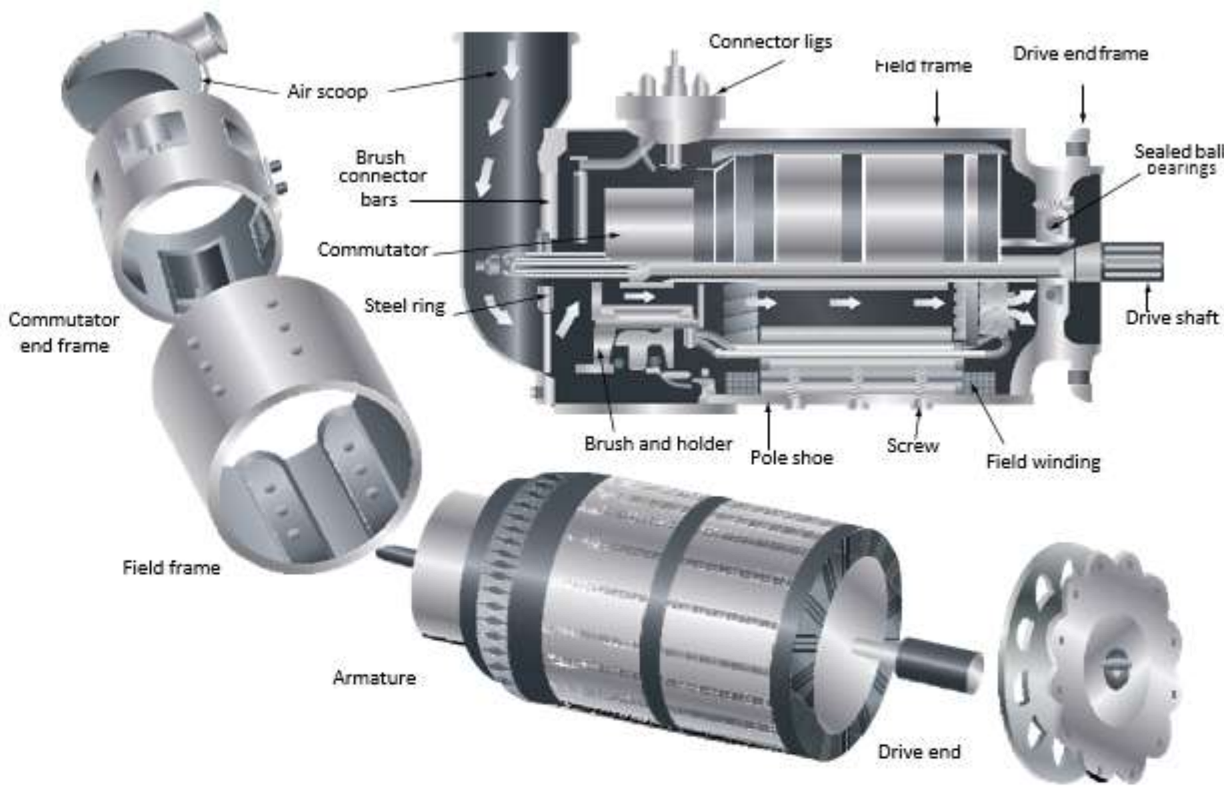
DC Generators, Armature, Commuters, and DC Motors



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DC Generators

Theory of Operation

In the study of alternating current, basic generator principles were introduced to explain the generation of an AC voltage by a coil rotating in a magnetic field. Since this is the basis for all generator operation, it is necessary to review the principles of generation of electrical energy.

When lines of magnetic force are cut by a conductor passing through them, voltage is induced in the conductor. The strength of the induced voltage is dependent upon the speed of the conductor and the strength of the magnetic field. If the ends of the conductor are connected to form a complete circuit, a current is induced in the conductor. The conductor and the magnetic field make up an elementary generator.

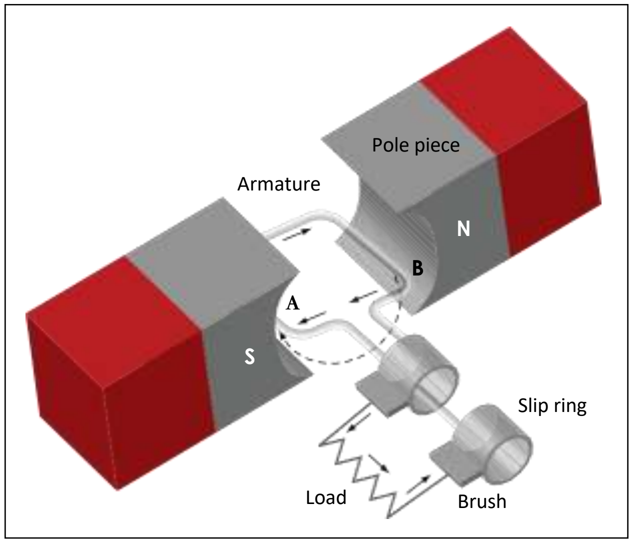

Figure 10-255. Inducing maximum voltage in an elementary generator.

This simple generator is illustrated in Figure 10-255, together with the components of an external generator circuit which collect and use the energy produced by the simple generator. The loop of wire (A and B of Figure 10-255) is arranged to rotate in a magnetic field. When the plane of the loop of wire is parallel to the magnetic lines of force, the voltage induced in the loop causes a current to flow in the direction indicated by the arrows in Figure 10-255. The voltage induced at this position is maximum, since the wires are cutting the lines of force at right angles and are thus cutting more lines of force per second than in any other position relative to the magnetic field. As the loop approaches the vertical position shown in Figure 10-256, the induced voltage

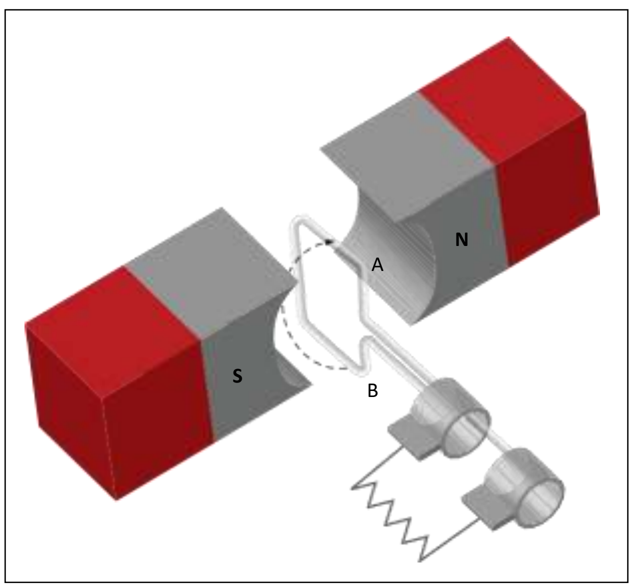

Figure 10-256. Inducing minimum voltage in an elementary generator.

decreases because both sides of the loop (A and B) are approximately parallel to the lines of force and the rate of cutting is reduced. When the loop is vertical, no lines of force are cut since the wires are momentarily traveling parallel to the magnetic lines of force, and there is no induced voltage. As the rotation of the loop continues, the number of lines of force cut increases until the loop has rotated an additional 90° to a horizontal plane. As shown in Figure 10-257, the number of lines of force cut and the induced voltage once again are maximum. The direction of cutting, however, is in the opposite direction to that occurring in Figures 10-255 and10-256, so the direction (polarity) of the induced voltage is reversed. As rotation of the loop continues, the number of lines of force having been cut again decreases, and the induced voltage becomes zero at the position shown in Figure 10-258, since the wires A and B are again parallel to the magnetic lines of force.

If the voltage induced throughout the entire 360° of rotation is plotted, the curve shown in Figure 10-259 results. This voltage is called an alternating volt- age because of its reversal from positive to negative value — first in one direction and then in the other.

To use the voltage generated in the loop for producing a current flow in an external circuit, some means must be provided to connect the loop of wire in series with the external circuit. Such an electrical connection can be effected by opening the loop of wire and connecting its two ends to two metal rings, called slip rings, against which two metal or carbon brushes ride. The brushes are connected to the external circuit. By replacing the slip rings of the basic AC generator with two half cylinders, called a commutator, a basic DC generator is obtained. [Figure 10-260] In this illustration, the black side of the coil is connected to the black segment, and the white side of the coil to the white segment. The segments are insulated from each other. The two stationary brushes are placed on opposite sides of the commutator and are so mounted that each brush contacts each segment of the commutator as the latter revolves simultaneously with the loop. The rotating parts of a DC generator (coil and commutator) are called an armature. The generation of an emf by the loop rotating in the magnetic field is the same for both AC and DC generators, but the action of the commutator produces a DC voltage.

Generation of a DC Voltage

Figure 10-261 illustrates in an elementary, step-by-step manner, how a DC voltage is generated. This is accomplished by showing a single wire loop rotating through a series of positions within a magnetic field.

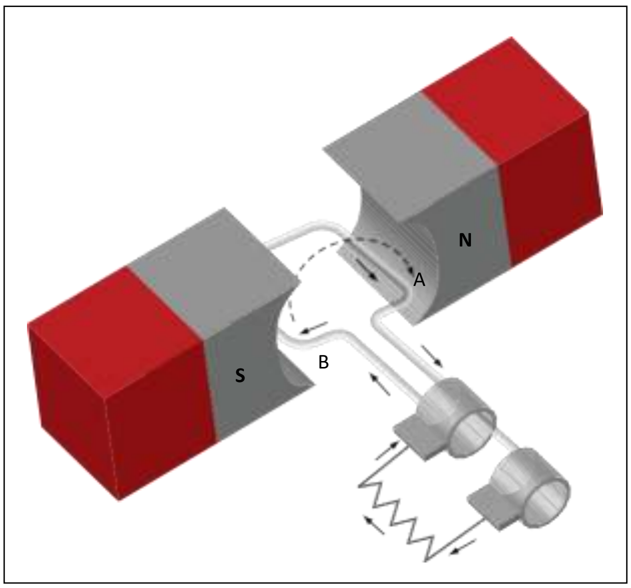

Figure 10-257. Inducing maximum voltage in the opposite direction.

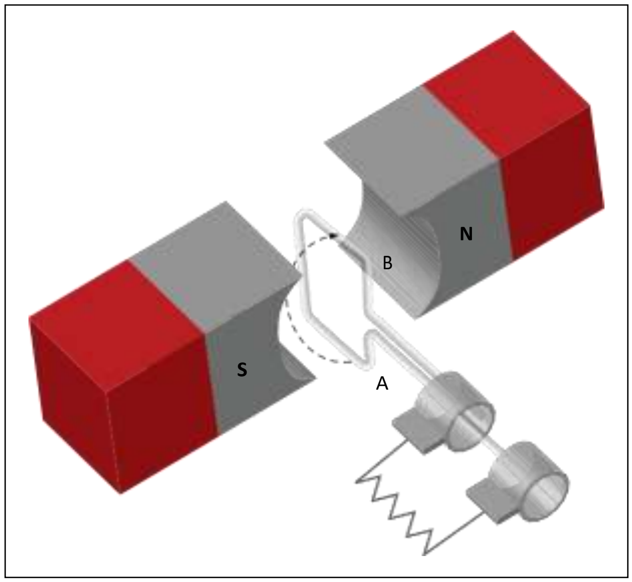

Figure 10-258. Inducing a minimum voltage in the opposite direction.

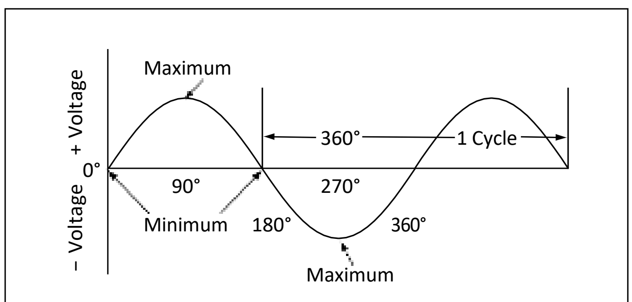

Figure 10-259. Output of an elementary generator.

