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DC Generators & Motors

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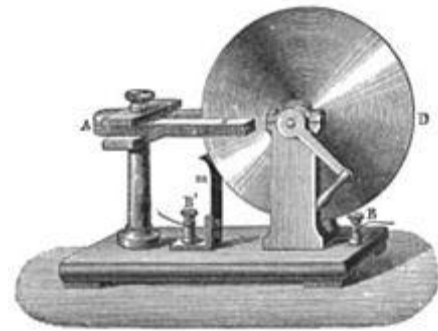# Direct Current Generators and Motors

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Introduction

An electric generator is a device that converts mechanical energy into electrical energy. A generator forces electric charge to flow through an external electrical circuit. The reverse conversion of electrical energy into mechanical energy is done by an electric motor, and motors and generators have many similarities. Many motors can be mechanically driven to generate electricity and frequently make acceptable generators.

Michael Faraday built the first electromagnetic generator, called the Faraday disk, a type of homopolar generator, using a copper disc rotating between the poles of a horseshoe magnet. It produced a small DC voltage. The image on the right is a Faraday disk, which is considered the first electric generator. The horseshoe-shaped magnet created a magnetic field through the disk. When the disk was turned, this induced an electric current radially outward from the center toward the rim. The current flowed out through the sliding spring contact, through the external circuit, and back into the center of the disk through the axle. So, Michael Faraday discovered the operating principle of electromagnetic generators. The principle, later called Faraday's law, is that an electromotive force is generated in an electrical conductor which encircles a varying magnetic flux.

This design was inefficient, due to self-cancelling counterflows of current in regions that were not under the influence of the magnetic field. While current was induced directly underneath the magnet, the current would circulate backwards in regions that were outside the influence of the magnetic field. This counterflow limited the power output to the pickup wires, and induced waste heating of the copper disc.

The dynamo was the first electrical generator capable of delivering power for industry. The dynamo uses electromagnetic induction to convert mechanical rotation into direct current through the use of a commutator. A dynamo machine consists of a stationary structure, which provides a constant magnetic field, and a set of rotating windings which turn within that field. On small machines the constant magnetic field may be provided by one or more permanent magnets; larger machines have the constant magnetic field provided by one or more electromagnets, which are usually called field coils. Through a series of accidental discoveries, the dynamo became the source of many later inventions, including the DC electric motor, the AC alternator, the AC synchronous motor, and the rotary converter.

Chapter 1
Direct Current Generators

Whenever a conductor is moved within a magnetic field in such a way that the conductor cuts across magnetic lines of flux, voltage is generated in the conductor. The *amount* of voltage generated depends on (1) the strength of the magnetic field, (2) the angle at which the conductor cuts the magnetic field, (3) the speed at which the conductor is moved, and (4) the length of the conductor within the magnetic field.

The *polarity* of the voltage depends on the direction of the magnetic lines of flux and the direction of movement of the conductor. To determine the direction of current in a given situation, the *left-hand rule for generators* is used. This rule is explained in the following manner. Extend the thumb, forefinger, and middle finger of your left hand at right angles to one another, as shown in Figure 1. Point your thumb in the direction the conductor is being moved (designated "F"). Point your forefinger in the direction of magnetic flux (designated "B"). Your middle finger will then point in the direction of current flow in an external circuit to which the voltage is applied (designated "I").
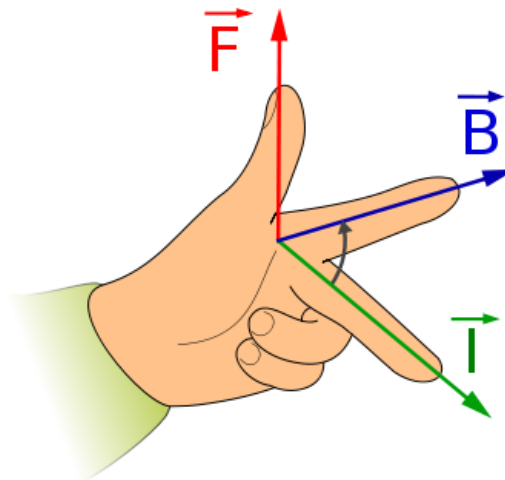
Left Hand Rule

Figure 1

The simplest elementary generator that can be built is an AC generator. Basic generating principles are most easily explained through the use of the elementary AC generator. For this reason, the AC generator will be discussed first. The DC generator will be discussed later. An elementary generator (Figure 2) consists of a wire loop placed so that it can be rotated in a stationary magnetic field. This will produce an induced EMF in the loop. Sliding contacts

(brushes) connect the loop to an external circuit load in order to pick up or use the induced electromotive force (EMF.)
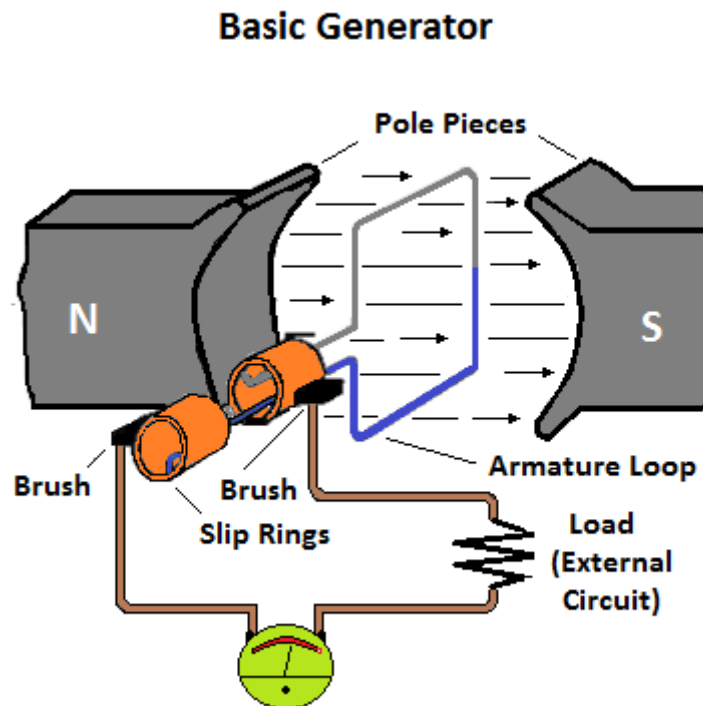
Basic Generator

Figure 2

The magnetic pole pieces (marked N and S) provide the magnetic field. The pole pieces are shaped and positioned as shown to concentrate the magnetic field as close as possible to the wire loop. The loop of wire that rotates through the field is called the *armature*. The ends of the armature loop are connected to rings called *slip rings*. They rotate with the armature. The brushes, usually made of carbon, with wires attached to them, ride against the rings. The generated voltage appears across these brushes.

