force, and armature reaction is almost eliminated. Compensating windings are costly, so they are generally used only on high-speed and high-voltage large-capacity generators.

Motor Reaction in a Generator

When a generator supplies current to a load, the load current creates a force that opposes the rotation of the generator armature. An *armature conductor* is represented in Figure 1-23. When a conductor is moved downward and the circuit is completed through an external load, current flows through the conductor in

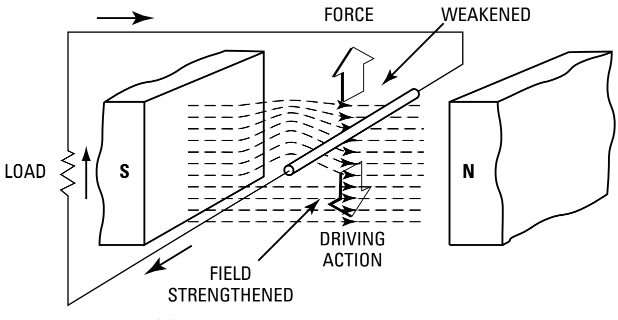

Figure 1-23 Motor reaction in a generator.

the direction indicated. This causes lines of force around it in a clockwise direction.

The interaction of the conductor field and the main field of the generator weakens the field above the conductor and strengthens it below the conductor. The field consists of lines that act like stretched rubber bands. Thus an upward reaction force is produced that opposes the downward driving force applied to the generator armature. If the current in the conductor increases, the reaction force increases. More force must then be applied to the conductor to keep it from slowing down.

With no armature current, no magnetic reaction exists. Therefore, the generator input power is low. As armature current increases, the reaction of each armature conductor against rotation increases. The driving power to maintain the generator armature speed must be increased. If the prime mover driving the generator is a gasoline engine, this effect is accomplished by opening the throttle of the carburetor. If the prime mover is a steam turbine, the main steam-admission valve is opened wide so that more steam can flow through the turbine.

Types of DC Generators

DC generators are classified by how excitation current is supplied to the field coils. There are two major classifications:

- Separately excited
- Self-excited

Self-exciting generators are further classified by the method of connecting the field coils. These include series-connected, shunt-connected, and compound-connected generators.

Separately Excited Generators

A separately excited generator is one for which the field current is supplied by another generator, by batteries, or by some other outside source. Figure 1-24 shows a typical circuit.

Figure 1-25 shows the voltage characteristics of a separately excited generator. When operated at constant speed with constant field excitation but not supplying current, the terminal voltage of this type of generator equals the generated voltage. When the unit is delivering current, the terminal voltage is less than the generated voltage. The total amount of voltage drop equals the drop due to armature reaction plus the voltage drop due to the resistance of the armature and the brushes. Separately excited generators, however, are seldom used.

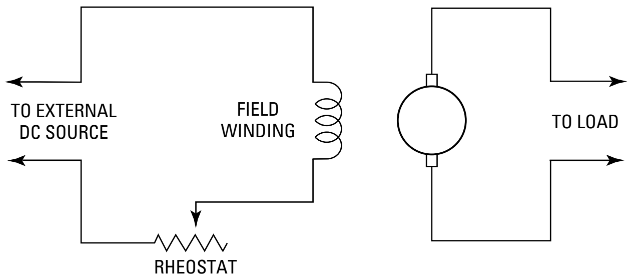

Figure 1-24 Connection of a separately excited DC generator.

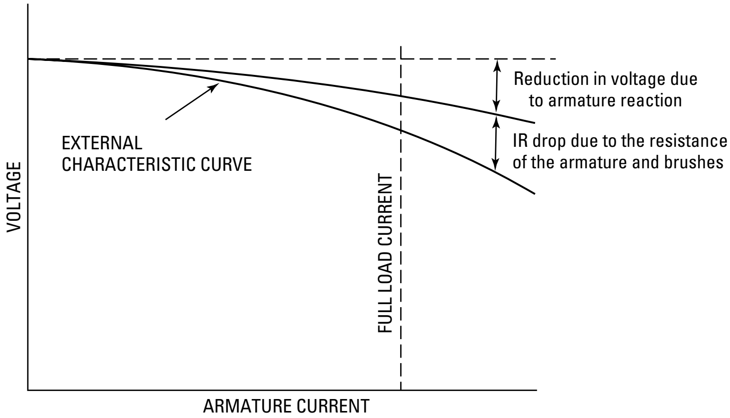

Figure 1-25 Voltage characteristics of a separately excited DC generator.

Self-Excited Generators

There are three types of self-excited generators:

- Series
- Shunt
- Compound

There are some variations of the compound type.

Series Generators

When all the windings are connected in series with the armature, a generator is series-connected. See Figure 1-26 for the typical series-connected circuit. Figure 1-27 shows the voltage characteristics of a

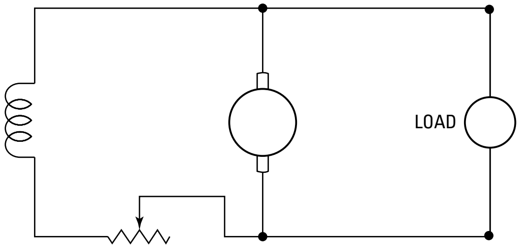

Figure 1-26 A typical series DC generator circuit.

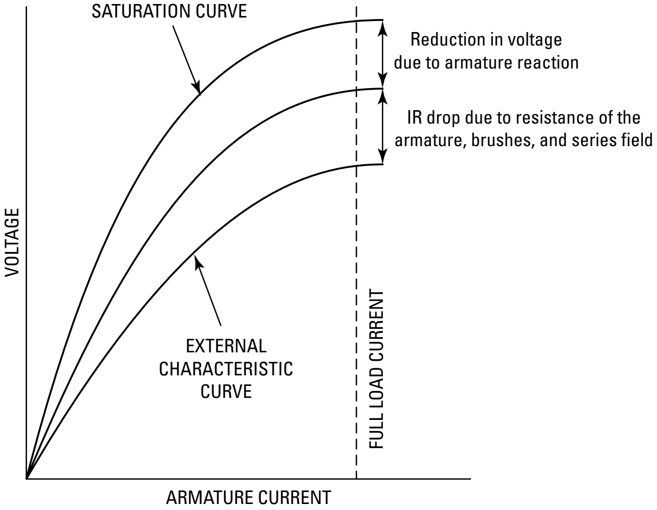

Figure 1-27 Voltage characteristics of a series DC generator.

series generator. With no load, the only voltage present is due to the cutting of the flux established by residual magnetism. (*Residual magnetism* is magnetism retained by the poles of a generator when it is not in operation.) However, when a load is applied or increased, the current through the field coil increases the flux. Therefore, the generated voltage increases. The voltage generated tends to increase directly as the current increases, but three factors lessen the voltage increase.

One factor is *saturation of the field core*. If field excitation is increased beyond the point at which the flux produced no longer increases directly as the exciting current, the core is said to be saturated. The second factor is *armature reaction*. The effect of this reaction increases as the current load increases. The third factor is *loss in terminal voltage*. This loss is caused by ohmic resistance of the armature winding, brushes, and series field. This loss increases as the unit is loaded. Since the terminal voltage of a series generator varies under changing load conditions, it is generally connected in a circuit that demands constant current. When used that way, it is sometimes referred to as a *constant-current generator*, even though it does not tend to maintain a constant current itself. Constant current is achieved by connecting a variable resistance in parallel with the series field. The variable resistance can be manually or automatically controlled. Thus, as the load is increased, the resistance of the shunt path is decreased. This permits more of the current to pass through it and maintains a relatively constant field.