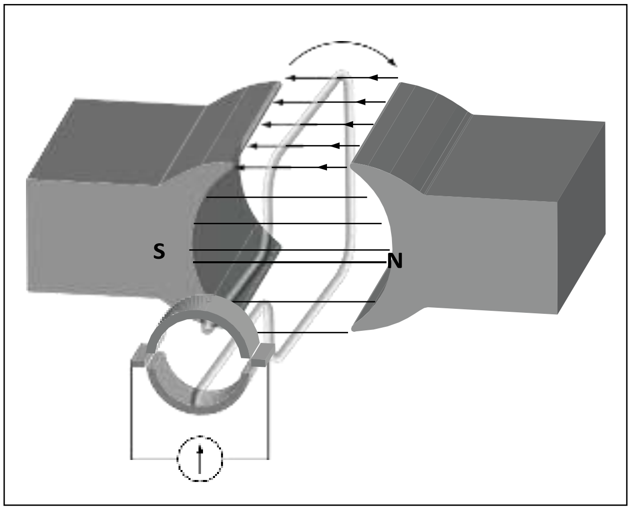

Figure 10-260. Basic DC generator.

Position A

The loop starts in position A and is rotating clockwise. However, no lines of force are cut by the coil sides, which means that no emf is generated. The black brush is shown coming into contact with the black segment of the commutator, and the white brush is just coming into contact with the white segment.

Position B

In position B, the flux is now being cut at a maximum rate, which means that the induced emf is maximum. At this time, the black brush is contacting the black segment, and the white brush is contacting the white segment. The deflection of the meter is toward the right, indicating the polarity of the output voltage.

Position C

At position C, the loop has completed 180° of rotation. Like position A, no flux lines are being cut and the output voltage is zero. The important condition to observe at position C is the action of the segments and brushes. The black brush at the 180° angle is contacting both black and white segments on one side of the commutator, and the white brush is contacting both segments on the other side of the commutator. After the loop rotates slightly past the 180° point, the black brush is contacting only the white segment, and the white brush is contacting only the black segment.

Because of this switching of commutator elements, the black brush is always in contact with the coil side moving downward, and the white brush is always in contact with the coil side moving upward. Though the current

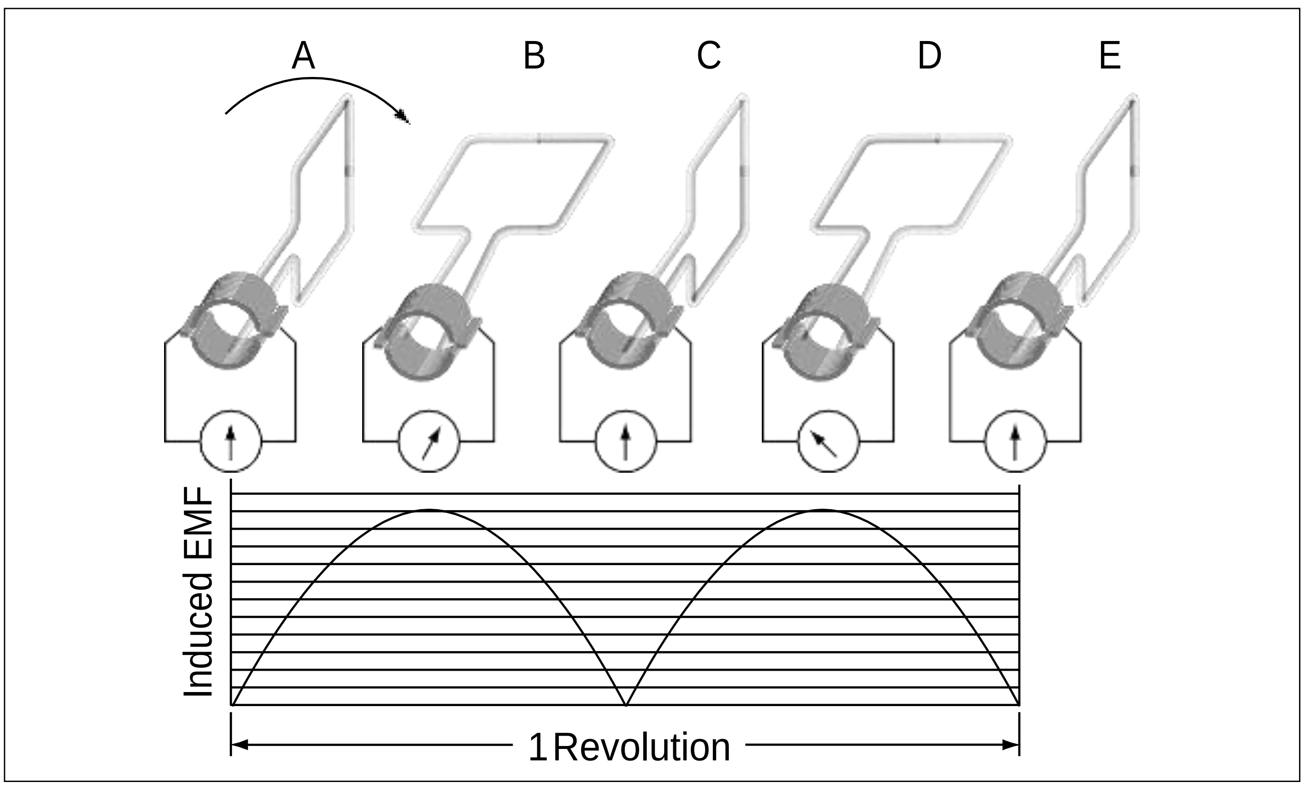

Figure 10-261. Operation of a basic DC generator.

actually reverses its direction in the loop in exactly the same way as in the AC generator, commutator action causes the current to flow always in the same direction through the external circuit or meter.

Position D

At position D, commutator action reverses the current in the external circuit, and the second half cycle has the same waveform as the first half cycle. The process of commutation is sometimes called rectification, since rectification is the converting of an AC voltage to a DC voltage.

The Neutral Plane

At the instant that each brush is contacting two segments on the commutator (positions A, C, and E in Figure 10-261), a direct short circuit is produced. If an emf were generated in the loop at this time, a high current would flow in the circuit, causing an arc and thus damaging the commutator. For this reason, the brushes must be placed in the exact position where the short will occur when the generated emf is zero. This position is called the neutral plane. If the brushes are installed properly, no sparking will occur between the brushes and the commutator. Sparking is an indication of improper brush placement, which is the main cause of improper commutation.

The voltage generated by the basic DC generator in Figure 10-261 varies from zero to its maximum value twice for each revolution of the loop. This variation of DC voltage is called “ripple,” and may be reduced by using more loops, or coils, as shown in A of Figure 10-262. As the number of loops is increased, the variation between maximum and minimum values of voltage is reduced (view B of Figure 10-262), and the output voltage of the generator approaches a steady DC value. In view A of Figure 10-262 the number of commutator segments is increased in direct proportion to the number of loops; that is, there are two segments for one loop, four segments for two loops, and eight segments for four loops.

The voltage induced in a single turn loop is small. Increasing the number of loops does not increase the maximum value of generated voltage, but increasing the number of turns in each loop will increase this value. Within narrow limits, the output voltage of a DC generator is determined by the product of the number of turns per loop, the total flux per pair of poles in the machine, and the speed of rotation of the armature.

An AC generator, or alternator, and a DC generator are identical as far as the method of generating voltage in the rotating loop is concerned. However, if the current is taken from the loop by slip rings, it is an alternating current, and the generator is called an AC generator, or alternator. If the current is collected by a commutator, it is direct current, and the generator is called a DC generator.

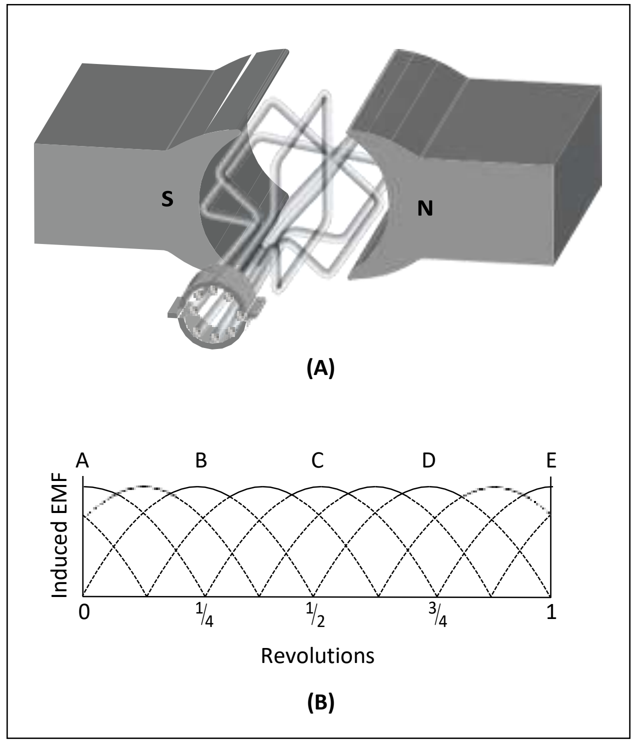

Figure 10-262. Increasing the number of coils reduces the ripple in the voltage.

Construction Features of DC Generators

Generators used on aircraft may differ somewhat in design, since various manufacturers make them. All, however, are of the same general construction and operate similarly. The major parts, or assemblies, of a DC generator are a field frame (or yoke), a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in Figure 10-263.

Field Frame

The field frame is also called the yoke, which is the foundation or frame for the generator. The frame has two functions: It completes the magnetic circuit between the poles and acts as a mechanical support for the other parts of the generator. In View A of Figure 10-264, the frame for a two-pole generator is shown in a cross-sectional view. A four-pole generator frame is shown in View B of Figure 10-264.

In small generators, the frame is made of one piece of iron, but in larger generators, it is usually made up of

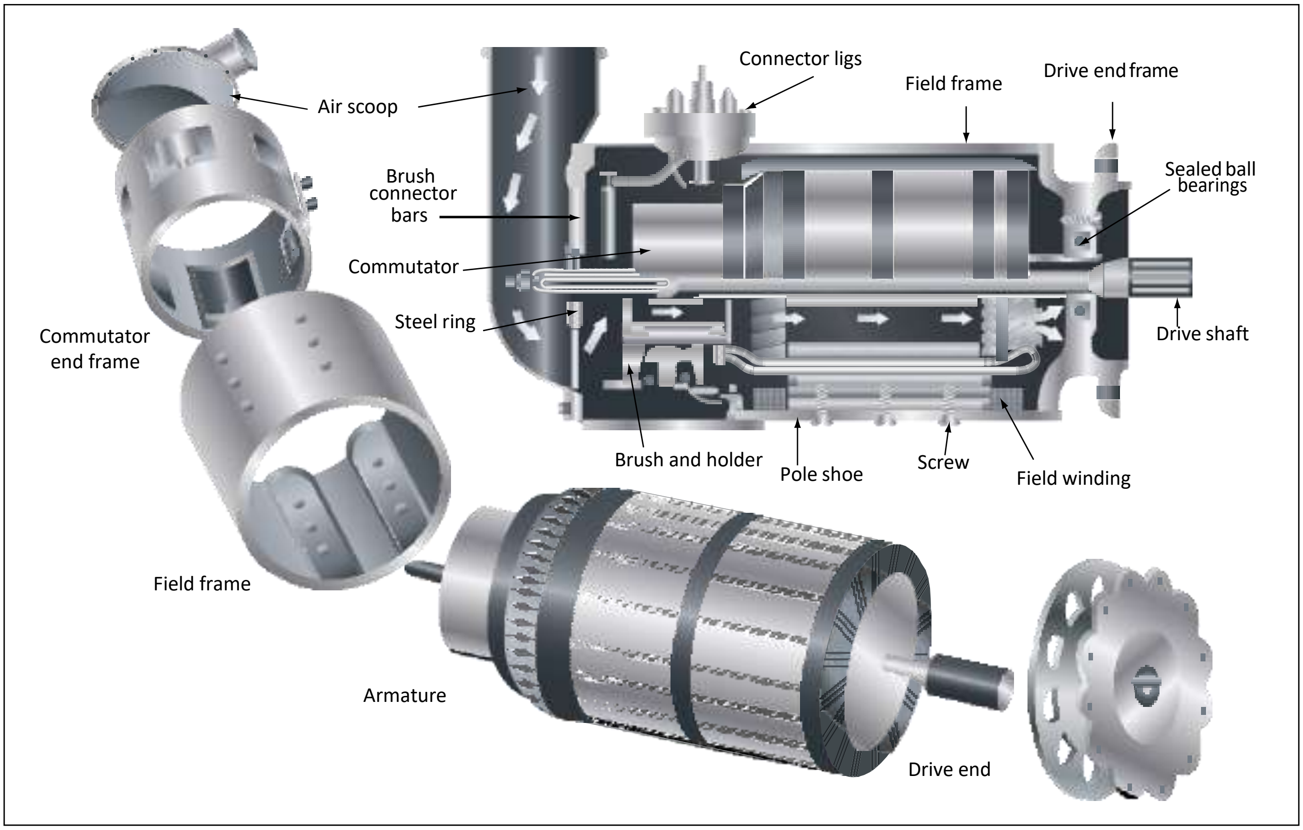

Figure 10-263. Typical 24-volt aircraft generator.