The elementary generator produces a voltage in the following manner (Figure 3). The armature loop is rotated in a clockwise direction. The initial or starting point is shown at position A. (This will be considered the zero-degree position.) At 0 degrees the armature loop is perpendicular to the magnetic field. The gray and blue conductors of the loop are moving parallel to the field. The instant the conductors are moving parallel to the magnetic field, they do not cut any lines of flux. Therefore, no EMF is induced in the conductors, and the meter at position A indicates zero. This position is called the *neutral plane*.

As the armature loop rotates from position A (0º) to position B (90º), the conductors cut through more and more lines of flux, at a continually increasing angle. At 90 degrees they are cutting through a maximum number of lines of flux and at maximum angle. The result is that between 0º and 90º, the induced EMF in the conductors builds up from zero to a maximum value. Observe

that from 0º to 90º, the blue conductor cuts <u>down</u> through the field. At the same time the gray conductor cuts UP through the field. The induced EMFs in the conductors are series-adding. This means the resultant voltage across the brushes (the terminal voltage) is the sum of the two induced voltages. The meter at position B reads maximum value.

As the armature loop continues rotating from 90º (position B) to 180º (position C), the conductors which were cutting through a maximum number of lines of flux at position B now cut through fewer lines. They are again moving parallel to the magnetic field at position C. They no longer cut through any lines of flux.

As the armature rotates from 90º to 180º, the induced voltage will decrease to zero in the same manner that it increased during the rotation from 0º to 90º. The meter again reads zero. From 0º to 180º the conductors of the armature loop have been moving in the same direction through the magnetic field.

Therefore, the polarity of the induced voltage has remained the same. This is shown by points A through C on the graph. As the loop rotates beyond 180º (position C), through 270º (position D), and back to the initial or starting point (position A), the direction of the cutting action of the conductors through the magnetic field reverses. Now the blue conductor cuts UP through the field while the gray conductor cuts <u>down</u> through the field. As a result, the polarity of the induced voltage reverses. Following the sequence shown by graph points C, D, and back to A, the voltage will be in the direction opposite to that shown from points A, B, and C. The terminal voltage will be the same as it was from A to C except that the polarity is reversed (as shown by the meter deflection at position D). The voltage output waveform for the complete revolution of the loop is shown on the graph in Figure 3.
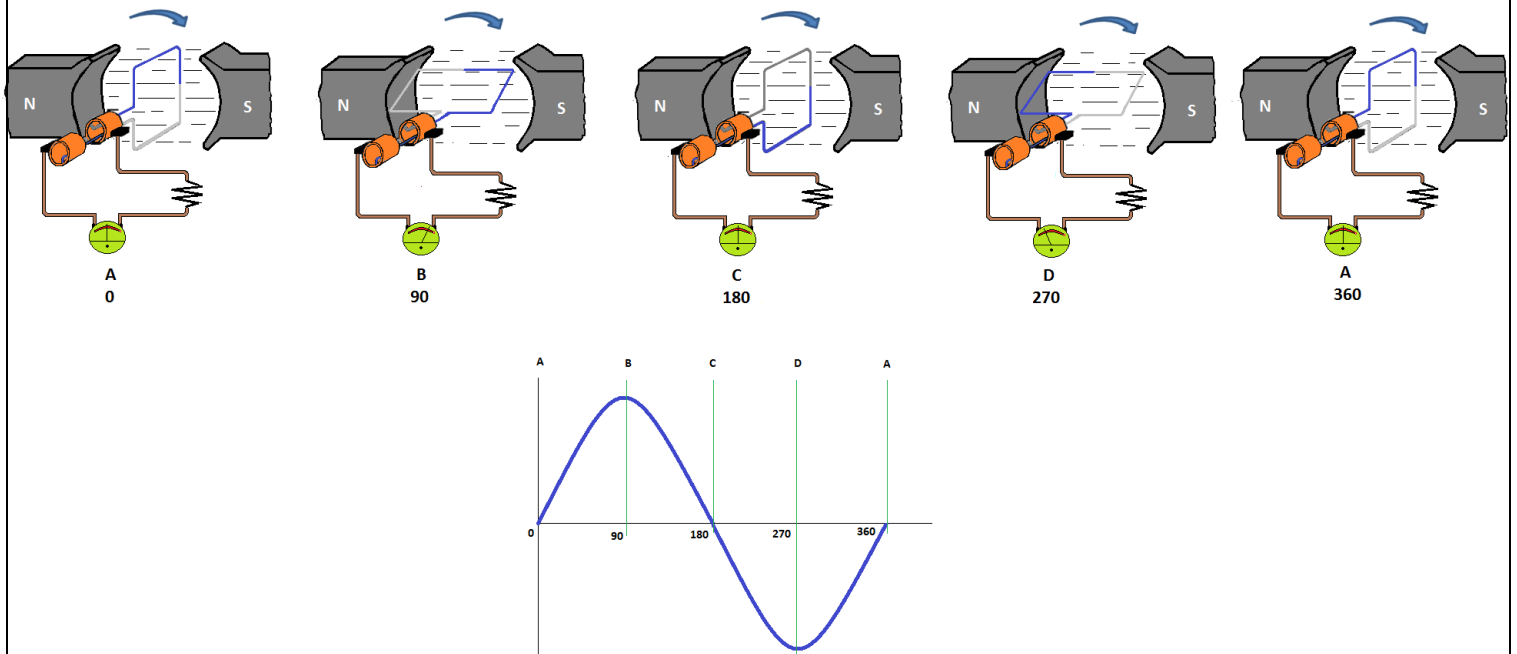
Generator Output through one Revolution

Figure 3

The Elementary DC Generator

A single-loop generator with each terminal connected to a segment of a two-segment metal ring is shown in Figure 4. The two segments of the split metal ring are insulated from each other. This forms a simple *commutator*. The commutator in a DC generator replaces the slip rings of the AC generator.