Shunt Generators

When the field windings are connected in parallel with the armature, the generator is shunt-connected. Figure 1-28 is a typical circuit of a shunt generator; Figure 1-29 shows the voltage characteristics of a shunt generator. A comparison of the voltage characteristics of a shunt generator shows they are similar to those of a separately excited generator. In both instances, the terminal voltage drops from the no-load value as the load is increased. But note that the terminal voltage of the shunt generator remains fairly constant until it approaches full load. This is true even though the graph of the shunt generator has an extra factor that causes the terminal voltage to decrease: the weakening of the field as the current approaches full load. It is, therefore, better to use a shunt generator, and not a separately excited or a series generator, when a constant voltage with a varying load is required. Shunt generators

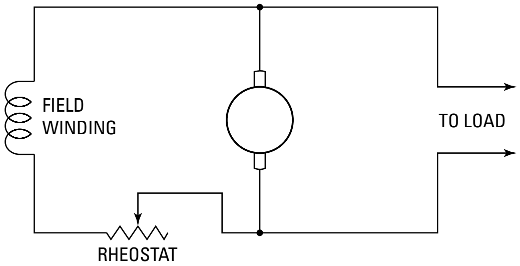

Figure 1-28 Connection of a shunt DC generator.

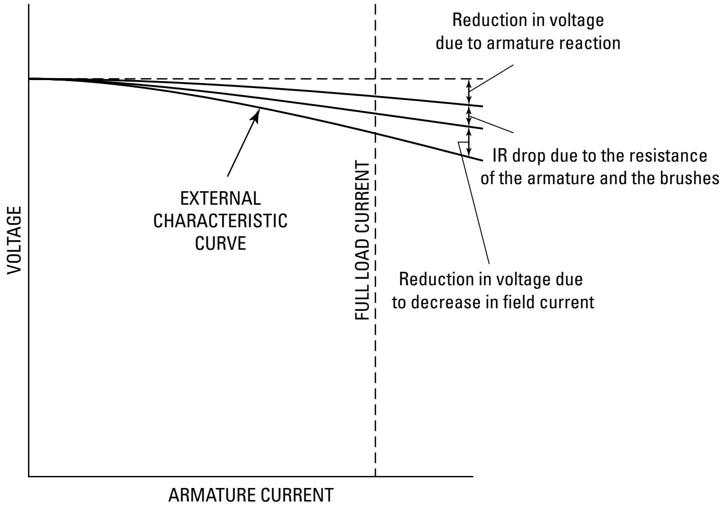

Figure 1-29 Voltage characteristics of a shunt DC generator.

are readily adaptable to applications where the speed of the prime mover cannot be held constant. Aircraft and automobile engines are typical examples of variable-speed prime movers that require a constant voltage. Constant voltage is obtained by controlling generator field current, which is accomplished by varying the shunt field resistance to compensate for changes in speed of the prime mover.

Compound Generators

If both a series and a shunt field are included in the same unit, it is possible to obtain a generator with a voltage-load characteristic somewhere between those of a series and a shunt generator. Figure 1-30 shows typical circuits of a compound-wound (series-shunt) DC generator. Figure 1-30, part A, is a cumulative compounded generator. Its series and shunt fields are wound to aid each other. Figure 1-31 shows the voltage characteristics of a compound-wound DC generator. By changing the number of turns in the series field, it is possible to obtain three distinct types of compound generators.

Overcompounded An *overcompounded generator* is one in which there are more turns in the series field than necessary to give about the same voltage at all loads. Thus, the terminal voltage at full load will be higher than the no-load voltage. This is desirable when

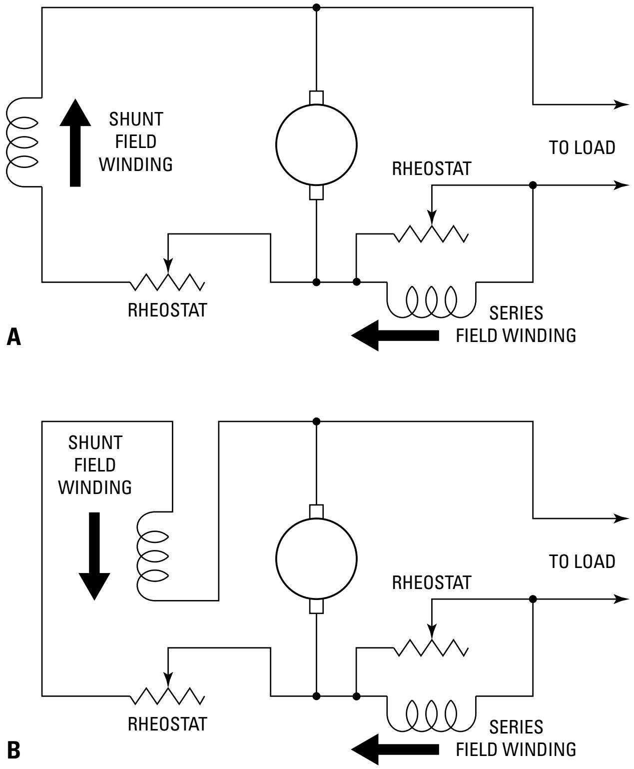

Figure 1-30 Typical compound-wound DC generator circuits.

power must be transmitted a long distance. The higher generated voltage compensates for the voltage loss in the transmission line.

Flat Compounded A *flat-compounded generator* is one in which the relationship of the turns in the series and shunt fields is such that their terminal voltage is about the same over the entire load range.

Undercompounded An *undercompounded generator* is one in which the series field does not have enough turns to compensate for the voltage drop of the shunt field. The voltage at full load is less than the no-load voltage. In an undercompounded generator, the series and shunt fields are connected so as to oppose rather than to aid one another. It is referred to as being *differentially compounded*. The terminal voltage of this type of generator decreases rapidly as the load increases. Undercompounded generators are used in applications where a short circuit might occur, as in an arc welder.

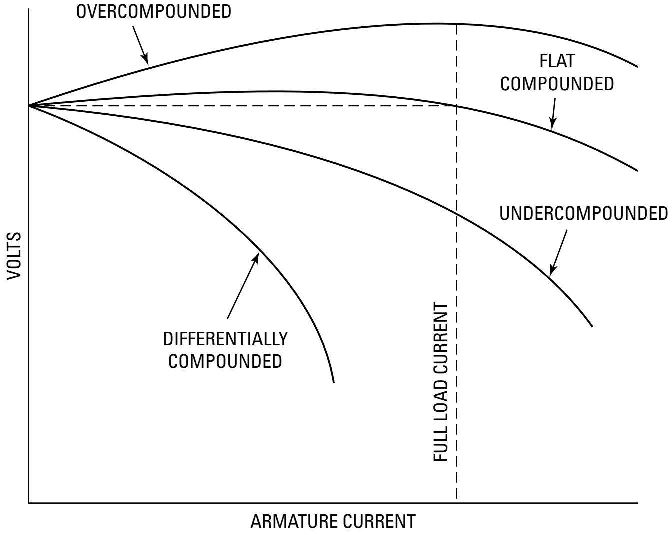

Figure 1-31 Voltage characteristics of a compound-wound DC generator.

Control of DC Generators

Generally, the DC generator is controlled by a resistor that produces variable resistance, called a *rheostat*. After the generator is brought up to speed by the prime mover, the rheostat is adjusted. The rheostat may be manually or automatically operated. The adjustment of the rheostat controls the amount of excited current fed to the field coils. Metering requires the use of a DC voltmeter and ammeter of appropriate ranges in the generator output circuit. Matched sets of shunt-wound or compound-wound generators with series-field equalizer connections are used for parallel operation. Precautions must be observed when connecting the machines to generator buses.

Series Generator

The series generator is classified as a *constant-speed generator*. It can be used to supply series motors, series arc-lighting systems, and voltage boosting on long DC feeder lines. The series generator is excited entirely by low-resistance field coils connected in series with the armature terminals and the load. The circuit of a DC series generator is shown in Figure 1-26. The voltage increases with load because the load current provides the necessary additional field excitation. Low-resistance shunts may be used across series field coils to obtain desired voltage characteristics. The series field of the generator is adjusted so the output voltage may be maintained at a constant value. Because series generators have poor voltage regulation, only a few are in use.