two parts bolted together. The frame has high magnetic properties and, together with the pole pieces, forms the major part of the magnetic circuit. The field poles, shown in Figure 10-264, are bolted to the inside of the frame and form a core on which the field coil windings are mounted.

The poles are usually laminated to reduce eddy current losses and serve the same purpose as the iron core of an electromagnet; that is, they concentrate the lines of force produced by the field coils. The entire frame including field poles, is made from high quality magnetic iron or sheet steel.

A practical DC generator uses electromagnets instead of permanent magnets. To produce a magnetic field of the necessary strength with permanent magnets would greatly increase the physical size of the generator.

The field coils are made up of many turns of insulated wire and are usually wound on a form that fits over the iron core of the pole to which it is securely fastened. [Figure 10-265] The exciting current, which is used to produce the magnetic field and which flows through the field coils, is obtained from an external source or from the generated DC of the machine. No electrical connection exists between the windings of the field coils and the pole pieces.

Most field coils are connected so that the poles show alternate polarity. Since there is always one north pole for each south pole, there must always be an even number of poles in any generator.

Note that the pole pieces in Figure 10-264 project from the frame. Because air offers a great amount of reluctance to the magnetic field, this design reduces the length of the air gap between the poles and the rotating armature and increases the efficiency of the generator. When the pole pieces are made to project as shown in Figure 10-264, they are called salient poles.

Armature

The armature assembly of a generator consists of many armature coils wound on an iron core, a commutator, and associated mechanical parts. These additional loops of wire are actually called windings and are evenly spaced around the armature so that the distance between each winding is the same. Mounted on a shaft, it rotates through the magnetic field produced by the field coils. The core of the armature acts as an iron conductor in the magnetic field and, for this reason, is laminated to prevent the circulation of eddy currents.

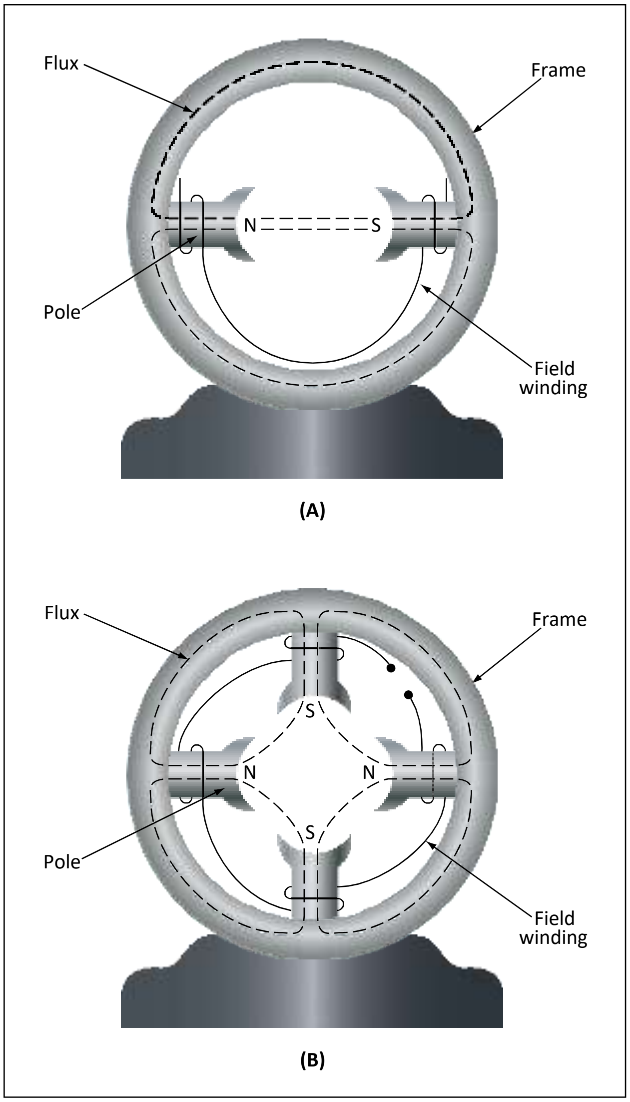

Figure 10-264. A two-pole and a four-pole frame assembly.

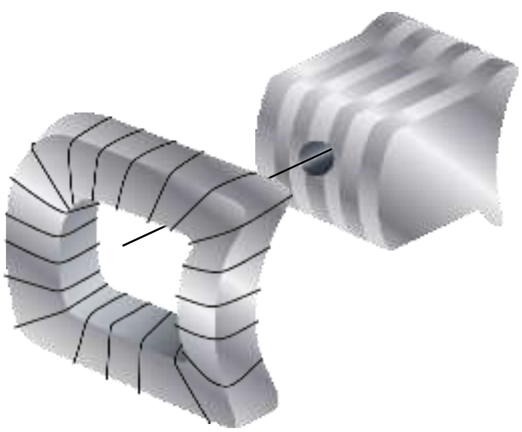

Figure 10-265. A field coil removed from a field pole.

Gramme-Ring Armature

There are two general kinds of armatures: the ring and the drum. Figure 10-266 shows a ring-type armature made up of an iron core, an eight-section winding, and an eight-segment commutator. The disadvantage of this arrangement is that the windings, located on the inner side of the iron ring, cut few lines of flux. As a result, they have very little voltage induced in them. For this reason, the Gramme-ring armature is not widely used.

Drum-Type Armature

A drum-type armature is shown in Figure 10-267. The armature core is in the shape of a drum and has slots cut into it where the armature windings are placed. The advantage is that each winding completely surrounds the core so that the entire length of the conductor cuts through the magnetic flux. The total induced voltage in this arrangement is far greater than that of the Gramme-ring type armature.

Drum-type armatures are usually constructed in one of two methods, each method having its own advantage. The two types of winding methods are the lap winding and the wave winding. Lap windings are used in generators that are designed for high current. The windings are connected in parallel paths and for this reason

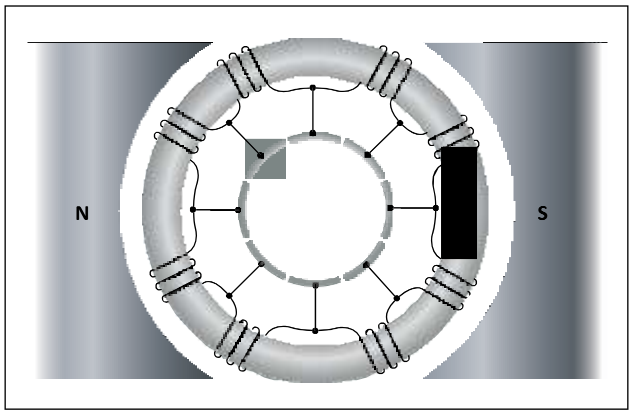

Figure 10-266. An eight-section, ring-type armature.

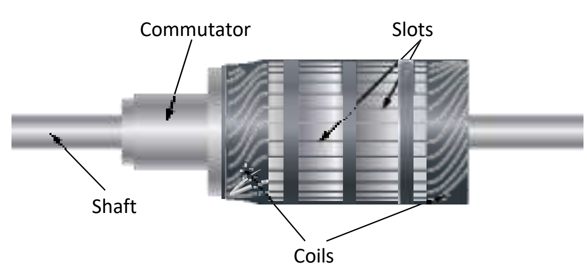

Figure 10-267. A drum-type armature.

require several brushes. The wave winding is used in generators that are designed for high voltage outputs. The two ends of each coil are connected to commutator segments separated by the distance between poles. This results in a series arrangement of the coils and is additive of all the induced voltages.

Commutators

Figure 10-268 shows a cross-sectional view of a typical commutator. The commutator is located at the end of an armature and consists of wedge shaped segments of hard drawn copper, insulated from each other by thin sheets of mica. The segments are held in place by steel V-rings or clamping flanges fitted with bolts. Rings of mica insulate the segments from the flanges. The raised portion of each segment is called a riser, and the leads from the armature coils are soldered to the risers. When the segments have no risers, the leads are soldered to short slits in the ends of the segments.

The brushes ride on the surface of the commutator, forming the electrical contact between the armature coils and the external circuit. A flexible, braided copper conductor, commonly called a pigtail, connects each brush to the external circuit. The brushes, usually made of high-grade carbon and held in place by brush holders insulated from the frame, are free to slide up and down in their holders in order to follow any irregularities in the surface of the commutator. The brushes are usually adjustable so that the pressure of the brushes on the commutator can be varied and the position of the brushes with respect to the segments can be adjusted.

The constant making and breaking of connections to the coils in which a voltage is being induced necessitates the use of material for brushes, which has a definite contact resistance. Also, this material must be such that the friction between the commutator and the brush is low, to prevent excessive wear. For these reasons, the material commonly used for brushes is high-grade carbon. The carbon must be soft enough to prevent undue wear of the commutator and yet hard enough to provide reasonable brush life. Since the

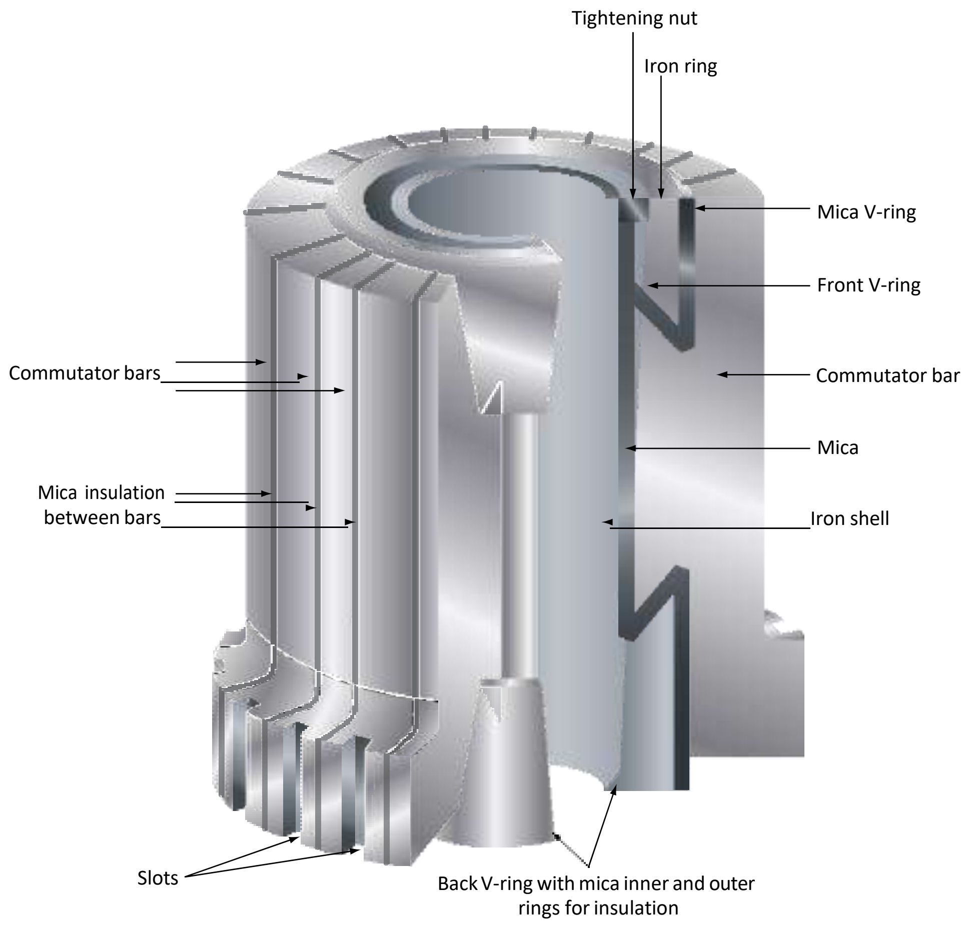

Figure 10-268. Commutator with portion removed to show construction.

contact resistance of carbon is fairly high, the brush must be quite large to provide a large area of contact. The commutator surface is highly polished to reduce friction as much as possible. Oil or grease must never be used on a commutator, and extreme care must be used when cleaning it to avoid marring or scratching the surface.