This is the main difference in their construction. The commutator mechanically reverses the armature loop connections to the external circuit. This occurs at the same instant that the polarity of the voltage in the armature loop reverses. Through this process the commutator changes the generated AC voltage to a pulsating DC voltage. This action is known as *commutation*. Commutation is described in detail later in this chapter.
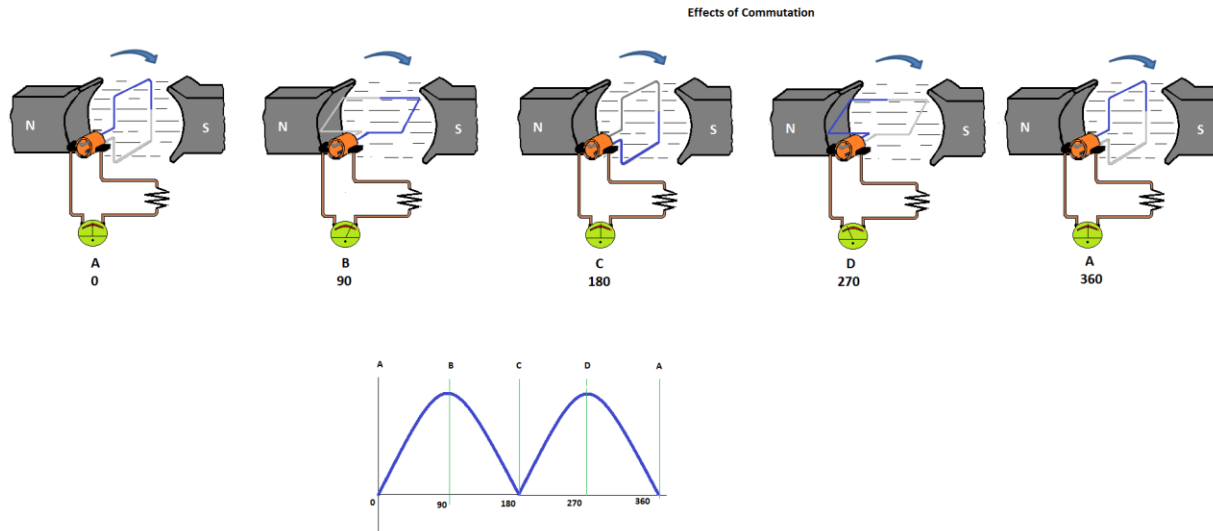
Effects of Commutation

Figure 4

For the remainder of this discussion, refer to Figure 4, parts A through D. This will help you in following the step-by-step description of the operation of a DC generator. When the armature loop rotates clockwise from position A to position B, a voltage is induced in the armature loop which causes a current in a direction that deflects the meter to the right. Current flows through loop, out of the negative brush, through the meter and the load, and back through the positive brush to the loop. Voltage reaches its maximum value at point B on the graph for reasons explained earlier. The generated voltage and the current fall to zero at position C. At this instant each brush makes contact with both segments of the commutator. As the armature loop rotates to position D, a voltage is again induced in the loop. In this case, however, the voltage is of opposite polarity.

The voltages induced in the two sides of the coil at position D are in the reverse direction to that of the voltages shown at position B. Note that the current is flowing from the blue side to the gray side in position B and from the gray side to the blue side in position D. However, because the segments of the commutator have rotated with the loop and are contacted by opposite brushes, the direction of current flow through the brushes and the meter remains the same as at position B. The voltage developed across the brushes is pulsating and unidirectional (in one direction only). It varies twice during each revolution between zero and maximum. This variation is called *ripple*.

A pulsating voltage, such as that produced in the preceding description, is unsuitable for most applications. Therefore, in practical generators more armature loops (coils) and more commutator segments are used to produce an output voltage waveform with less ripple.

Effects of Adding Additional Coils and Poles

The effects of additional coils may be illustrated by the addition of a second coil to the armature. The commutator must now be divided into four parts since there are four coil ends (see Figure 5). The coil is rotated in a clockwise direction from the position shown. The voltage induced in the gray coil, *decreases for the next 90º* of rotation (from maximum to zero). The voltage induced in the blue coil increases from zero to maximum at the same time. Since there are four segments in the commutator, a new segment passes each brush every 90º instead of every 180º. This allows the brush to switch from the gray coil to the blue coil at the instant the voltages in the two coils are equal. The brush remains in contact with the blue coil as its induced voltage increases to maximum, level B in the graph. It then decreases to level A, 90º later. At this point, the brush will contact the gray coil again.