Shunt Generator

The shunt DC generator can be called a *constant-potential generator*. It is seldom used for lighting and power because of its poor voltage regulation. The field coils in this type of generator have a comparatively high resistance; they are connected across the armature terminals in series with the rheostat. A DC shunt generator circuit is shown in Figure 1-28. Shunt generators sometimes have separate excitation. This prevents reversal of the generator polarity and allows better voltage regulation. Shunt generators are frequently used with automatic voltage regulators as exciters for AC generators.

Compound Generator

The compound generator is the most widely used DC generator. The speed of a compound generator affects its generating characteristics. Therefore, the compounding can be varied. The engine governor can be adjusted for the proper no-load voltage. The range of the shunt-field rheostat and the engine characteristic limit the amount of speed variation that can be obtained. Compound generators can be connected either cumulatively or differentially.

Direct-Current Motors

A machine that converts electrical energy into mechanical energy is called a *motor.* The functions of a DC generator and a DC motor are interchangeable in that a generator may be operated as a motor, and vice versa. Structurally, the two machines are identical. The motor, like the generator, consists of an electromagnet, an armature, and a commutator with its brushes.

Figure 1-10 will serve to illustrate the operation of a direct-current motor as well as a generator. The magnetic field, as indicated, will be the same for a motor because of current flowing in the field windings. Now, let the outside current at *A* have a voltage applied that causes a current to flow in the armature loop, as indicated by the arrows.

It must be remembered that any current flowing in a loop or coil of wire produces a magnetic field. This is exactly what happens in the armature of this motor. In addition, a second magnetic field is produced, with poles N and S perpendicular to the armature loop. The north pole of the main magnetic field attracts the south pole of the armature, and since the loop is free, it will revolve. At the instant the north and south poles become exactly opposite, however, the commutator reverses the current in the armature, making the poles of the field and the armature opposite, and the loop is then repelled and forced to revolve further. Again the armature current is reversed when unlike poles approach, and the armature is free to revolve. This continues as long as there is current in the armature and field windings.

It should be observed that, in an actual motor, there is more than one loop (called an *armature coil*), each with its terminals connected to adjacent commutator segments (Figure 1-11). Hence, the attracting and repelling action is correspondingly more powerful and also more uniform than that of the weak and unstable action obtained with the single-loop armature described here.

The various types of direct-current motors as well as their operating characteristics and control methods are fully treated in a later chapter.

Alternating-Current Motors

When a coil of wire is rotated in a magnetic field, the current changes its direction every half turn. Thus, there are two alternations of current for each revolution of a bipolar machine. As previously noted, this alternating current is rectified by the use of a commutator in a direct-current generator. In an alternating-current generator, also termed an *alternator,* the current induced in the armature is led out through *slip rings* or *collector rings,* as shown in Figure 1-32.

A magnetic field is established between the north pole and the south pole by means of an exciting current flowing in winding *W.* A loop of wire, *L,* in this field is arranged so that it can be rotated on axis *X,* and the ends of this loop are brought out to slip rings *SS,* on which brushes *BB* can slide.

This circuit, of which the rotating loop is a part, is completed through the slip rings at *A.* When the loop is rotating, voltage is produced in conductors *F* and *G,* which will cause a current to flow out to *A* where the circuit is completed.

The simplified machine represented in Figure 1-32 is a two-pole, single-phase, revolving-armature, alternating-current generator. The magnetic field—the coils of wire and iron core—are called simply the field of the generator. The rotating loop in which the voltage is induced is called the armature.

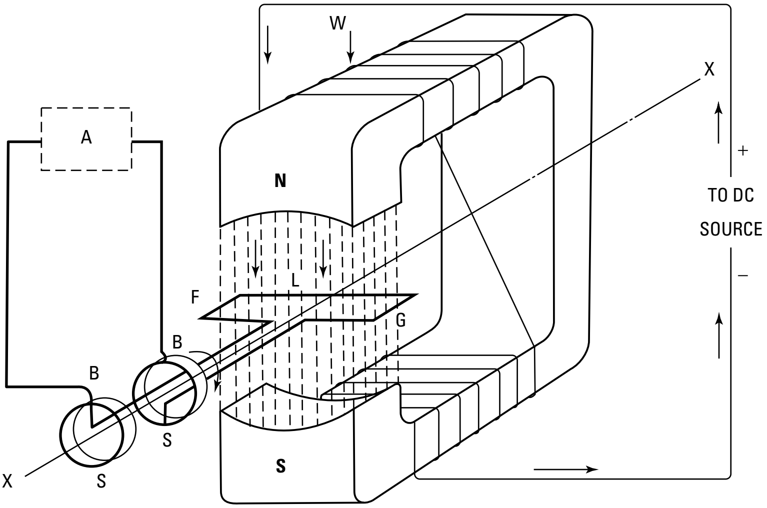

Figure 1-32 An elementary alternating-current (AC) generator of the rotating-armature type. The slip rings and brushes are used to collect the current from the armature.

The rotating-armature type of generator is generally used only on small machines, whereas large machines almost without exception are built with rotating fields.

If the voltage completes 60 cycles in one second, the generator is termed a *60-hertz* machine. The current that this voltage will cause to flow will be a 60-hertz current. The term *hertz* (Hz) indicates cycles per second.

Polyphase Machines

A two-phase generator is actually a combination of two single-phase generators, as shown in Figure 1-33. The armatures of these two machines are mounted on one shaft and must revolve together, always at right angles to each other. If the voltage waves or curves are plotted as in Figure 1-34, it will be found that when phase 1 is in such a position that the voltage is at a maximum, phase 2 will be in such a position that the voltage in it is zero. A quarter of a cycle later, phase 1 will be zero and phase 2 will have advanced to a position previously occupied by 1, and its voltage will be at a maximum. Thus, phase 2 follows phase 1 and the voltage is always exactly a quarter of a cycle behind because of the relatively mechanical positions of the armatures.

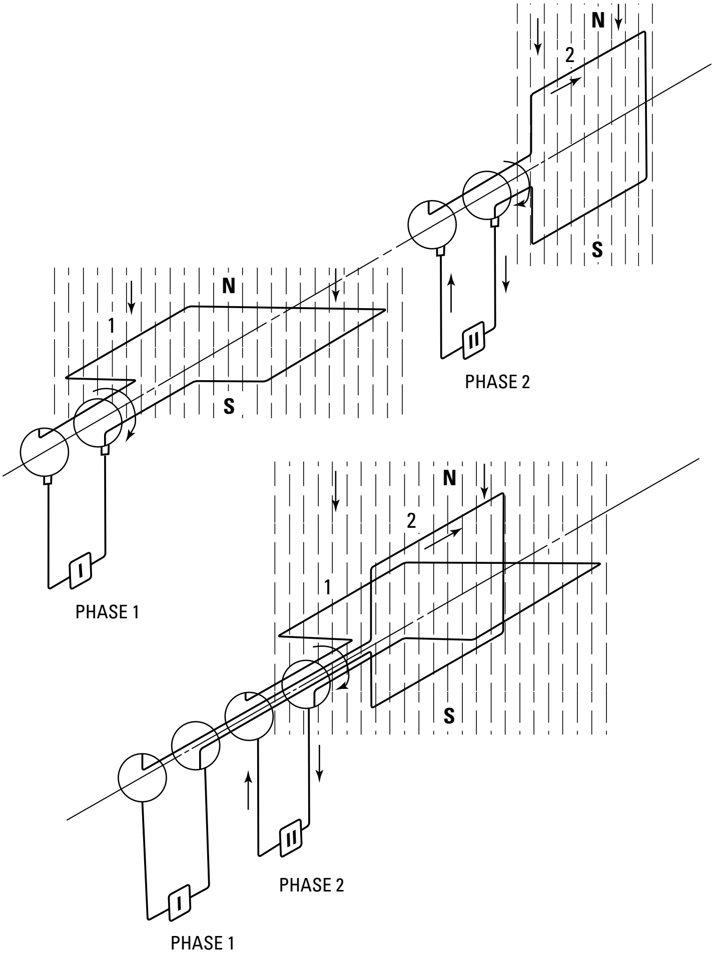

Figure 1-33 An elementary two-phase AC machine constructed by combining the two single-phase machines shown at the top of the illustration.