Armature Reaction

Current flowing through the armature sets up electromagnetic fields in the windings. These new fields tend to distort or bend the magnetic flux between the poles of the generator from a straight-line path. Since armature current increases with load, the distortion becomes greater with an increase in load. This distortion of the magnetic field is called armature reaction. [Figure 10-269]

Armature windings of a generator are spaced so that, during rotation of the armature, there are certain positions when the brushes contact two adjacent segments, thereby shorting the armature windings to these segments. When the magnetic field is not distorted, there is usually no voltage being induced in the shorted windings, and therefore no harmful results occur from the shorting of the windings. However, when the field is distorted, a voltage is induced in these shorted windings, and sparking takes place between the brushes and the commutator segments. Consequently, the commutator becomes pitted, the wear on the brushes becomes excessive, and the output of the generator is reduced. To correct this condition, the brushes are set so that the plane of the coils, which are shorted by the brushes, is perpendicular to the distorted magnetic field, which is accomplished by moving the brushes forward in the direction of rotation. This operation is called shifting the brushes to the neutral plane, or plane of commutation. The neutral plane is the position where the plane of the two opposite coils is perpendicular to the magnetic field in the generator. On a few generators, the brushes can be shifted manually ahead of the normal neutral plane to the neutral plane caused by field distortion. On nonadjustable brush generators, the manufacturer sets the brushes for minimum sparking.

Compensating windings or interpoles may be used to counteract some of the effects of field distortion, since shifting the brushes is inconvenient and unsatisfactory, especially when the speed and load of the generator are changing constantly.

Compensating Windings

The compensating windings consist of a series of coils embedded in slots in the pole faces. These coils are also connected in series with the armature. Consequently, this series connection with the armature produces a magnetic field in the compensating windings that varies directly with the armature current. The compensating windings are wound in such a manner that the magnetic field produced by them will counteract the magnetic field produced by the armature. As a result, the neutral plane will remain stationary any magnitude of armature current. With this design, once the brushes are set correctly, they do not need to be moved again. Figure 10-270A illustrates how the windings are set into the pole faces.

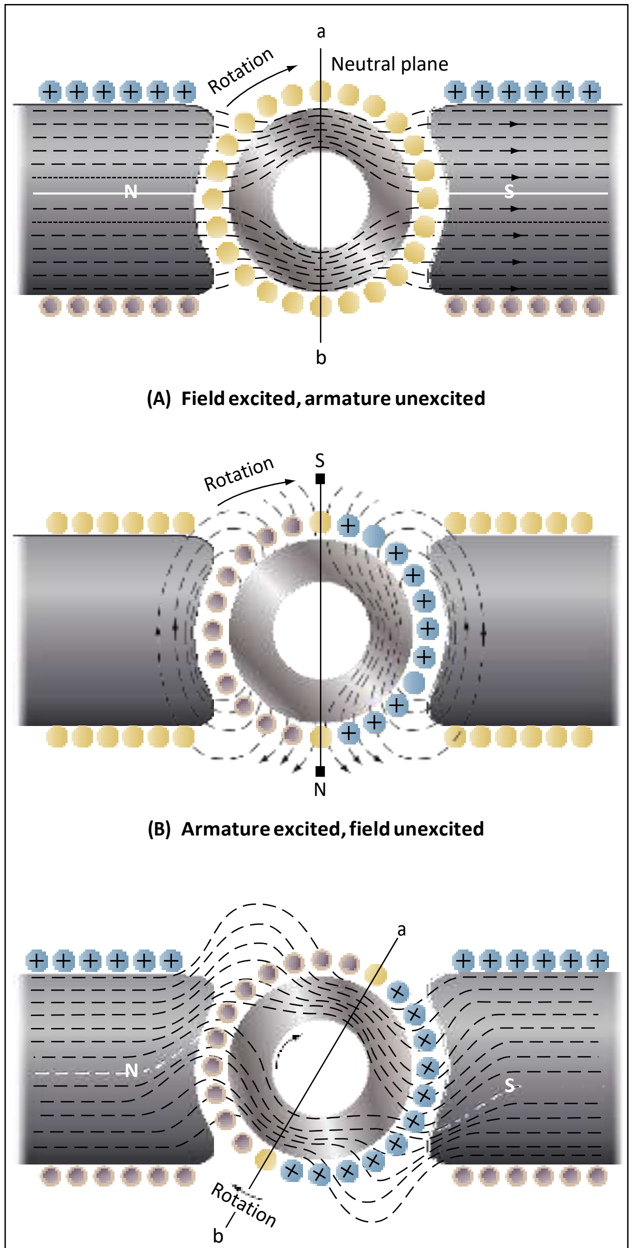

Figure 10-269. Armature reaction.

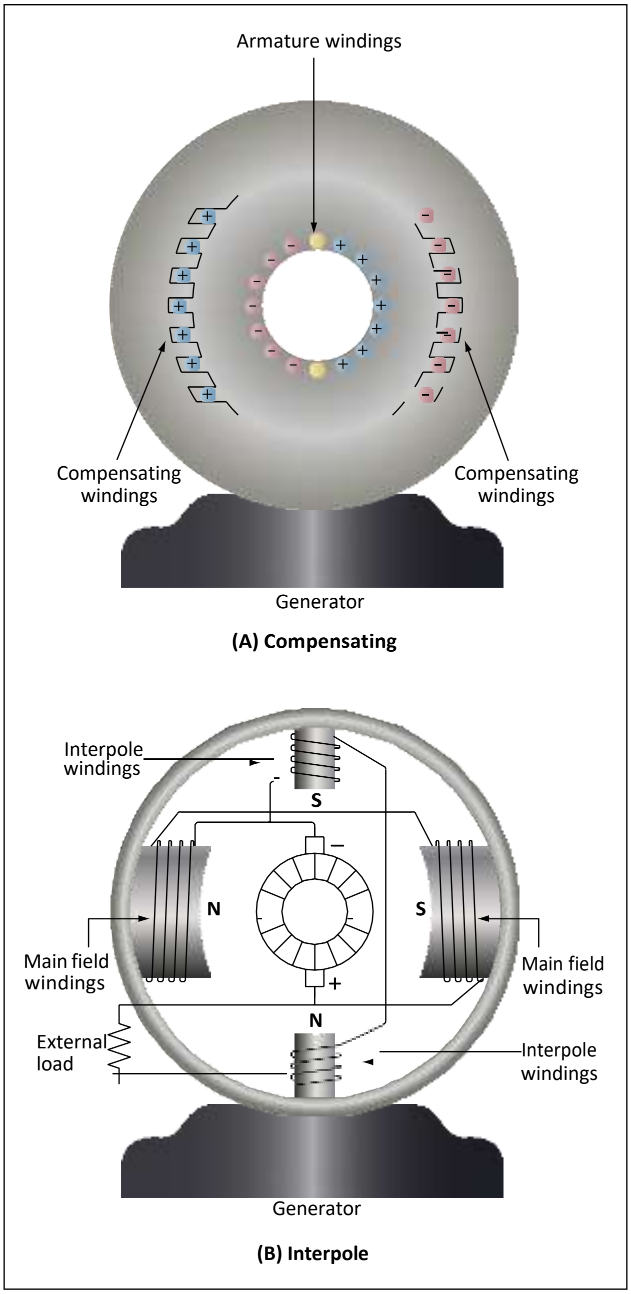

Figure 10-270. Simple two-pole generator with two interpoles.

Interpoles

An interpole is a pole placed between the main poles of a generator. An example of interpole placement is shown in Figure 10-270B. This is a simple two-pole generator with two interpoles.

An interpole has the same polarity as the next main pole in the direction of rotation. The magnetic flux produced by an interpole causes the current in the armature to change direction as an armature winding passes under it. This cancels the electromagnetic fields about the armature windings. The magnetic strength of the interpoles varies with the load on the generator; and since field distortion varies with the load, the magnetic field of the interpoles counteracts the effects of the field set up around the armature windings and minimizes field distortion. Thus, the interpole tends to keep the neutral plane in the same position for all loads on the generator; therefore, field distortion is reduced by the interpoles, and the efficiency, output, and service life of the brushes are improved.

Types of DC Generators

There are three types of DC generators: series wound, shunt wound, and shunt series or compound wound. The difference in type depends on the relationship of the field winding to the external circuit.

Series Wound DC Generators

The field winding of a series generator is connected in series with the external circuit, called the load. [Figure 10-271] The field coils are composed of a few turns of large wire; the magnetic field strength depends more on the current flow rather than the number of turns in the coil. Series generators have very poor voltage regulation under changing load, since the greater the current through the field coils to the external circuit, the greater the induced emf and the greater the terminal or output voltage. Therefore, when the load is increased, the voltage increases; likewise, when the load is decreased, the

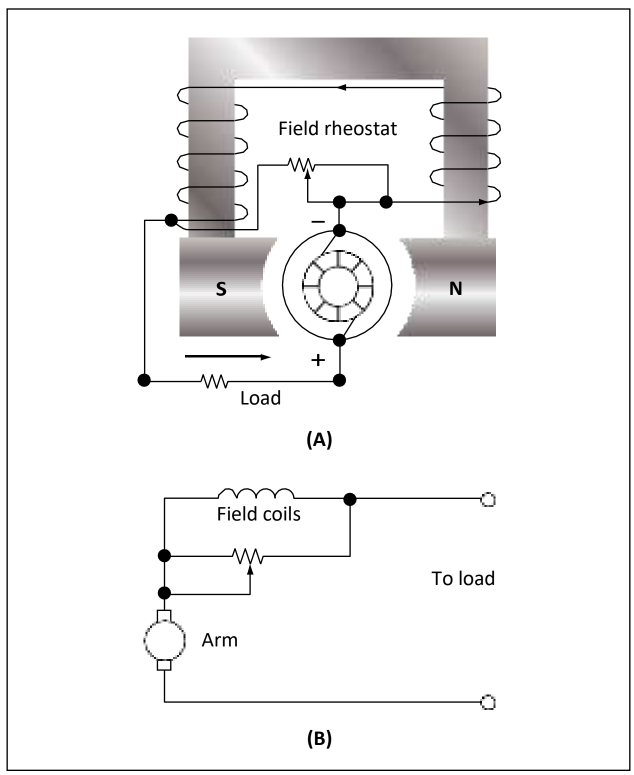

Figure 10-271. Diagram and schematic of a series wound generator.

voltage decreases. The output voltage of a series wound generator may be controlled by a rheostat in parallel with the field windings, as shown in Figure 10-271A. Since the series wound generator has such poor regulation, it is never employed as an airplane generator. Generators in airplanes have field windings, which are connected either in shunt or in compound.