Effects of Additional Coils

Pole Pieces

N   S

Commutator

Two Coil
Armature

Generator Terminal Voltage

B

A

0   45   90   135   180   225   270   315   360
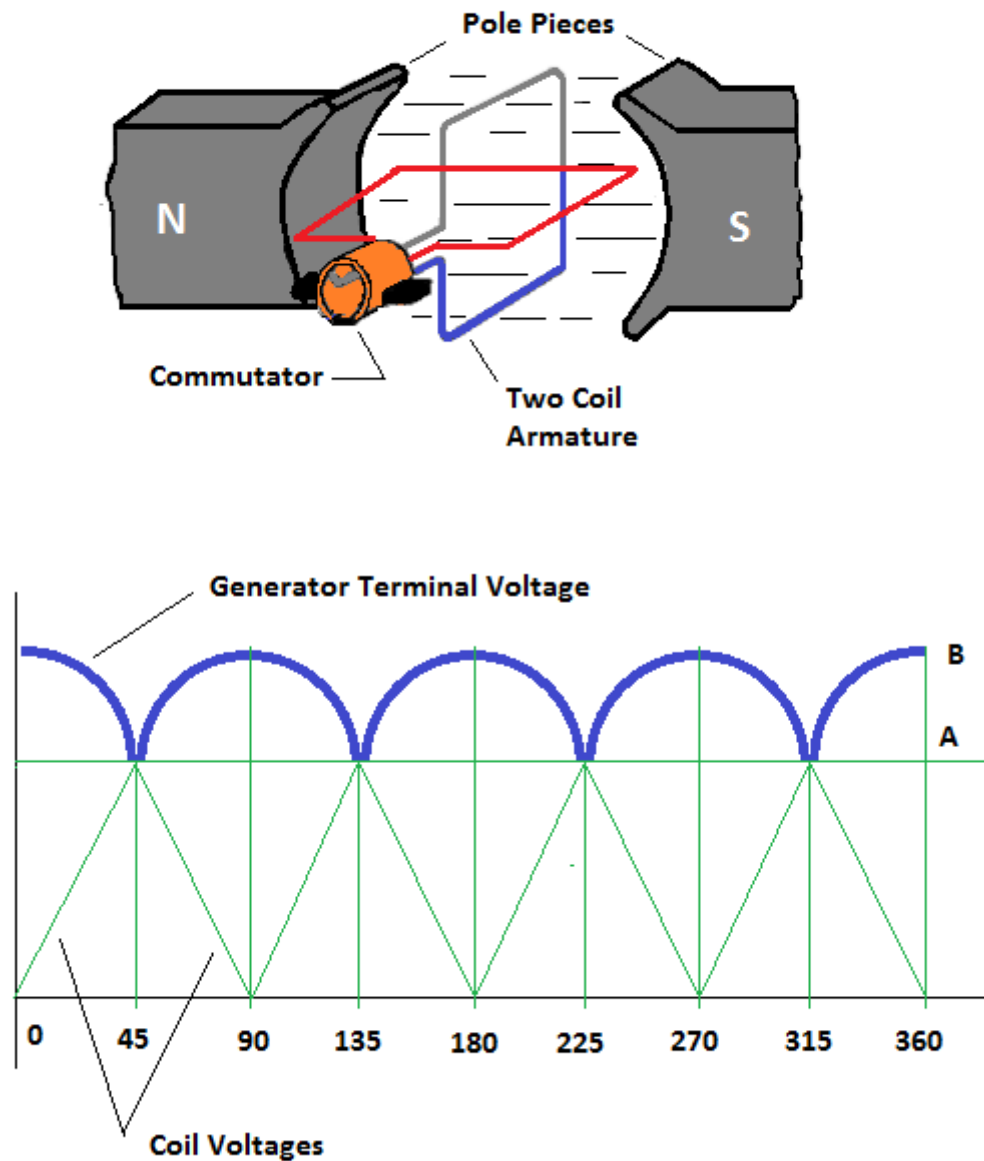
Coil Voltages

Figure 5

The graph in Figure 5 shows the ripple effect of the voltage when two armature coils are used. Since there are now four commutator segments in the commutator and only two brushes, the voltage cannot fall any lower than at point A. Therefore, the ripple is limited to the rise and fall between points A and B on the graph. By adding more armature coils, the ripple effect can be further reduced. Decreasing ripple in this way increases the effective voltage of the output.

Effective voltage is the equivalent level of DC voltage, which will cause the same average current through a given resistance. By using additional armature coils, the voltage across the

brushes is not allowed to fall to as low a level between peaks. Compare the graphs in Figures 4 and 5. Notice that the ripple has been reduced. Practical generators use many armature coils. They also use more than one pair of magnetic poles. The additional magnetic poles have the same effect on ripple as did the additional armature coils. In addition, the increased number of poles provides a stronger magnetic field (greater number of flux lines). This, in turn, allows an increase in output voltage because the coils cut more lines of flux per revolution.

Electromagnetic Poles

Nearly all practical generators use electromagnetic poles instead of the permanent magnets used in our elementary generator. The electromagnetic field poles consist of coils of insulated copper wire wound on soft iron cores, as shown in Figure 6. The main advantages of using electromagnetic poles are (1) increased field strength and (2) a means of controlling the strength of the fields. By varying the input voltage, the field strength is varied. By varying the field strength, the output voltage of the generator can be controlled.
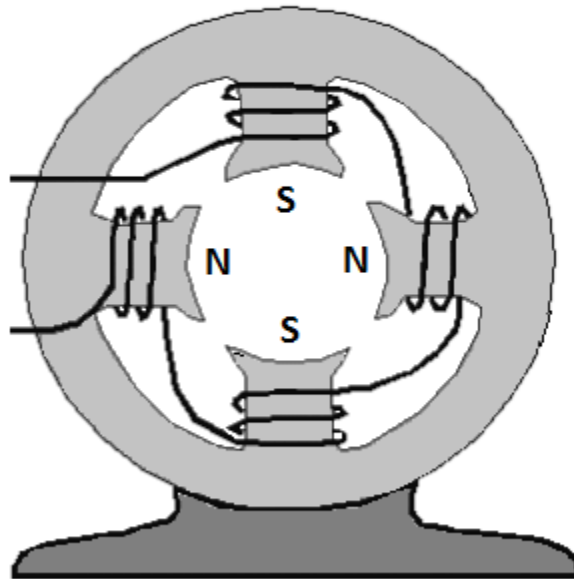
Four-Pole Generator

Figure 6

Commutation

Commutation is the process by which a DC voltage output is taken from an armature that has an AC voltage induced in it. You should remember from our discussion of the elementary DC generator that the commutator mechanically reverses the armature loop connections to the external circuit. This occurs at the same instant that the voltage polarity in the armature loop

reverses. A DC voltage is applied to the load because the output connections are reversed as each commutator segment passes under a brush. The segments are insulated from each other.