It has been found economical to have more than one coil for each pole of the field. Because of this, present-day AC generators are built as three-phase units in which there are three sets of coils on the armature. These three sets of armature coils may each be used separately to supply electricity to three separate lighting circuits.

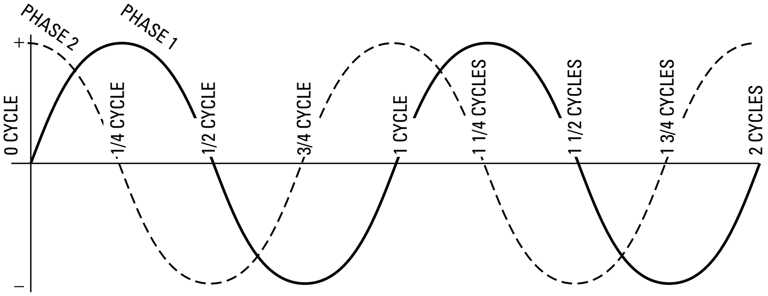

Figure 1-34 Curves representing the voltage in two separate loops of wire that are positioned at right angles to each other and rotating together.

In a three-phase generator, three single-phase coils (or windings) are combined on a single shaft and rotate in the same magnetic field, as shown in Figure 1-35. Each end of each coil is brought out through a slip ring to an external circuit. The voltage in each phase alternates exactly one-third of a cycle after the one ahead of it

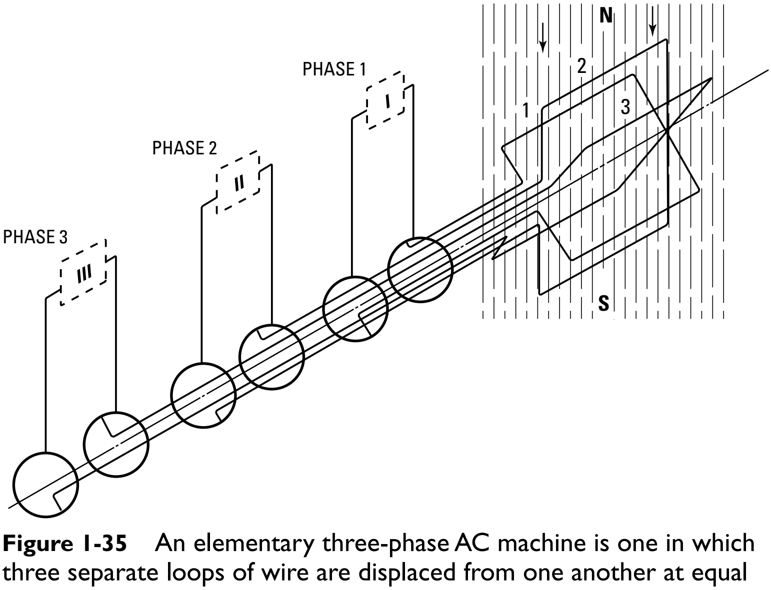

Figure 1-35 An elementary three-phase AC machine is one in which three separate loops of wire are displaced from one another at equal angles, the loops made to rotate in the same magnetic field, and each loop brought out to a separate pair of slip rings.

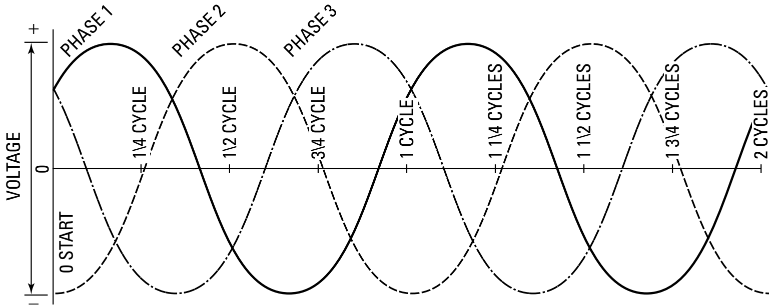

Figure 1-36 Curves illustrating the voltage variation in a three-phase machine. One cycle of rotation produces 1 Hz of alternating current.

because of the mechanical arrangement of the windings on the armature. Thus, when the voltage in phase 1 is approaching a maximum positive, as shown in Figure 1-36, the voltage in phase 2 is at a maximum negative, and the voltage in phase 3 is declining. The succeeding variations of these voltages are as indicated.

In practice, the ends of each phase winding are not brought out to separate slip rings, but are connected as shown in Figure 1-37.

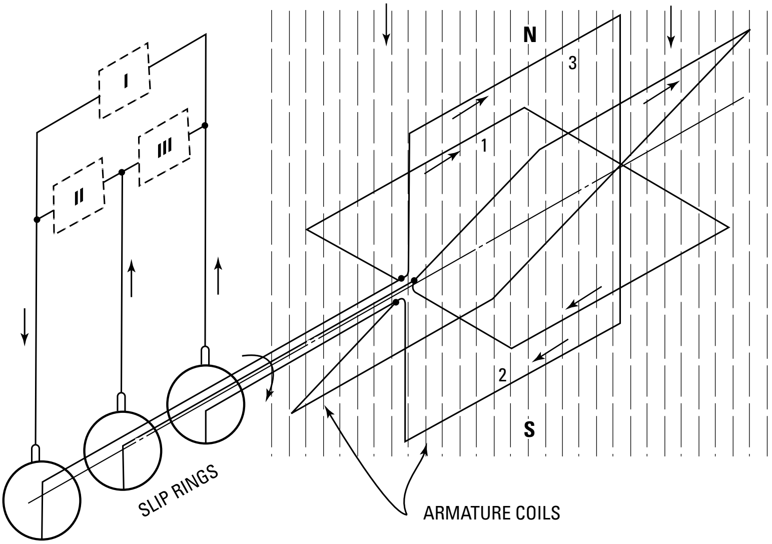

Figure 1-37 Commercial three-phase machines usually have the separate loops of wire connected as shown. This requires only three slip rings.

This arrangement makes only three leads necessary for a three-phase winding, each lead serving two phases. This allows each pair of wires to act like a single-phase circuit that is substantially independent of the other phases.

Revolving Magnetic Field

In the diagrams studied thus far, the poles producing the magnetic field have been stationary on the frame of the machine, and the armature in which the voltages are produced rotates. This arrangement is universally employed in direct-current machines, but alternating-current motors and generators generally have revolving fields because they need only two slip rings.

When the revolving-field construction is employed, the two slip rings need only carry the low-voltage exciting current to the field. For a three-phase machine with a rotating armature, at least three slip rings would be required for the armature current, which is often at a high voltage and therefore would require a large amount of insulation, adding to the cost of construction. A schematic of a single-phase AC generator with revolving field is shown in Figure 1-38.