Shunt Wound DC Generators

A generator having a field winding connected in parallel with the external circuit is called a shunt generator, as shown in views A and B of Figure 10-272. The field coils of a shunt generator contain many turns of small wire; the magnetic strength is derived from the large number of turns rather than the current strength through the coils. If a constant voltage is desired, the shunt wound generator is not suitable for rapidly fluctuating loads. Any increase in load causes a decrease in the terminal or output voltage, and any decrease in load causes an increase in terminal voltage; since the armature and the load are connected in series, all current flowing in the external circuit passes through the armature winding. Because of the resistance in the armature winding, there is a voltage drop (IR drop = current × resistance). As the load increases, the armature current increases and the IR drop in the armature increases. The voltage delivered to the terminals is the difference between the induced voltage and the voltage drop; therefore, there is a decrease in terminal voltage. This decrease in voltage causes a decrease in field strength, because the current in the field coils decreases in proportion to the decrease in terminal voltage; with a weaker field, the voltage is further decreased. When the load decreases, the output voltage increases accordingly, and a larger current flows in the windings. This action is cumulative, so the output voltage continues to rise to a point called field saturation, after which there is no further increase in output voltage.

The terminal voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings as shown in Figure 10-272A. As the resistance is increased, the field current is reduced; consequently, the generated voltage is reduced also. For a given setting of the field rheostat, the terminal voltage at the armature brushes will be approximately equal to the generated voltage minus the IR drop produced by the load current in the armature; thus, the voltage at the terminals of the generator will drop as the load is applied. Certain voltage sensitive devices are available which automatically adjust the field rheostat to compensate for variations in load. When

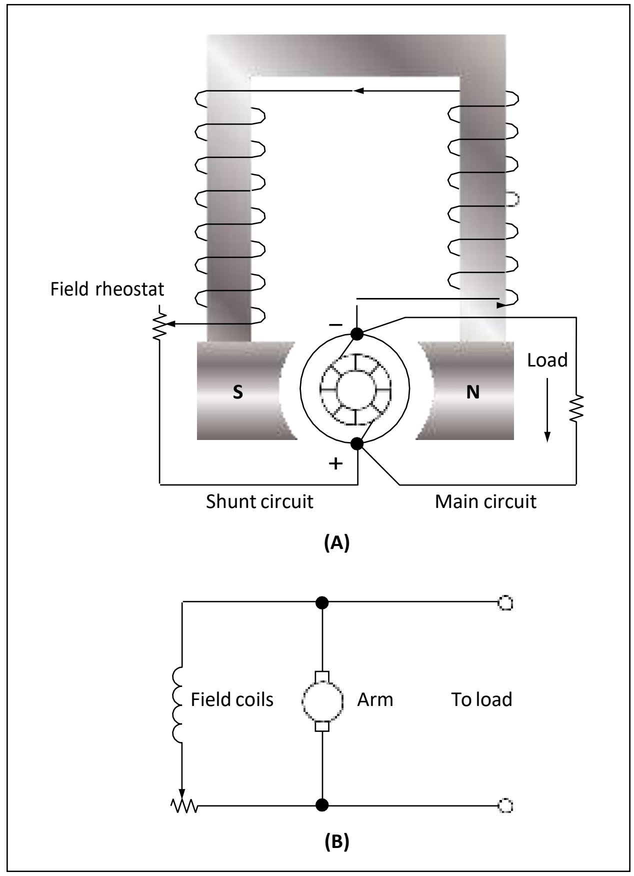

Figure 10-272. Shunt wound generator.

these devices are used, the terminal voltage remains essentially constant.

Compound Wound DC Generators

A compound wound generator combines a series winding and a shunt winding in such a way that the characteristics of each are used to advantage. The series field coils are made of a relatively small number of turns of large copper conductor, either circular or rectangular in cross section, and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and, therefore, contribute a magnetomotive force which influences the main field flux of the generator. A diagrammatic and a schematic illustration of a compound wound generator is shown in A and B of Figure 10-273.

If the ampere turns of the series field act in the same direction as those of the shunt field, the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator, by increasing the number of parallel paths across the generator terminals. Thus,

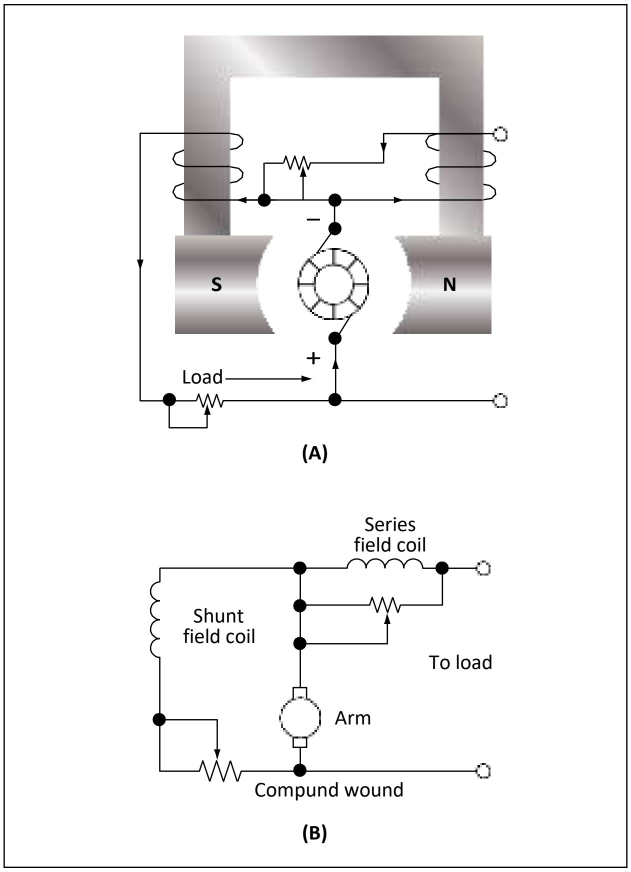

Figure 10-273. Compound wound generator.

the decrease in total load resistance with added load is accompanied by an increase in armature circuit and series field circuit current. The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field as determined by the shunt field current. Thus, the terminal voltage of the generator may increase or decrease with load, depending on the influence of the series field coils. This influence is referred to as the degree of compounding. A flat compound generator is one in which the no load and full load voltages have the same value; whereas an under compound generator has a full load voltage less than the no load value, and an over compound generator has a full load voltage which is higher than the no load value. Changes in terminal voltage with increasing load depend upon the degree of compounding.

If the series field aids the shunt field, the generator is said to be cumulative compounded.

If the series field opposes the shunt field, the machine is said to be differentially compounded, or is called a differential generator. Compound generators are usually designed to be overcompounded. This feature permits varied degrees of compounding by connecting a variable shunt across the series field. Such a shunt is sometimes called a diverter. Compound generators are used where voltage regulation is of prime importance.

Differential generators have somewhat the same characteristics as series generators in that they are essentially constant current generators. However, they generate rated voltage at no load, the voltage dropping materially as the load current increases. Constant current generators are ideally suited as power sources for electric arc welders and are used almost universally in electric arc welding.

If the shunt field of a compound generator is connected across both the armature and the series field, it is known as a long shunt connection, but if the shunt field is connected across the armature alone, it is called a short shunt connection. These connections produce essentially the same generator characteristics.

A summary of the characteristics of the various types of generators discussed is shown graphically in Figure 10-274.

Generator Ratings

A generator is rated in power output. Since a generator is designed to operate at a specified voltage, the rating usually is given as the number of amperes the generator can safely supply at its rated voltage.

Generator rating and performance data are stamped on the nameplate attached to the generator. When replacing a generator, it is important to choose one of the proper rating.

The rotation of generators is termed either clockwise or counterclockwise, as viewed from the driven end. Usually, the direction of rotation is stamped on the data

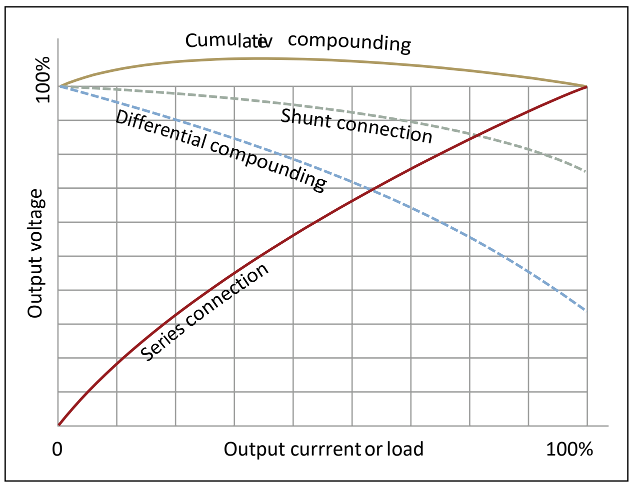

Figure 10-274. Generator characteristics.

plate. If no direction is stamped on the plate, the rotation may be marked by an arrow on the cover plate of the brush housing. It is important that a generator with the correct direction of rotation be used; otherwise, the voltage will be reversed.

The speed of an aircraft engine varies from idle rpm to takeoff rpm; however, during the major portion of a flight, it is at a constant cruising speed. The generator drive is usually geared to revolve the generator between 1-1/8 and 1-1/2 times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Termed the "coming in" speed, it is usually about 1,500 rpm.

Generator Terminals

On most large 24-volt generators, electrical connections are made to terminals marked B, A, and E. The positive armature lead in the generator connects to the B terminal. The negative armature lead connects to the E terminal. The positive end of the shunt field winding connects to terminal A, and the opposite end connects to the negative terminal brush. Terminal A receives current from the negative generator brush through the shunt field winding. This current passes through the voltage regulator and back to the armature through the positive brush. Load current, which leaves the armature through the negative brushes, comes out of the E lead and passes through the load before returning to the armature through the positive brushes.

DC Generator Maintenance

Inspection

The following information about the inspection and maintenance of DC generator systems is general in nature because of the large number of differing aircraft generator systems. These procedures are for familiarization only. Always follow the applicable manufacturer's instructions for a given generator system.

In general, the inspection of the generator installed in the aircraft should include the following items:

1. Security of generator mounting.
2. Condition of electrical connections.
3. Dirt and oil in the generator. If oil is present, check engine oil seal. Blow out dirt with compressed air.
4. Condition of generator brushes.
5. Generator operation.
6. Voltage regulator operation.

Condition of Generator Brushes

Sparking of brushes quickly reduces the effective brush area in contact with the commutator bars. The degree of such sparking should be determined. Excessive wear warrants a detailed inspection.

The following information pertains to brush seating, brush pressure, high mica condition, and brush wear. Manufacturers usually recommend the following procedures to seat brushes that do not make good contact with slip rings or commutators.

Lift the brush sufficiently to permit the insertion of a strip of No. 000, or finer, sandpaper under the brush, rough side out. [Figure 10-275] Pull the sandpaper in the direction of armature rotation, being careful to keep the ends of the sandpaper as close to the slip ring or commutator surface as possible in order to avoid rounding the edges of the brush.

When pulling the sandpaper back to the starting point, raise the brush so it does not ride on the sandpaper. Sand the brush only in the direction of rotation.