In Figure 7, commutation occurs simultaneously in the two coils that are briefly short-circuited by the brushes. Coil B is short-circuited by the negative brush. Coil Y, the opposite coil, is short-circuited by the positive brush. The brushes are positioned on the commutator so that each coil is short-circuited as it moves through its own electrical neutral plane. As you have seen previously, there is no voltage generated in the coil at that time. Therefore, no sparking can occur between the commutator and the brush. Sparking between the brushes and the commutator is an indication of improper commutation. Improper brush placement is the main cause of improper commutation.
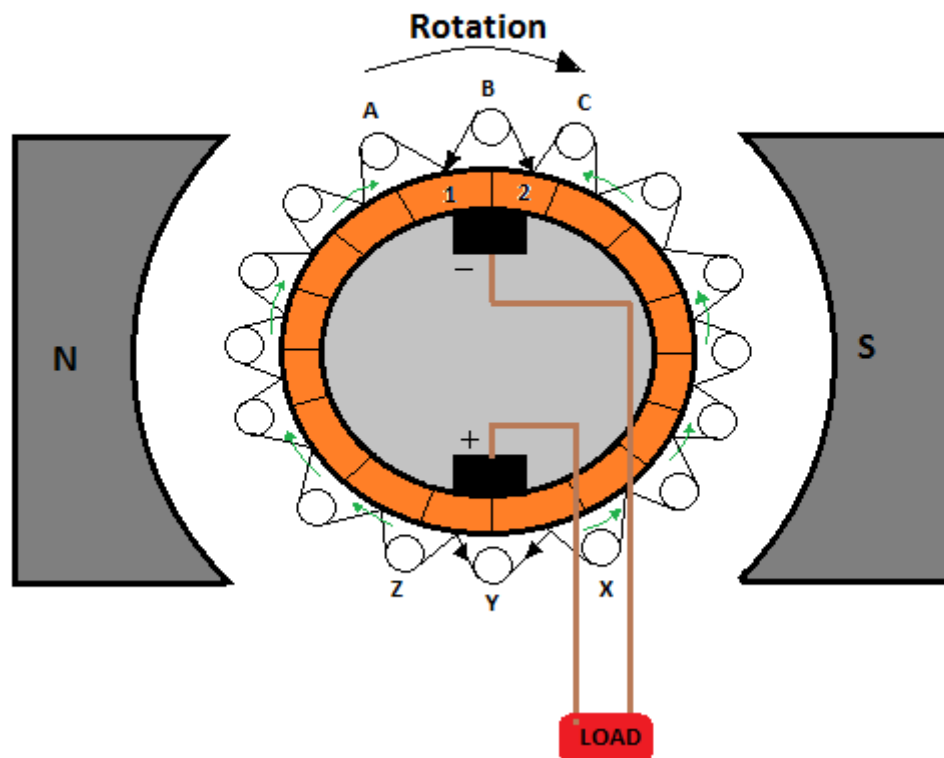

Figure 7

Armature Reaction

As you know that all current-carrying conductors produce magnetic fields. The magnetic field produced by current in the armature of a DC generator affects the flux pattern and distorts the main field. This distortion causes a shift in the neutral plane, which affects commutation. This change in the neutral plane and the reaction of the magnetic field is called *armature reaction*.

You know that for proper commutation, the coil short-circuited by the brushes must be in the neutral plane. Consider the operation of a simple two-pole DC generator, shown in Figure 8. View A of the Figure shows the field poles and the main magnetic field. The armature is shown in a simplified view in views B and C with the cross section of its coil represented as little circles. The symbols within the circles represent arrows. The dot represents the point of the arrow coming toward you, and the cross represents the tail, or feathered end, going away from you. When the armature rotates clockwise, the sides of the coil to the left will have current flowing toward you, as indicated by the dot. The side of the coil to the right will have current flowing away from you, as indicated by the cross. The field generated around each side of the coil is shown in view B of Figure 8. This field increases in strength for each wire in the armature coil, and sets up a magnetic field almost perpendicular to the main field.
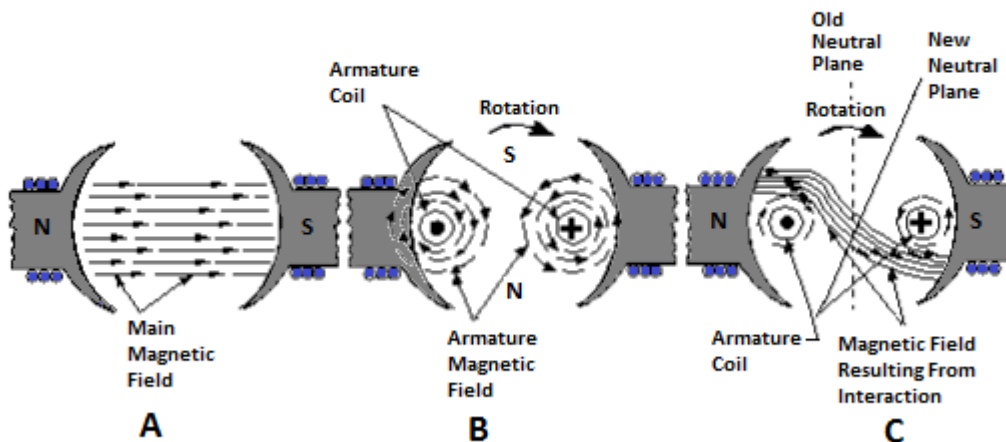
Armature Reaction

Figure 8

Now you have two fields — the main field, view A, and the field around the armature coil, view B. View C of Figure 8 shows how the armature field distorts the main field and how the neutral plane is shifted in the direction of rotation. If the brushes remain in the old neutral plane, they will be short circuiting coils that have voltage induced in them. Consequently, there will be arcing between the brushes and commutator. To prevent arcing, the brushes must be shifted to the new neutral plane.

Compensating Windings and Interpoles

However, shifting the brushes to the advanced position (the new neutral plane) does not completely solve the problems of armature reaction. The effect of armature reaction varies with the load current. Therefore, each time the load current varies, the neutral plane shifts. This means the brush position must be changed each time the load current varies.

In small generators, the effects of armature reaction are reduced by actually mechanically shifting the position of the brushes. The practice of shifting the brush position for each current variation is only used in small generators. In larger generators, other means are taken to eliminate armature reaction. *Compensating windings or interpoles* are used for this purpose (Figure 9). The compensating windings consist of a series of coils embedded in slots in the pole faces. These coils are connected in series with the armature. The series-connected compensating windings produce a magnetic field, which varies directly with armature current. Because the compensating windings are wound to produce a field that opposes the magnetic field of the armature, they tend to cancel the effects of the armature magnetic field. The neutral plane will remain stationary and in its original position for all values of armature current. Because of this, once the brushes have been set correctly, they do not have to be moved again.