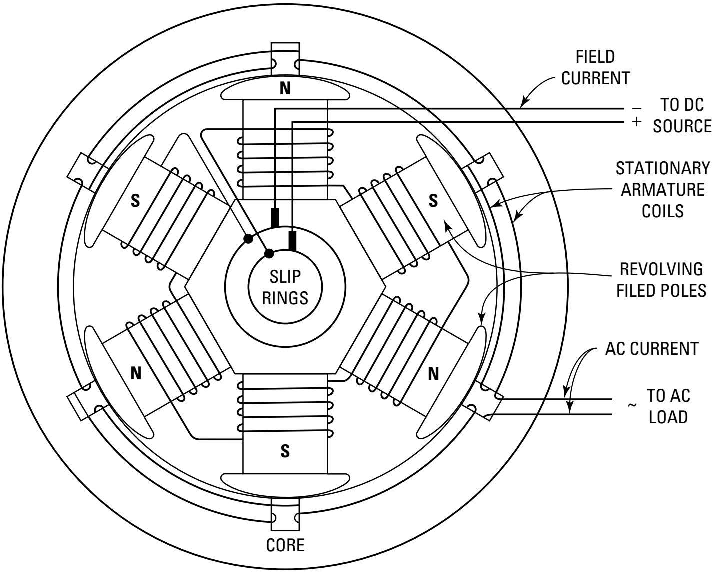

Figure 1-38 Construction details of an AC generator having six poles and a revolving field. If this generator is to deliver 60 Hz current, it must be driven at a speed of exactly 1200 rpm.

The operation of practically all polyphase alternating-current motors depends on a revolving magnetic field that pulls the rotating part of the motor around with it.

To produce a rotating field, assume that two alternating currents of the same frequency and potential, but differing in phase by 90°, are available. Connect them to two sets of coils wound on the inwardly projecting poles of a circular iron ring, as illustrated in Figure 1-39. It will be noted that when the current in phase 1 is at a maximum, the current in phase *2* is zero. Poles *A* and A_1 are magnetized, while poles *B* and B_1 are demagnetized. The magnetic flux is in a direction from N to S, as indicated by the arrow in the center of diagram I.

Referring to the voltage curves, it will be found that one-eighth of a cycle (45°) later, the current in phase 1 has decreased to the same value to which the current in phase 2 has increased. The four poles are now equally magnetized, and the magnetic flux takes the direction of the arrow shown in the center of diagram II.

One-eighth of a cycle later, the current in phase 1 has dropped to zero, while the current in phase 2 is at its maximum. With reference to diagram III, in Figure. 1-39, this condition indicates that poles *A* and A_1 are demagnetized, but that poles *B* and B_1 are magnetized, with the flux from N to S, as shown by the center arrow.

Continuing the analysis, notice that after an additional one-eighth of a cycle, the current in both phases 1 and 2 has decreased and that the four poles are again equally magnetized, with the magnetic flux in the direction as indicated by the center arrow in diagram IV. If this process is continued at successive intervals during a complete period or cycle of change in the alternating current, the magnetic flux represented by the arrow will make a complete revolution for each cycle of the current.

The action of the current is inducing a rotating magnetic field, which would cause a magnet to revolve on its axis according to the periodicity of the impressed alternating current. This analysis explains the action in a two-phase motor. The rotating magnetic field in a three-phase AC motor having any number of poles can be similarly obtained.

Synchronous Motors

Any AC generator can be employed as a motor, provided that it is first brought up to the exact speed of a similar generator supplying the current to it, and provided that it is then put in step with the alternations of the supplied current. Such a machine is called a *synchronous motor.* However, because of complications in starting,

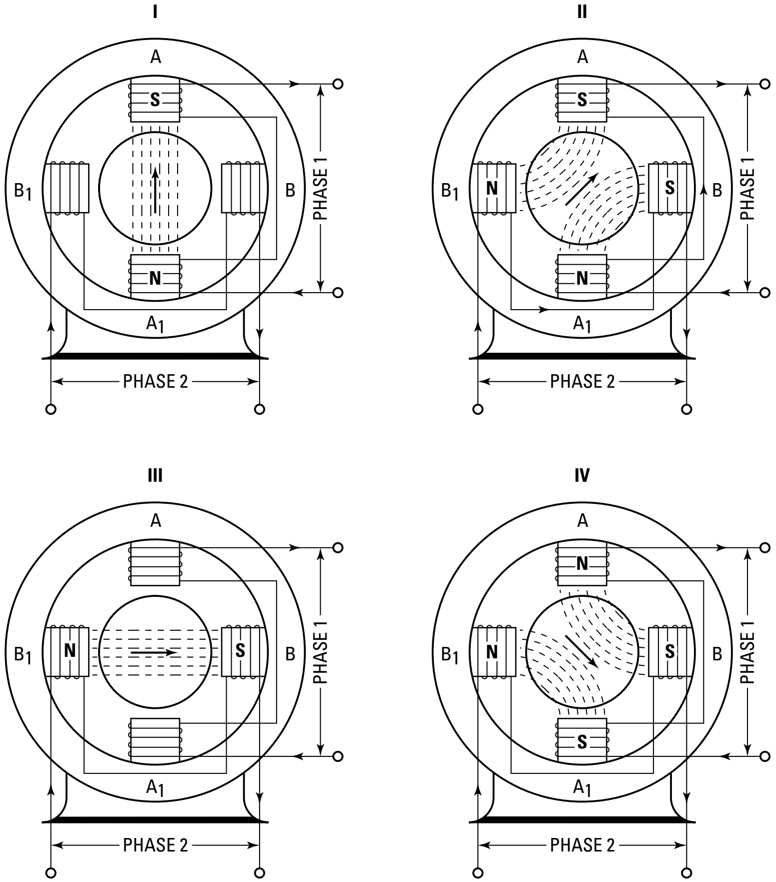

Figure 1-39 Illustrating how a rotating magnetic field is produced by two currents 90° apart.

most synchronous motors of late construction are equipped with a *damper* or *amortisseur* winding, which produces a starting torque, permitting them to be started as induction motors.

The speed of a synchronous motor depends on the frequency of the current supplied to it and the number of poles in the motor. The equation for the speed is

$$\text{revolutions per minute} = \frac{\text{frequency} \times 60}{\text{number of pairs of poles}}$$

Since a synchronous motor runs at exactly this speed, it is a relatively simple matter to calculate the speed of any motor provided that the number of poles and the frequency of the source are known. Thus, for example, an eight-pole synchronous motor operating from a 60-Hz source has a speed of

$$\text{rpm} = \frac{60 \times 60}{4} = 900 \text{ rpm}$$

Induction Motors

Although the synchronous motor is used commercially in certain applications, the induction motor is used more extensively because of its simplicity. There are two principal classes of polyphase motors, namely:

- Squirrel cage
- Wound rotor

By definition, an induction motor is one in which the magnetic field in the rotor is induced by currents flowing in the stator. The rotor has no connections whatever to the supply line.

Squirrel-Cage Motor

This type of induction motor consists of a *stator,* which is identical to the armature of a synchronous motor, with a "squirrel-cage" rotor with bearings to support it. Because the stator receives the power from the line, it is often called the *primary* and the rotor the *secondary.*

In an induction motor of this type, the squirrel-cage winding takes the place of the field in the synchronous motor. The squirrel cage consists of a number of metal bars connected at each end to supporting metal rings. As in the synchronous motor, a rotating field is set up by the currents in the armature.

As this field revolves, it cuts the squirrel-cage conductors, and voltages are set up in them exactly as though the conductors were cutting the field in any other motor. These voltages cause current to flow in the squirrel-cage circuit, through the bars under the north poles into the ring, back to the bars under the adjacent south poles, into the other ring, and back to the original bars under the north pole, completing the circuit.

The current flowing in the squirrel cage, down one group of bars and back in the adjacent group, makes a loop that establishes magnetic fields with north and south poles in the rotor core. This loop consists of one turn, but there are several conductors in parallel and the currents may be large. These poles in the rotor, attracted by the poles of the revolving field, set up the currents in the armature winding and follow them around in a manner similar to that in which the field poles follow the armature poles in a synchronous motor.