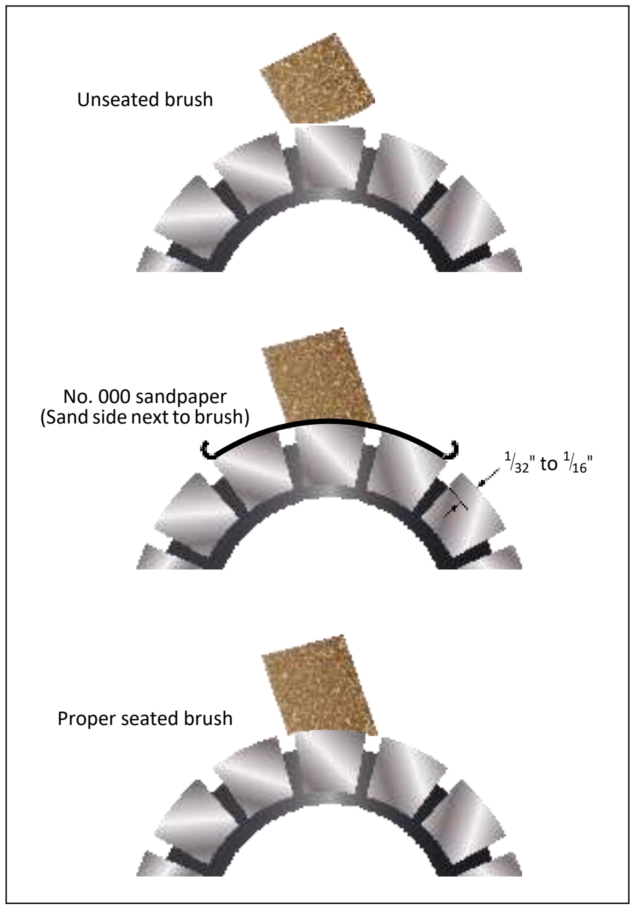

Figure 10-275. Seating brushes with sandpaper.

After the generator has run for a short period, brushes should be inspected to make sure that pieces of sand have not become embedded in the brush and are collecting copper.

Under no circumstances should emery cloth or similar abrasives be used for seating brushes (or smoothing commutators), since they contain conductive materials that will cause arcing between brushes and commutator bars.

Excessive pressure will cause rapid wear of brushes. Too little pressure, however, will allow "bouncing" of the brushes, resulting in burned and pitted surfaces.

A carbon, graphite, or light metalized brush should exert a pressure of 1½ to 2½ psi on the commutator. The pressure recommended by the manufacturer should be checked by the use of a spring scale graduated in ounces. Brush spring tension is usually adjusted between 32 to 36 ounces; however, the tension may differ slightly for each specific generator.

When a spring scale is used, the measurement of the pressure that a brush exerts on the commutator is read directly on the scale. The scale is applied at the point of contact between the spring arm and the top of the brush, with the brush installed in the guide. The scale is drawn up until the arm just lifts off the brush surface. At this instant, the force on the scale should be read.

Flexible low resistance pigtails are provided on most heavy current carrying brushes, and their connections should be securely made and checked at frequent intervals. The pigtails should never be permitted to alter or restrict the free motion of the brush.

The purpose of the pigtail is to conduct the current, rather than subjecting the brush spring to currents that would alter its spring action by overheating. The pigtails also eliminate any possible sparking to the brush guides caused by the movement of the brushes within the holder, thus minimizing side wear of the brush.

Carbon dust resulting from brush sanding should be thoroughly cleaned from all parts of the generators after a sanding operation. Such carbon dust has been the cause of several serious fires as well as costly damage to the generator.

Operation over extended periods of time often results in the mica insulation between commutator bars protruding above the surface of the bars. This condition is called "high mica" and interferes with the contact of the brushes to the commutator. Whenever this condition exists, or if the armature has been turned on a lathe, carefully undercut the mica insulation to a depth equal to the width of the mica, or approximately 0.020 inch.

Each brush should be a specified length to work properly. If a brush is too short, the contact it makes with the commutator will be faulty, which can also reduce the spring force holding the brush in place. Most manufacturers specify the amount of wear permissible from a new brush length. When a brush has worn to the minimum length permissible, it must be replaced.

Some special generator brushes should not be replaced because of a slight grooving on the face of the brush. These grooves are normal and will appear in AC and DC generator brushes which are installed in some models of aircraft generators. These brushes have two cores made of a harder material with a higher expansion rate than the material used in the main body of the brush. Usually, the main body of the brush face rides on the commutator. However, at certain temperatures, the cores extend and wear through any film on the commutator.

DC 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.

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 10-276. 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 Figure 10-276A, 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 Figure 10-276B. 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.

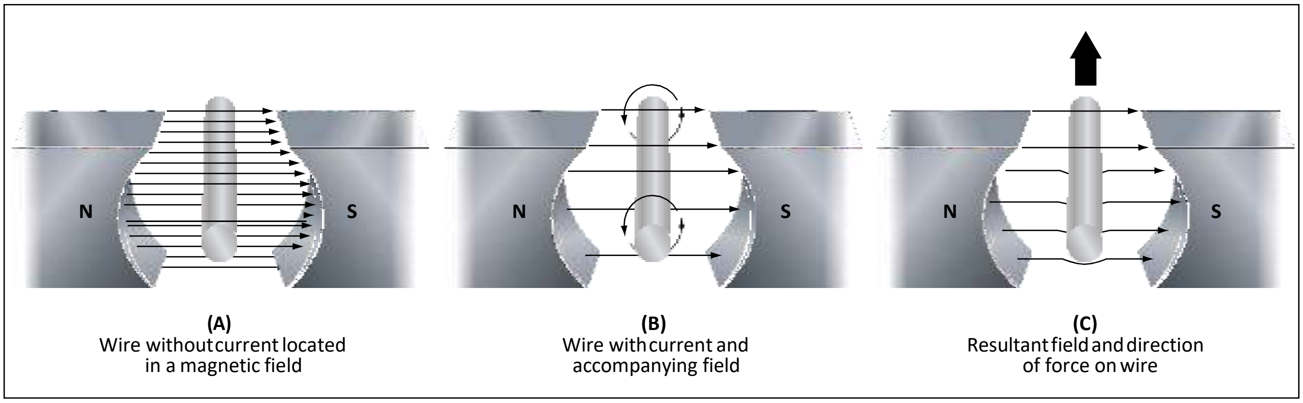

Figure 10-276. Force on a current carrying wire.

Since the current carrying wire produces a magnetic field, a reaction occurs between the field 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 Figure 10-276C. 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 10-277. 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, 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 the coil to rotate. In the coil shown in Figure 10-278, 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

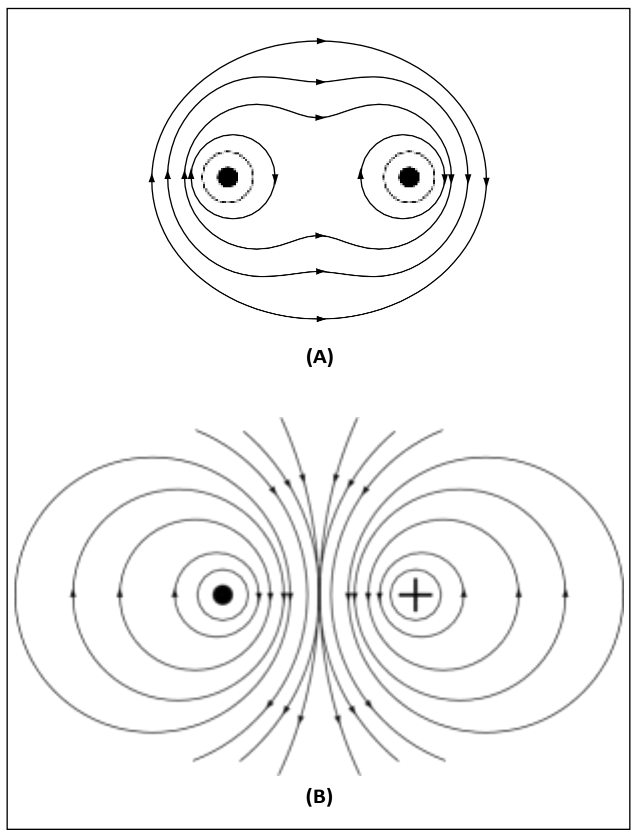

Figure 10-277. Fields surrounding parallel conductors.

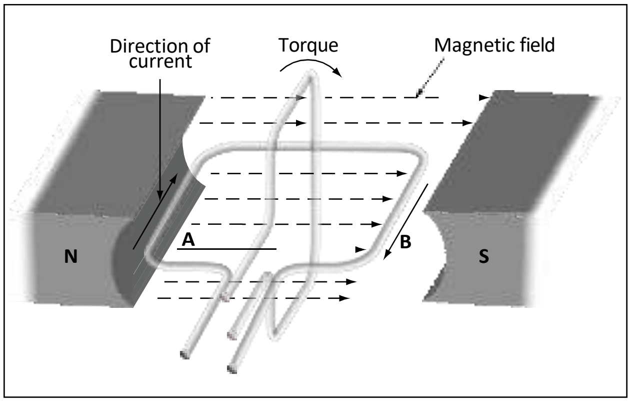

Figure 10-278. Developing a torque.

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 10-278 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 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 10-279, 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.

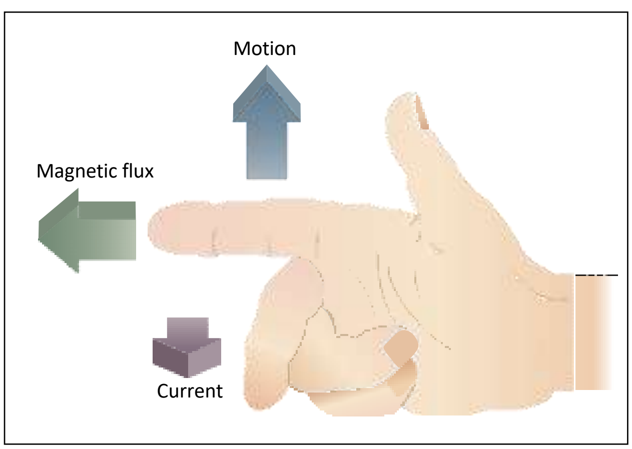

Figure 10-279. Right-hand motor rule.

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 that produces a strong field. Since there is 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 10-280. 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 DC 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 DC motor. Figure 10-281 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, must continue rotating. It is therefore necessary 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

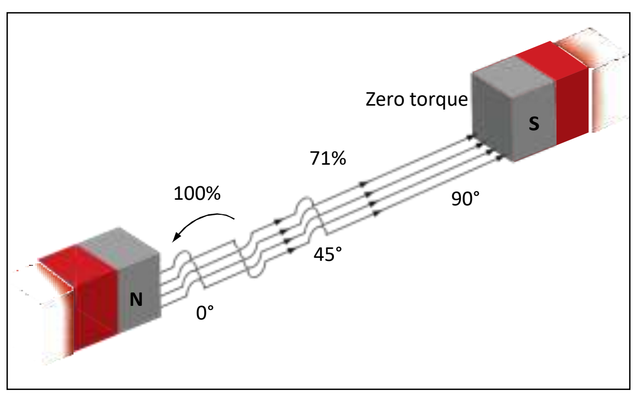

Figure 10-280. Torque on a coil at various angles of rotation.