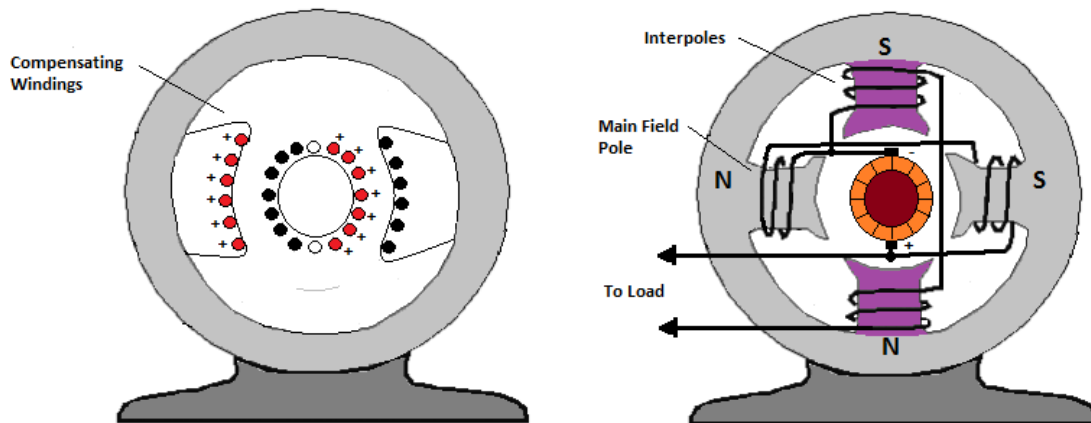## Compensating Windings and Interpoles

Figure 9

Another way to reduce the effects of armature reaction is to place small auxiliary poles called "interpoles" between the main field poles. The interpoles have a few turns of large wire and are connected in series with the armature. Interpoles are wound and placed so that each interpole has the same magnetic polarity as the main pole ahead of it, in the direction of rotation. The field generated by the interpoles produces the same effect as the compensating winding. This field, in effect, cancels the armature reaction for all values of load current by causing a shift in the neutral plane opposite to the shift caused by armature reaction. The amount of shift caused by the interpoles will equal the shift caused by armature reaction since both shifts are a result of armature current.

Motor Reaction in a Generator

When a generator delivers current to a load, the armature current creates a magnetic force that opposes the rotation of the armature. This is called *motor reaction*. A single armature conductor is represented in Figure 10, view A. When the conductor is stationary, no voltage is generated

and no current flows. Therefore, no force acts on the conductor. When the conductor is moved downward (Figure 10, view B) and the circuit is completed through an external load, current flows through the conductor in the direction indicated. This sets up lines of flux around the conductor in a clockwise direction.