There is, however, one interesting and important difference between the synchronous motor and the induction motor: The rotor of the latter does not rotate as fast as the rotating field in the armature. If the squirrel cage were to go as fast as the rotating field, the conductors in it would be standing still with respect to the rotating field, rather than cutting across it. Thus, there could be no voltage induced in the squirrel cage, no currents in it, no magnetic poles set up in the rotor, and no attraction between it and the rotating field in the stator. The rotor revolves just enough slower than the rotating field in the stator to allow the rotor conductors to cut the rotating magnetic field as it slips by, and thus induces the necessary currents in the rotor windings.

This means that the motor can never rotate quite as fast as the revolving field, but is always slipping back. This difference in speed is called the *slip*. The greater the load, the greater the slip will be—that is, the slower the motor will run—but even at full load, the slip is not too great. In fact, this motor is commonly considered to be a constant-speed device. The various classes of squirrel-cage motors, and their operation and control, are given in a later chapter.

Wound-Rotor Motor

This type of induction motor differs from the squirrel-cage type in that it has wire-coil windings in it instead of a series of conducting bars in the rotor. These insulated coils are grouped to form definite polar areas having the same number of poles as the stator. The rotor windings are brought out to slip rings whose brushes are connected to variable external resistances (Figure 1-40).

By inserting external resistance in the rotor circuit when starting, a high torque can be developed with a comparatively low starting current. As the motor accelerates up to speed, the resistance is gradually reduced until, at full speed, the rotor is short-circuited. By varying the resistance at the rotor circuit, the motor speed can be regulated within practical limits.

This method of speed control is well-suited for the wound-rotor motor because it is already equipped with a starting resistance in each phase of the rotor circuit. By making these resistances of large-enough, current-carrying capacity to prevent dangerous heating in

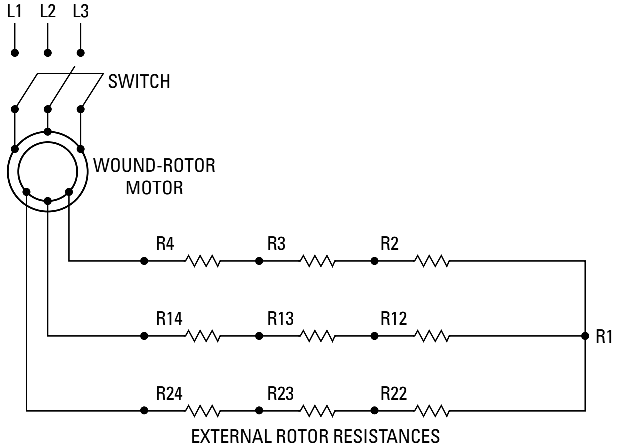

Figure 1-40 Wiring diagram showing the connections between the slip rings and external resistances for a wound-rotor motor. The resistances are connected to a drum controller, the drum rotation of which determines the amount of resistance in the circuit and thus the speed of the motor.

continuous service, the same resistances can also serve to regulate the speed. Although effective speed control is best secured by the use of direct-current motors, the wound-rotor motor, because of its adjustable rotor resistance, possesses one of the few methods of speed control available for alternating-current motors.

Slip

The speed of a synchronous motor is constant for any given frequency and number of poles in the motor. In an induction motor, however, this exact relationship does not exist, because the rotor slows down when the load is applied. The ratio of the speed of the field (relative to the rotor) to synchronous speed is termed the *slip*. It is usually written:

$$s = \frac{N_s - N}{N_s}$$

where s is the slip (usually expressed as a percentage of synchronous speed), N_s is the synchronous speed, N is the actual rotor speed.

For example, a six-pole, 60-Hz motor would have a synchronous speed of 1200 rpm. If its rotor speed were 1164 rpm, the slip would be:

$$s = \frac{1200 - 1164}{1200} = 0.03, \quad \text{or} \quad 3\%$$

Single-Phase Motors

Single-phase induction motors may be divided into two principal classes, namely

- Split-phase
- Commutator

Split-phase motors are further subdivided into resistance-start, reactor-start, split-capacitor, and capacitor-start motors. Commutator-type motors are subdivided into two groups, series and repulsion, and each of these is further subdivided into several types and combinations of types.

These two classes and subdivisions represent various electrical modifications of single-phase induction motors, where one modification must be used to produce the necessary starting torque. All methods serve to increase the phase angle between the main winding and the starting winding so as to produce a rotating magnetic field similar to that in a two-phase motor.

Resistance-Start Motors

A resistance-start motor is a form of split-phase motor having a resistance connected in series with the starting (sometimes called *auxiliary*) winding. A schematic diagram of this type of motor may be represented as in Figure 1-41. This shows a resistance connected in series with the starting winding to provide a two-phase rotating-field effect for starting. When the motor reaches approximately 75 percent of its rated speed, a centrifugal switch opens to disconnect the starting winding from the line. This motor is known as resistance-start, split-phase type and is commonly used on washing machines and similar appliances. It is not practical to build such motors for the heavier types of starting duty.

Split-Capacitor Motors

In a split-capacitor motor (Figure 1-42), two stationary windings are connected to a single-phase line. The capacitor has the peculiar characteristic of shifting the phase of the current in coil 2 with

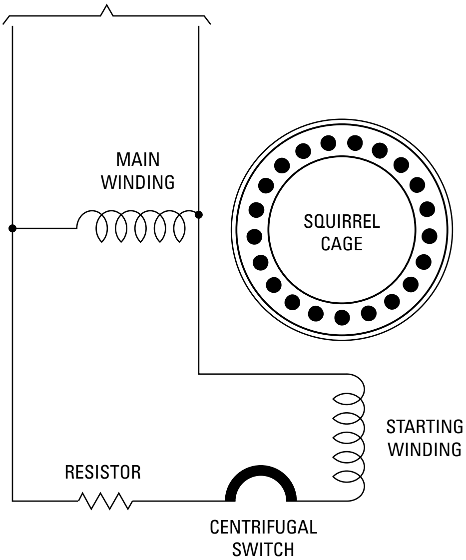

Figure 1-41 Schematic diagram showing the winding arrangement of a resistance-start, split-phase, induction motor.

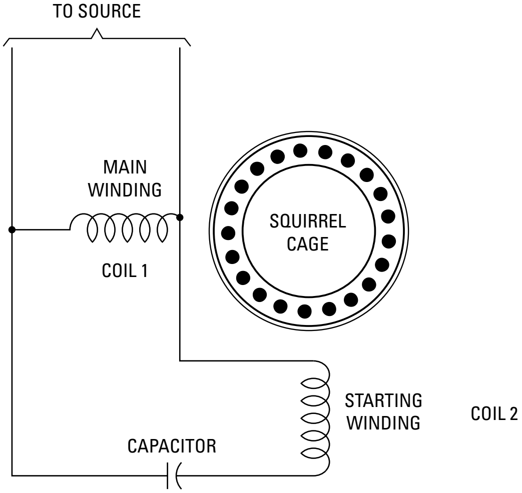

Figure 1-42 Schematic diagram of a split-capacitor motor.

respect to the current in coil 1. This provides the same action as in the two-phase motor discussed previously, producing the rotating field effect to rotate the squirrel-cage rotor. The capacitor is mounted permanently in the circuit. Because capacitors for continuous duty are expensive and somewhat bulky, it is not practical to make this motor for heavy-duty starting.

Capacitor-Start Motors

In applications where a high starting torque is required, a motor such as that shown in Figure 1-43 is employed. This is only another form of split-phase motor having a capacitor (or condenser, as it was once called) connected in series with the starting winding. The construction is similar to the split-capacitor motor, but differs mainly in that the starting winding is disconnected at approximately 75 percent of rated speed by a centrifugal switch, as in the case of the resistance-start motor.