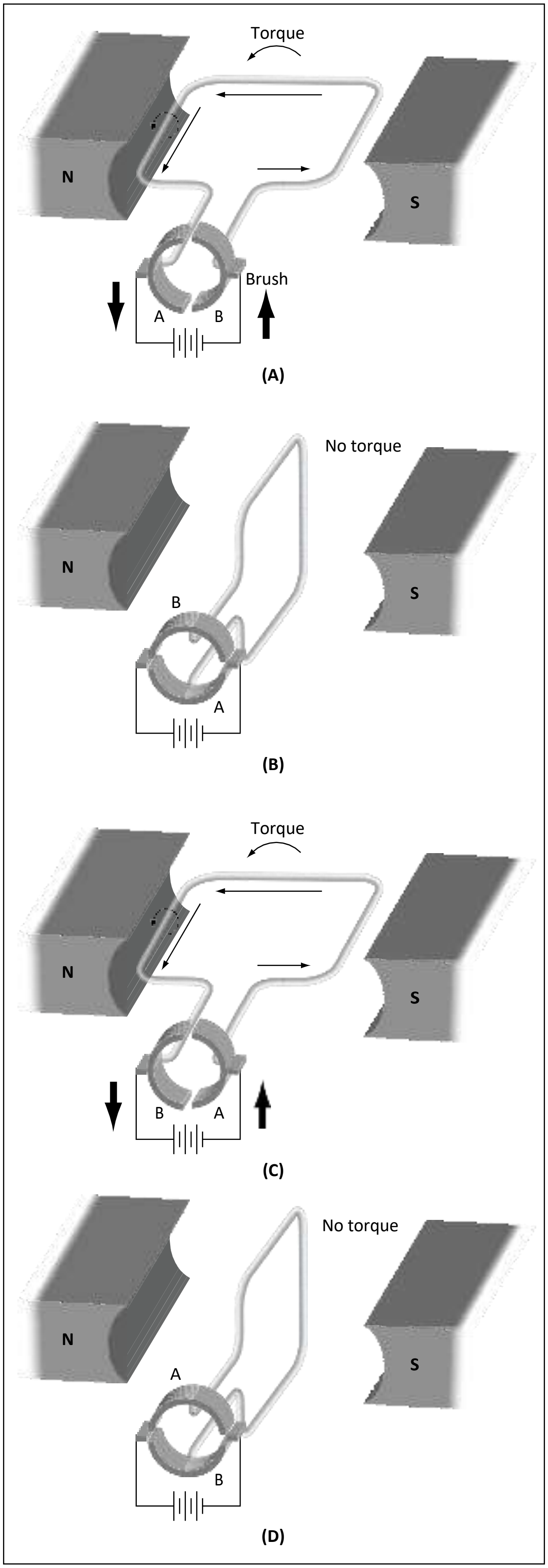

Figure 10-281. Basic DC motor operation.

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 10-281, 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.

Position A

When the coil is positioned as shown in Figure 10-281A, 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 is being cut by the coil.

Position B

When the coil has rotated 90° to the position shown in Figure 10-281B, 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.

Position C

On passing through the position shown in Figure 10-281C, the torque again reaches maximum.

Position D

Continued rotation carries the coil again to a position of minimum torque, as in Figure 10-281D. 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 DC 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.

DC Motor Construction

The major parts in a practical motor are the armature assembly, the field assembly, the brush assembly, and the end frame. [Figure 10-282]

Armature Assembly

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

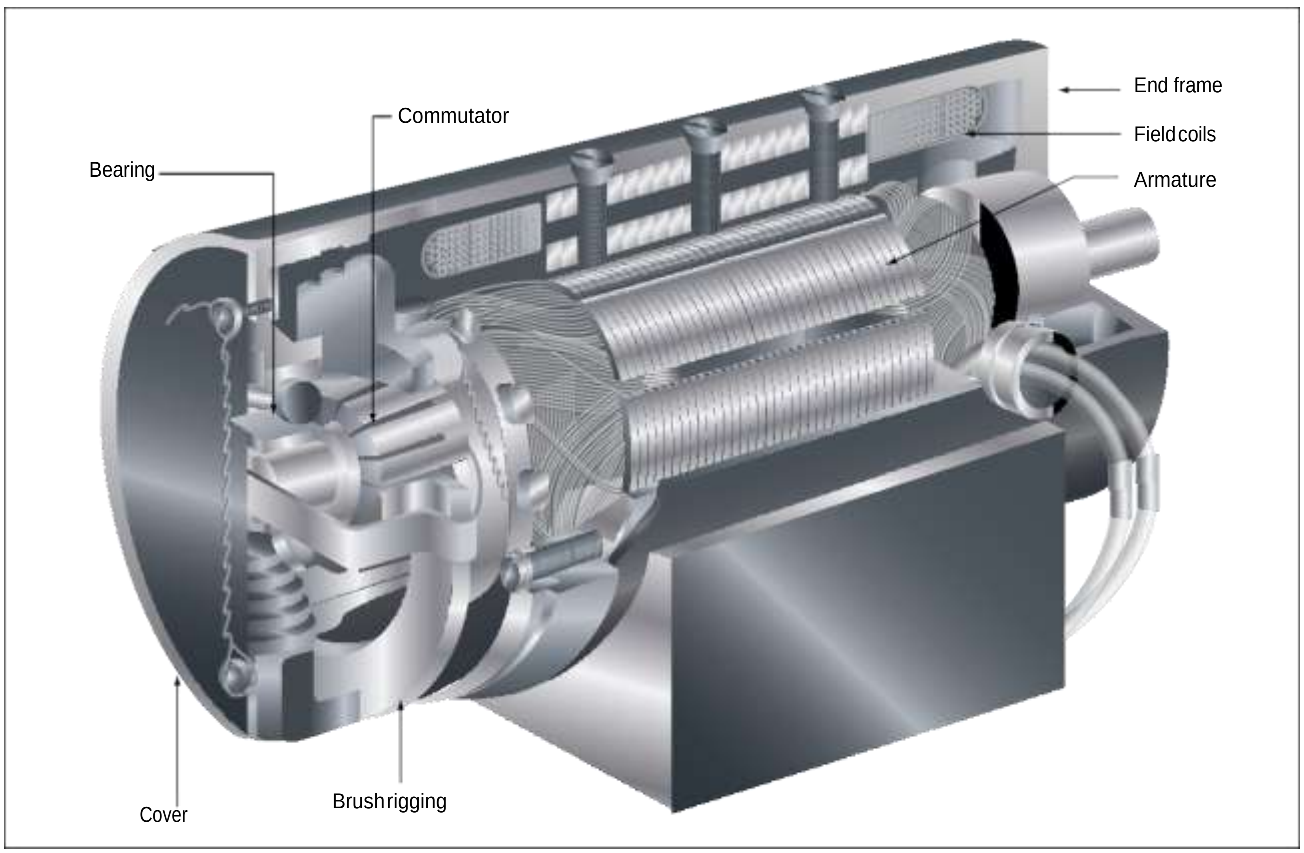

Figure 10-282. Cutaway view of practical DC motor.

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 10-283.

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 DC Motors

There are three basic types of DC 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 DC 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 are shown in Figure 10-284. The same current flowing through the field winding also flows 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 start-

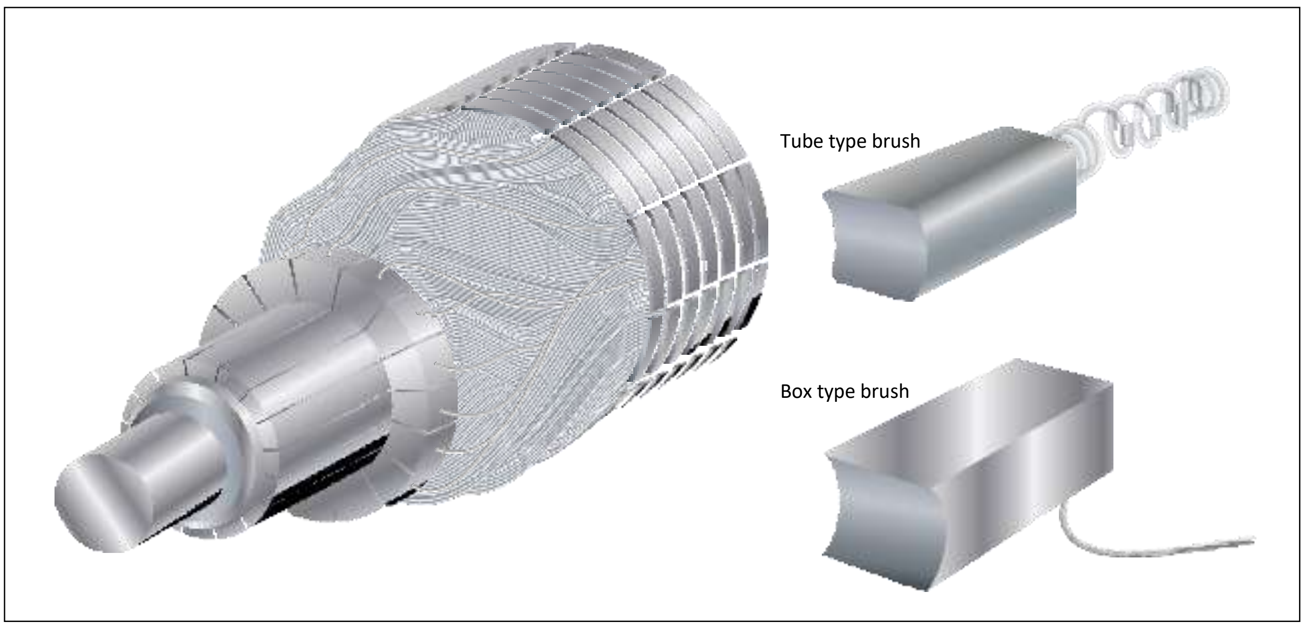

Figure 10-283. Commutator and brushes.

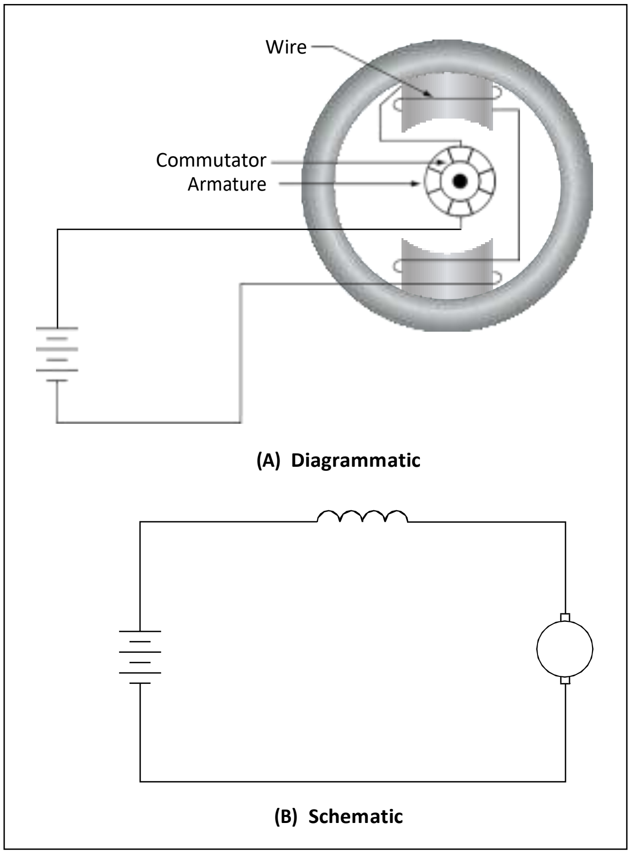

Figure 10-284. Series motor.

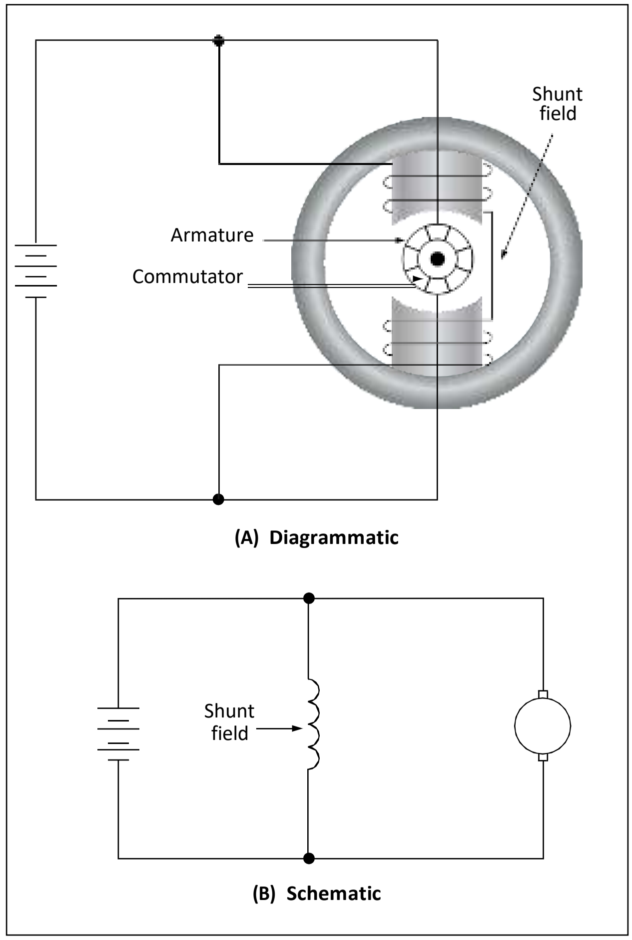

Figure 10-285. Shunt motor.

ers and for raising and lowering landing gears, cowl flaps, and wing flaps.