Motor Reaction is a Generator

A

B

Reaction
Force

Field
Weakened

Load

Field
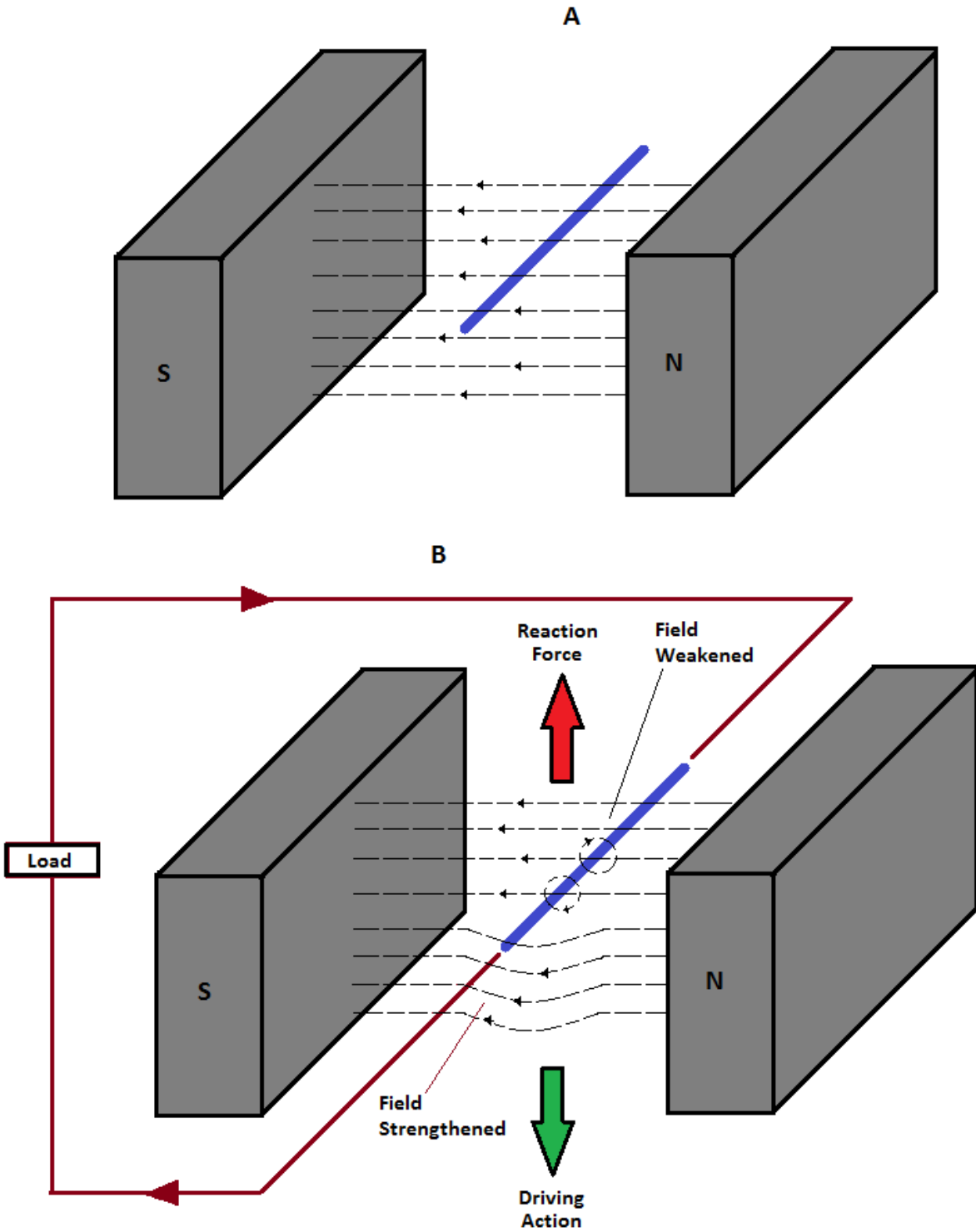Strengthened

Driving
Action

Figure 10

The interaction between the conductor field and the main field of the generator weakens the field above the conductor and strengthens the field below the conductor. The main field consists of lines that now act like stretched rubber bands. Thus, an upward reaction force is produced that acts in opposition to the downward driving force applied to the armature conductor. If the current in the conductor increases, the reaction force increases. Therefore, more force must be applied to the conductor to keep it moving.

With no armature current, there is no magnetic (motor) reaction. Therefore, the force required to turn the armature is low. As the armature current increases, the reaction of each armature conductor against rotation increases. The actual force in a generator is multiplied by the number of conductors in the armature. The driving force required to maintain the generator armature speed must be increased to overcome the motor reaction. The force applied to turn the armature must overcome the motor reaction force in all DC generators. The device that provides the turning force applied to the armature is called the *prime mover*. The prime mover may be an electric motor, a gasoline engine, a steam turbine, or any other mechanical device that provides turning force.

Armature Losses

In DC generators, as in most electrical devices, certain forces act to decrease the efficiency. These forces, as they affect the armature, are considered as losses and may be defined as follows:

- I^2R, or copper loss in the winding
- Eddy current loss in the core
- Hysteresis loss (a sort of magnetic friction)

Copper Losses
The power lost in the form of heat in the armature winding of a generator is known as *copper loss*. Heat is generated any time current flows in a conductor. Copper loss is an I^2R loss, which increases as current increases. The amount of heat generated is also proportional to the resistance of the conductor. The resistance of the conductor varies directly with its length and inversely with its cross-sectional area. Copper loss is minimized in armature windings by using large diameter wire.

Eddy Current Losses
The core of a generator armature is made from soft iron, which is a conducting material with desirable magnetic characteristics. Any conductor will have currents induced in it when it is rotated in a magnetic field. These currents that are induced in the generator armature core are called *eddy currents*. The power dissipated in the form of heat, as a result of the eddy currents, is considered a loss.

Eddy currents, just like any other electrical currents, are affected by the resistance of the material in which the currents flow. The resistance of any material is inversely proportional to its cross-sectional area. Figure 11, view A, shows the eddy currents induced in an armature core that is a solid piece of soft iron. Figure 11, view B, shows a soft iron core of the same size, but made up of several small pieces insulated from each other. This process is called *lamination*. The currents in each piece of the laminated core are considerably less than in the solid core because the resistance of the pieces is much higher. (Resistance is inversely proportional to cross-sectional area.) The currents in the individual pieces of the laminated core are so small that the sum of the individual currents is much less than the total of eddy currents in the solid iron core.

Eddy Currents in DC Generator Armature Cores
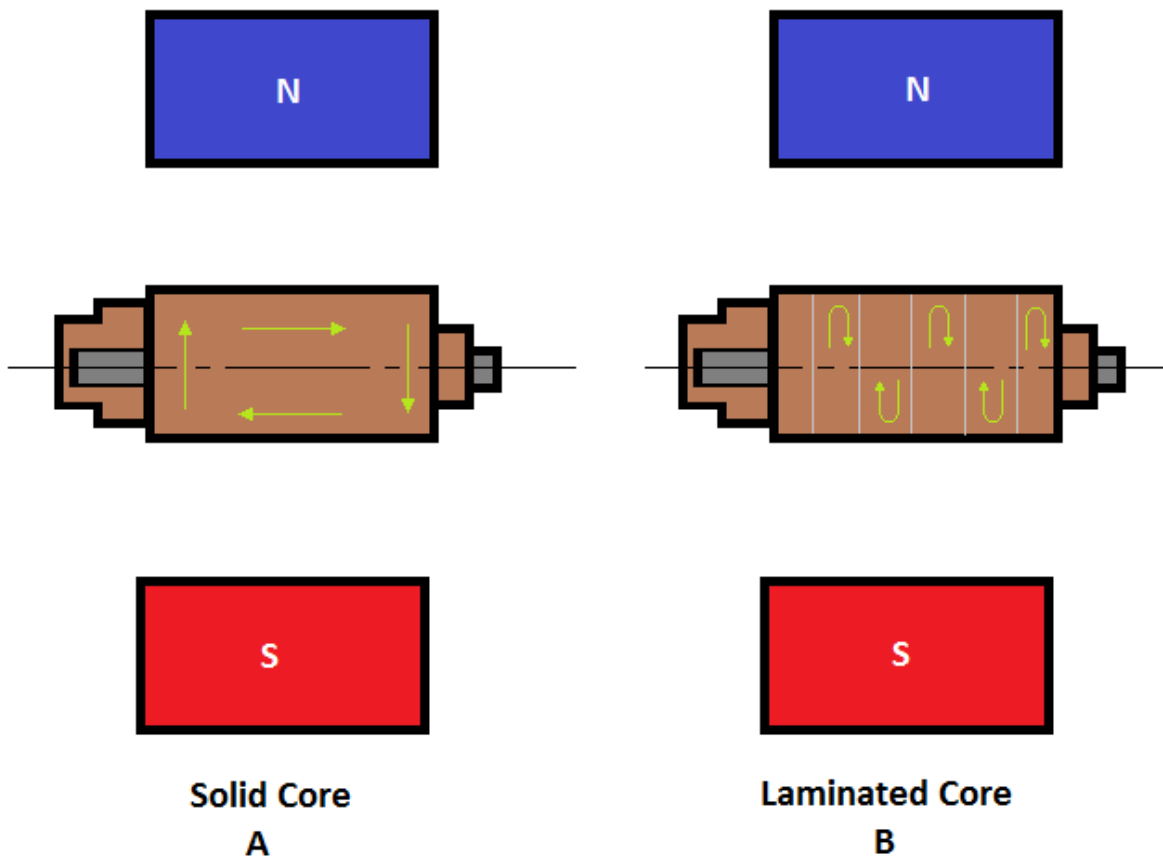

Solid Core
A

Laminated Core
B

Figure 11

As you can see, eddy current losses are kept low when the core material is made up of many thin sheets of metal. Laminations in a small generator armature may be as thin as 1/64 inch. The laminations are insulated from each other by a thin coat of lacquer or, in some instances, simply by the oxidation of the surfaces. Oxidation is caused by contact with the air while the laminations are being annealed. The insulation value need not be high because the voltages induced are very small.