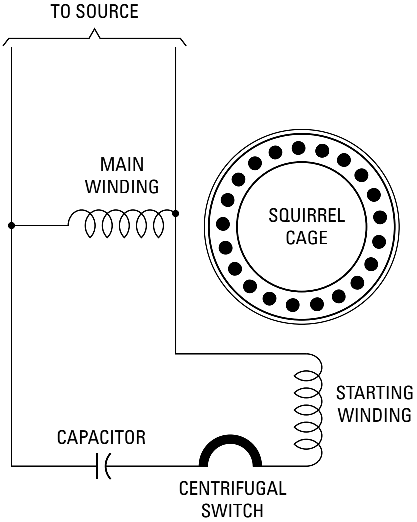

Figure 1-43 Winding connections in a capacitor motor.

The centrifugal switch is mounted on the motor shaft and, as the name implies, works on the centrifugal principle, disconnecting the starting winding when the speed at which the switch is set is reached. The capacitor-start motor has a greater starting ability than the resistance-start motor. Because the capacitor is in use only during the starting period, a high capacity can be obtained economically for this short-term duty.

Shaded-Pole Motors

Another type of single-phase induction motor is schematically represented in Figure 1-44. This motor consists principally of a squirrel-cage rotor and two or more coils with an iron core to increase the magnetic effect. Part of one end of this core is surrounded by a heavy copper loop known as the *shading ring.* This ring has the characteristic of delaying the flow of magnetism through it. With alternating current applied to the coil, the magnetism is strong first at *A,* and then slightly later at *B.* This gives a rotating-field effect that causes rotation of the squirrel cage in the direction in which the shading ring points. A motor thus constructed is known as a *shaded-pole motor.*

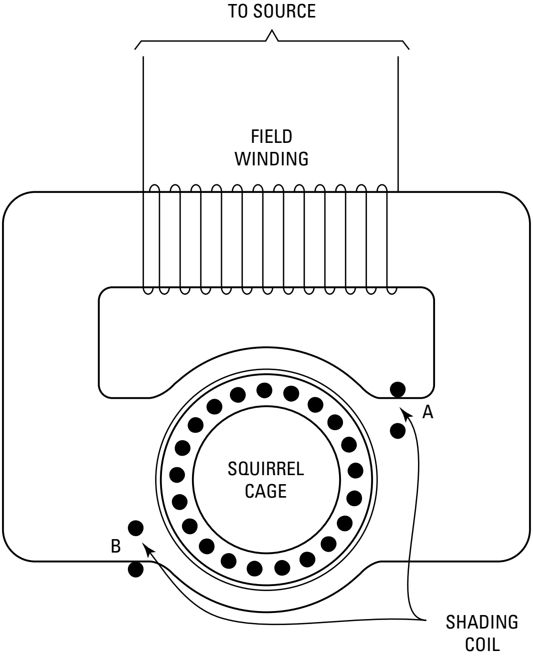

Figure 1-44 Arrangement of the windings in a skeleton-type, shaded-pole motor.

Because of the limitations of force and current possible in shading poles, it is not feasible to build efficient motors of this type larger than approximately 1⁄20 hp (or 37.3 W). These motors are

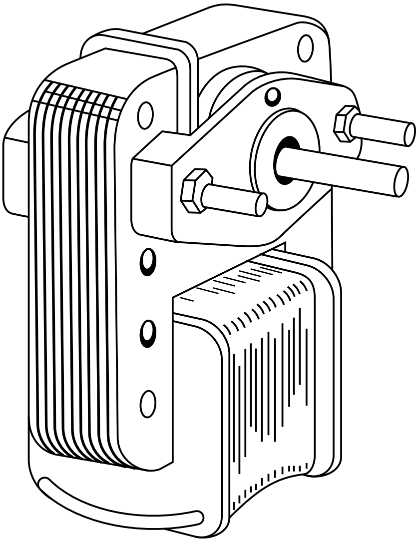

Figure 1-45 Small shaded-pole fan motor.

used principally on small fans, agitators, and timing devices (Figure 1-45).

Repulsion-Start Induction Motors

Repulsion-start induction motors are operated in various ways. In the running position, the brushes may or may not be raised. If the same rotor winding is used for both starting and running, the commutator is short-circuited at about 75 percent of rated speed to obtain a rotor winding approximating the squirrel cage in its functioning. Other designs have two rotor winding, that is, a squirrel cage and a wound winding for running and starting, respectively. In this type, no rotor mechanism is required because the magnetic conditions automatically transfer the burden from one winding to the other as the motor comes up to speed.

Repulsion starting may best be explained by the action of a wire connected to a battery and moved across the face of a magnet. Here, there is a force on the wire that, for example, tends to move it upward or downward, depending on the direction in which the current is flowing. It can thus be demonstrated that a current-carrying wire in a magnetic field has a force acting on it that tends to move it in a certain direction. Also, if the direction of the current flowing through the wire is reversed, the force and motion are also reversed.

Repulsion starting operates on this principle. Current is caused to flow in the wires of the rotor winding, and these wires are affected by a magnetic field.

Figure 1-46 shows a stationary C-shaped iron core on which is mounted a coil connected to a single-phase supply line. In the opening of the C is a ring of iron on which is wound a continuous and uniform coil. The path of the magnetism produced by the coil wound on the C-shaped core is around through the C-shaped core, and, dividing equally, half of the magnetism passes through each half of the iron ring.

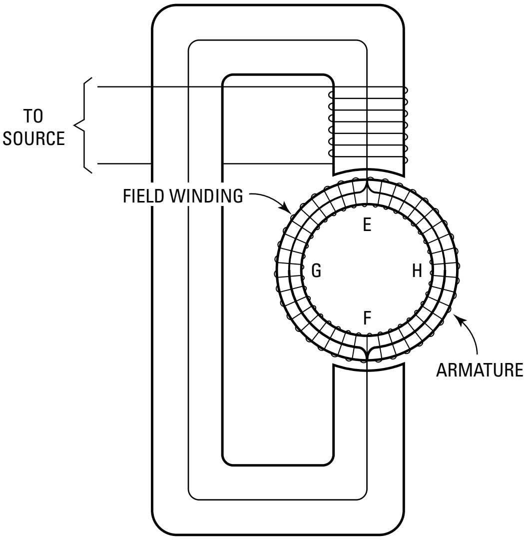

Figure 1-46 Illustration to show the operating principles of a repulsion-start induction motor.

The winding and the magnetism are identical in both halves of the ring. Thus, any effect that the magnetism may have on the winding between *E* and *G* will be the same as that produced in windings *E* and *H*. This can be proven by connecting an ammeter between points *G* and *H*. It will be found that no current is flowing between these two points. By further tests it can be shown that maximum current will flow when a wire is connected between *E* and *F.* Thus, the first requirement of our principle has been satisfied: With a wire connecting *E* and *F,* there is a current flowing in the rotor winding.

Assume that the current flows upward in this wire from *F* to *E.* At point *E,* it divides equally, half going to the winding to the left of *E,* and the other half to the right. Referring to the wires on the outer surface of the ring, those on the right have the current flowing toward the observer, while those on the left have the current flowing away. Thus the magnetic field from the C-shaped core tends to force the wires on the right in one direction and those on the left in the other direction. The forces are equal and opposite so that they neutralize each other and no motion takes place.

In order for the rotor to rotate, it is necessary to add a magnetic field that can effectively react with the current in the rotor winding. This is done readily by adding another C-shaped core with its own coil, as shown in Figure 1-47. The rotor-winding current under each tip of this C-shaped core is all in the same direction, and rotation is obtained. The wire from *E* to *F* in Figure 1-46 has been replaced with stationary brushes so that a connection is maintained as the rotor turns.