Shunt DC Motor

In the shunt motor, the field winding is connected in parallel or in shunt with the armature winding. [Figure 10-285] 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 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 DC 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 10-286. 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.

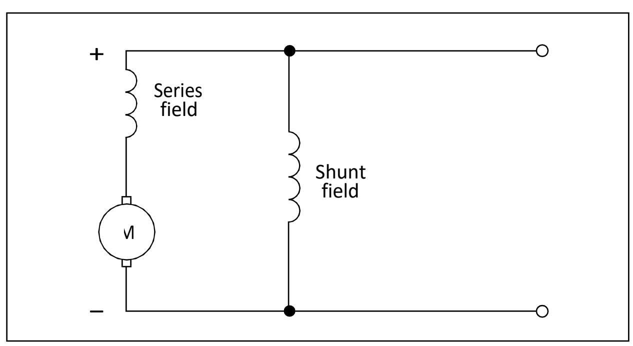

Figure 10-286. Compound motor.

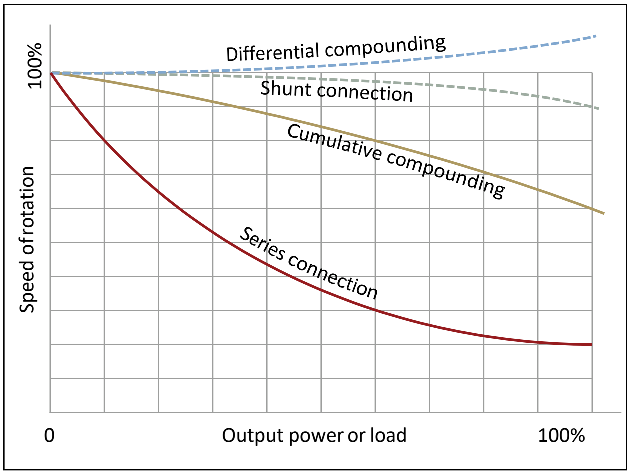

Figure 10-287. Load characteristics of DC motors.

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.

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 DC motors is shown in Figure 10-287.

Counter Electromotive Force (emf)

The armature resistance of a small, 28-volt DC 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 emf (electromotive force) and is opposite in direction to the voltage applied to the motor from the external source.

Counter emf opposes the current, which causes the armature to rotate. The current flowing through the armature, therefore, decreases as the counter emf increases. The faster the armature rotates, the greater the counter emf. 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 emf 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 emf will be generated, and the current drawn from the external source will increase. In a shunt motor, the counter emf 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 emf decreases, more current flows through the armature, but the magnetism in the field is unchanged. When the series motor slows down, the counter emf 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.

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 10-288 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 10-289, 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 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.

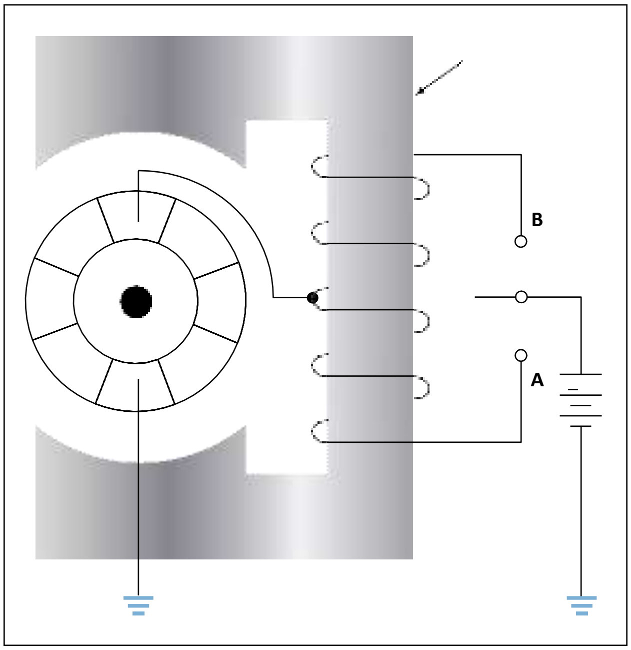

Figure 10-288. Split field series motor.

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 emf is generated in the armature windings. When the field current is decreased, the field strength decreases, and the motor speeds up because the counter emf 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 10-290] The speed depends on the amount of current that 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,

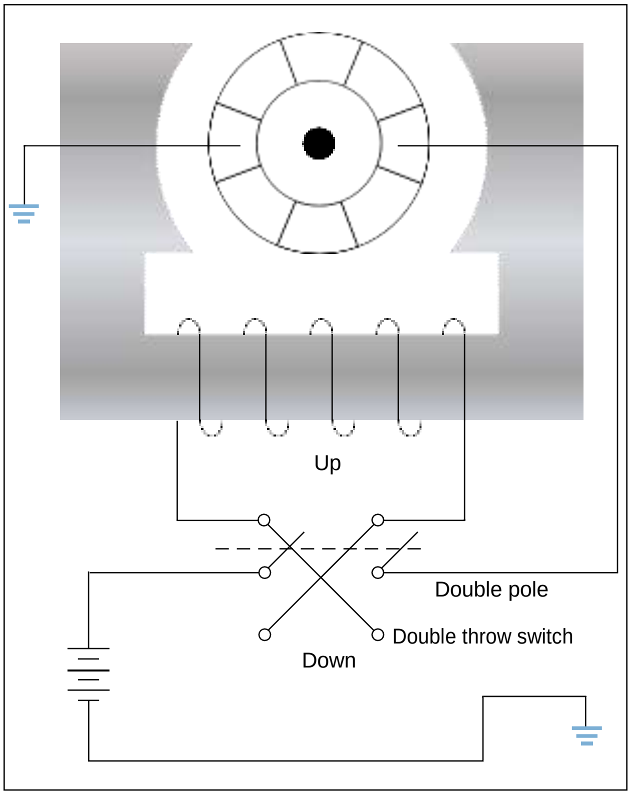

Figure 10-289. Switch method of reversing motor direction.

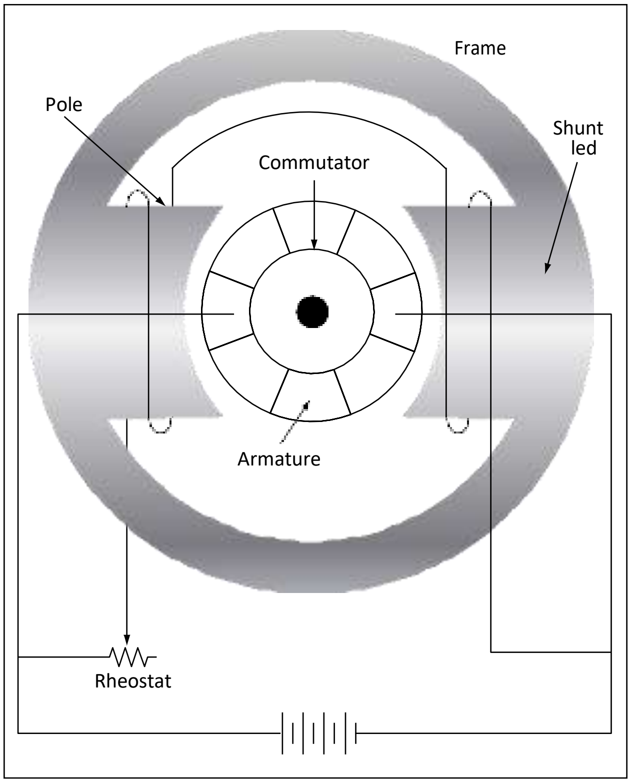

Figure 10-290. Shunt motor with variable speed control.

there is a decrease in the strength of the magnetic field and in the counter emf. This momentarily increases the armature current and the torque. The motor will then automatically speed up until the counter emf 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 emf increases momentarily and decreases the armature current. As a result, the torque decreases and the motor slows down until the counter emf decreases to its former value; then the motor operates at a lower fixed speed than before.

In the series motor, 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 10-291]

Energy Losses in DC 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

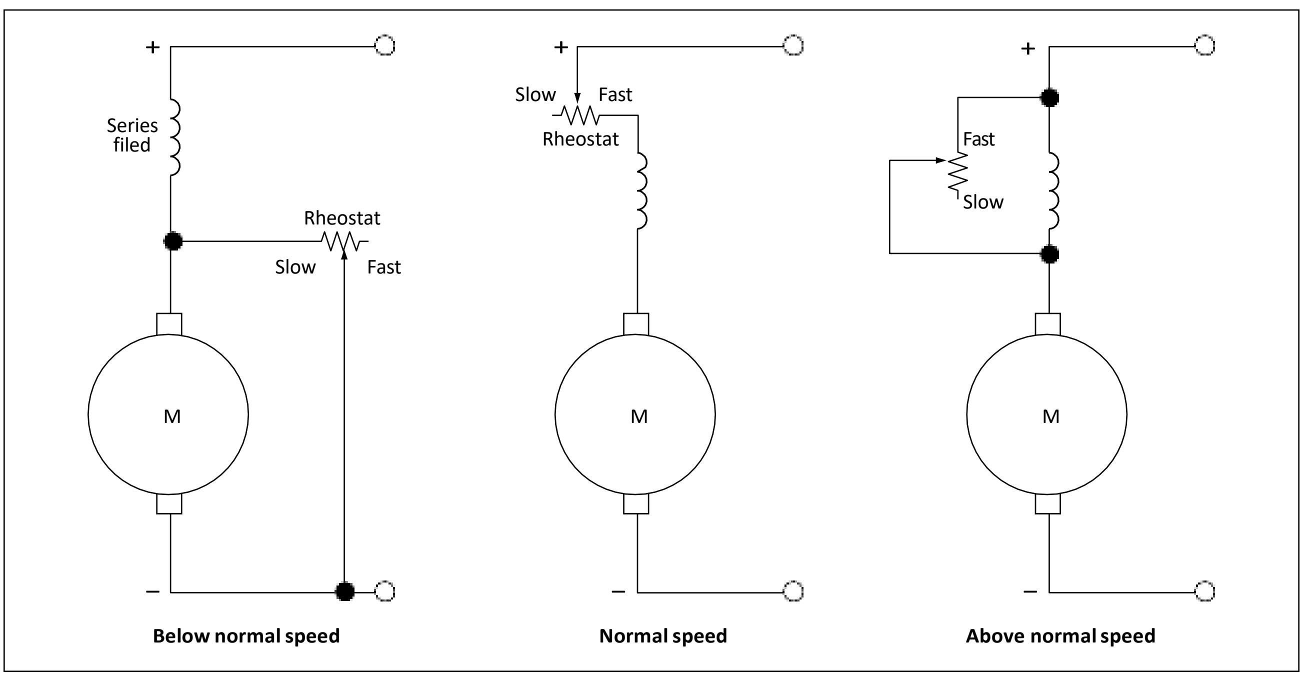

Figure 10-291. Controlling the speed of a series DC motor.

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 (DC 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 emf 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 DC 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 DC 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. A low battery usually causes the chattering of the relay switch, which controls the motor. 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.