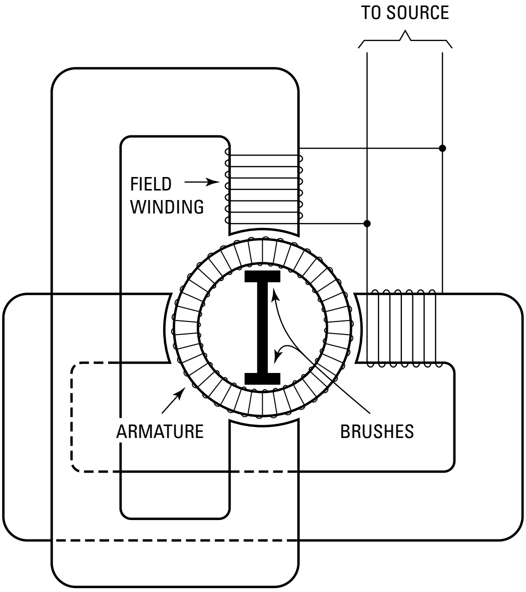

Figure 1-47 Schematic diagram of a repulsion-start induction motor.

Motor Control

Although the function of motor control is fully covered later in this book, a brief outline of its essentials will be of aid in further study of the various types of motors and their associated control circuits.

The elementary functions of control are starting, stopping, and reversing of the motor. These, however, are only a few of the many contributions that the control renders to efficient operation of industrial motors.

The most common control functions of industrial motors are

- To limit torque on the motor and machine
- To limit motor starting current
- To protect the motor from overheating
- To stop the motor quickly
- To regulate speed
- Miscellaneous functions

Limiting Torque

One example of the need for limiting torque is that of a belt-driven, motor-operated machine throwing the belt when the motor is started. The pulleys may be correctly lined up and the belt tension may be correct, and yet the belt is thrown off in starting. This is the result of applying torque too quickly at standstill, and can be avoided by limiting the torque on the motor in starting. As another example, the blades on centrifugal fans can be sheared off if too much torque is applied to the fan in starting.

Limiting Starting Current

It is common to see DC motors flash over at the commutator when too much current is applied to the motor in bringing it up to speed. Also, it is common to see lights blink when a motor on the same power circuit is started. True, this blinking of lights can be reduced by selecting a motor with the right characteristics, but usually the real solution is the selection of a control that limits the starting current, either by inserting resistance in the circuit or by using a reduced-voltage source of power.

Protection from Overheating

Motors are designed to produce full-load torque for a definite period without overheating. While the motor is capable of exceeding its normal output for limited periods, there is nothing inherent in the motor to keep its temperature within safe limits. It is therefore the function of the control to prevent the motor from overheating excessively without shutting it down unnecessarily.

Quick Stopping

Where a driven machine has high inertia, it will continue to run for a considerable time after the power has been disconnected. There are several types of controls, such as electric brakes, to stop a motor quickly. The one most generally used on AC motors is the plugging switch. To plug a motor, it is necessary only to disconnect it from the line, and then reconnect it so that the power applied to the motor tends to drive it in the opposite direction. This brakes the motor rapidly to a standstill, at which time the plugging switch cuts off the reverse power.

Speed Regulation

Fans are sometimes run at various speeds, depending on the ventilation requirements. For some applications, it is advisable to use a two-speed motor, but where a greater variety of speeds is required, a motor with variable speed control may be the best solution to the problem.

Miscellaneous Control Functions

Adequate control equipment covers various other protective functions, which are not as common as those enumerated previously. Among these are *reverse-phase protection,* which prevents a motor from running in the wrong direction if a phase is inadvertently reversed; *open-phase protection,* which prevents the motor from running on single phase in case a fuse blows, and *undervoltage protection,* which prevents a motor from starting after a power failure unless started by the operator.

Summary

If the south-seeking (S) pole of a magnet is brought near the S pole of a suspended magnet, the poles repel each other. Likewise, if the two north-seeking (N) poles are brought together, they repel each other. However, if an N pole is brought near the S pole or if an S pole is brought near the N pole, the two unlike poles attract each other. In other words, *like poles repel each other, and unlike poles attract each other.* Experiments have shown these attracting or repelling forces between magnetic poles vary inversely as the square of the distance between the poles.

Oersted discovered the relation between magnetism and electricity in the early nineteenth century. He observed that when a wire connecting the poles of a battery was held *over* a compass needle, the N pole of the needle was deflected in one direction when the current flowed, and a wire placed *under* the compass needle caused the N pole of the needle to be deflected in the opposite direction. The compass needle indicates the direction of the magnetic lines of force, and an electric current sets up a magnetic field at right angles to the conductor. The so-called *left-hand rule* is a convenient method for determining the direction of the magnetic flux around a straight wire carrying a current: *If the wire is held in the left hand, with the thumb pointed in the direction of the current, the fingers will point in the direction of the magnetic field.* Conversely, if the direction of the magnetic field around a conductor is known, the direction of the current in the conductor can be determined by applying the rule.

An *electromagnet* is a soft-iron core surrounded by a coil of wire. The magnetic strength of an electromagnet can be changed by changing the strength of its applied current. When the current is interrupted, the iron core returns to its natural state. This loss of magnetism is not complete, however, because a small amount of magnetism, or *residual magnetism,* remains. The electromagnet is used in many electrical devices, including electric bells, telephones, motors, and generators. The polarity of an electromagnet can be determined by means of the left-hand rule, as follows: *Grasp the coil with the left hand; with the fingers pointing in the direction of the current in the coil, the thumb will point to the north pole of the coil.*

If a coil of wire having many turns is moved up and down over one pole of a horseshoe magnet, a momentary electric current without an apparent electrical source is produced. This current produced by moving the coil of wire in a magnetic field is called an *induced current.* Lenz's law states that an induced current has such a direction that its magnetic action tends to resist the motion by which it is produced. The generator and the motor are examples of useful applications of induced currents.

A *generator* converts mechanical energy into electrical energy. Its essential parts are a magnetic field, usually produced by permanent magnets, and a moving coil or coils called the *armature.*

The DC generator is classified either as a separately excited or a self-excited type. The separately excited generator has very little practical use; the self-excited generator is the one most often used. The self-excited DC generator can be broken down into a number of classificatons: the series, shunt, compound, overcompound, flat compound, and undercompound. Each type has particular advantages and disadvantages according to its load and speed of rotation.

Some of these generator types cannot be regulated in terms of a constant voltage output; they are used for other purposes where voltage regulation is not so important.

A *motor* converts electrical energy into mechanical energy. The motor, like the generator, consists of an electromagnet, an armature, and a commutator with its brushes.

The two principal classes of polyphase induction motors are the *squirrel-cage* motor and the *wound-rotor* motor. By definition, an induction motor is one in which the magnetic field in the rotor is induced by currents flowing in the stator. The rotor has no connection whatever to the supply line.

Single-phase motors can be divided into two principal classes as follows:

1. Split-phase
    - **a.** Resistance-start
    - **b.** Split-capacitor
    - **c.** Capacitor-start
    - **d.** Repulsion-start
2. Commutator
    - **a.** Series
    - **b.** Repulsion

Review Questions

1. How can the direction of the magnetic field around a straight wire carrying a current be determined?
2. Describe the basic construction of an electromagnet.
3. How can the polarity of an electromagnet be determined?
4. How is an "induced current" produced?
5. What is the basic difference between a generator and a motor?
6. What is the function of a DC generator?
7. How are the commutator segments of a DC generator insulated?
8. What materials are used to make brushes for a DC generator and/or motor?
9. How is the neutral plane of a generator shifted?
10. How are DC generators classified?

11. What is the only type of compound generator commonly used?
12. What is the name of the mechanical power source used to drive generators?
13. How are the effects of armature reaction overcome or reduced permanently in a generator?
14. Why will a shunt generator build up to full terminal voltage with no external load connected?
15. What is the name given to power lost in heat in the windings of a generator due to the flow of current through the copper?
16. As armature current of a generator increases, what happens to the motor reaction force?
17. How can compound generators be connected?
18. What is the name given to the part of a DC generator into which the working voltage is induced?
19. What are the two principal types of induction motors?
20. What are the two principal types of single-phase motors?