Most generators use armatures with laminated cores to reduce eddy current losses.

Hysteresis Losses

Hysteresis loss is a heat loss caused by the magnetic properties of the armature. When an armature core is in a magnetic field, the magnetic particles of the core tend to line up with the magnetic field. When the armature core is rotating, its magnetic field keeps changing direction. The continuous movement of the magnetic particles, as they try to align themselves with the magnetic field, produces molecular friction. This, in turn, produces heat. This heat is transmitted to the armature windings. The heat causes armature resistances to increase.

To compensate for hysteresis losses, heat-treated silicon steel laminations are used in most DC generator armatures. After the steel has been formed to the proper shape, the laminations are heated and allowed to cool. This annealing process reduces the hysteresis loss to a low value.

The Practical DC Generator

The actual construction and operation of a practical DC generator differs somewhat from our elementary generators. The differences are in the construction of the armature, the manner in which the armature is wound, and the method of developing the main field.

A generator that has only one or two armature loops has high ripple voltage. This results in too little current to be of any practical use. To increase the amount of current output, a number of loops of wire are used. These additional loops do away with most of the ripple. The loops of wire, called windings, are evenly spaced around the armature so that the distance between each winding is the same.

The commutator in a practical generator is also different. It has several segments instead of two or four, as in our elementary generators. The number of segments must equal the number of armature coils.

Gramme-Ring Armature

The diagram of a *gramme-ring* armature is shown in Figure 12, view A. Each coil is connected to two commutator segments as shown. One end of coil "1" goes to segment A, and the other end of coil "1" goes to segment B. One end of coil "2" goes to segment C, and the other end of coil "2" goes to segment B. The rest of the coils are connected in a like manner, in series, around the armature. To complete the series arrangement, coil "8" connects to segment A. Therefore, each coil is in series with every other coil.
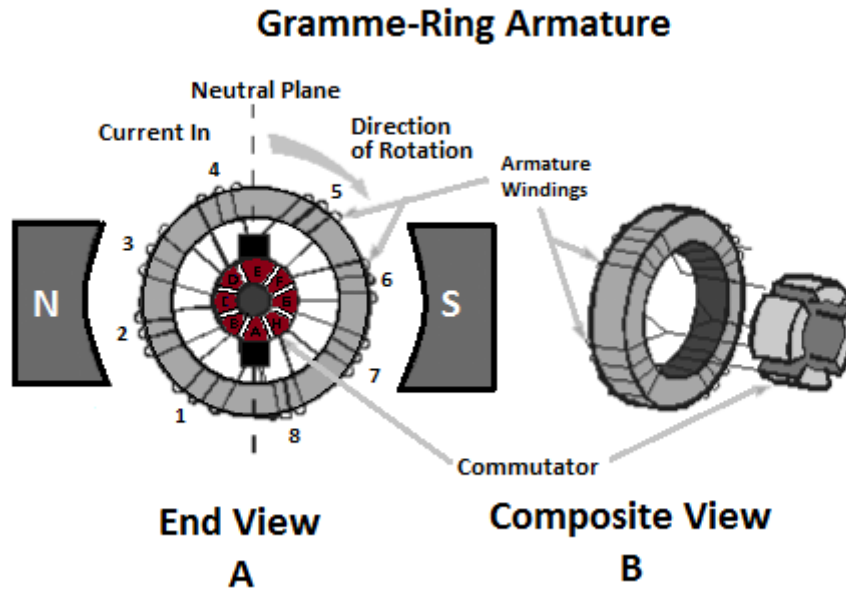
Gramme-Ring Armature

Figure 12

Figure 12, view B shows a composite view of a Gramme-ring armature. It illustrates more graphically the physical relationship of the coils and commutator locations.

The windings of a Gramme-ring armature are placed on an iron ring. A disadvantage of this arrangement is that the windings located on the inner side of the iron ring cut few lines of flux. Therefore, they have little, if any, 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 13. The armature windings are placed in slots cut in a drum-shaped iron core. Each winding completely surrounds the core so that the entire length of the conductor cuts the main magnetic field. Therefore, the total voltage induced in the armature is greater than in the Gramme-ring. You can see that the drum-type armature is much more efficient than the Gramme-ring. This accounts for the almost universal use of the drum-type armature in modem DC generators.
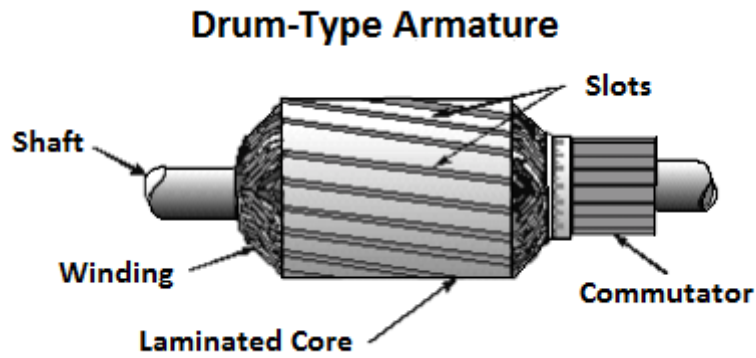
Drum-Type Armature

Figure 13

Drum-type armatures are wound with either of two types of windings — the *lap winding* or the *wave winding*.

The lap winding is illustrated in Figure 14, view A This type of winding is used in DC generators designed for high-current applications. The windings are connected to provide several parallel paths for current in the armature. For this reason, lap-wound armatures used in DC generators require several pairs of poles and brushes.
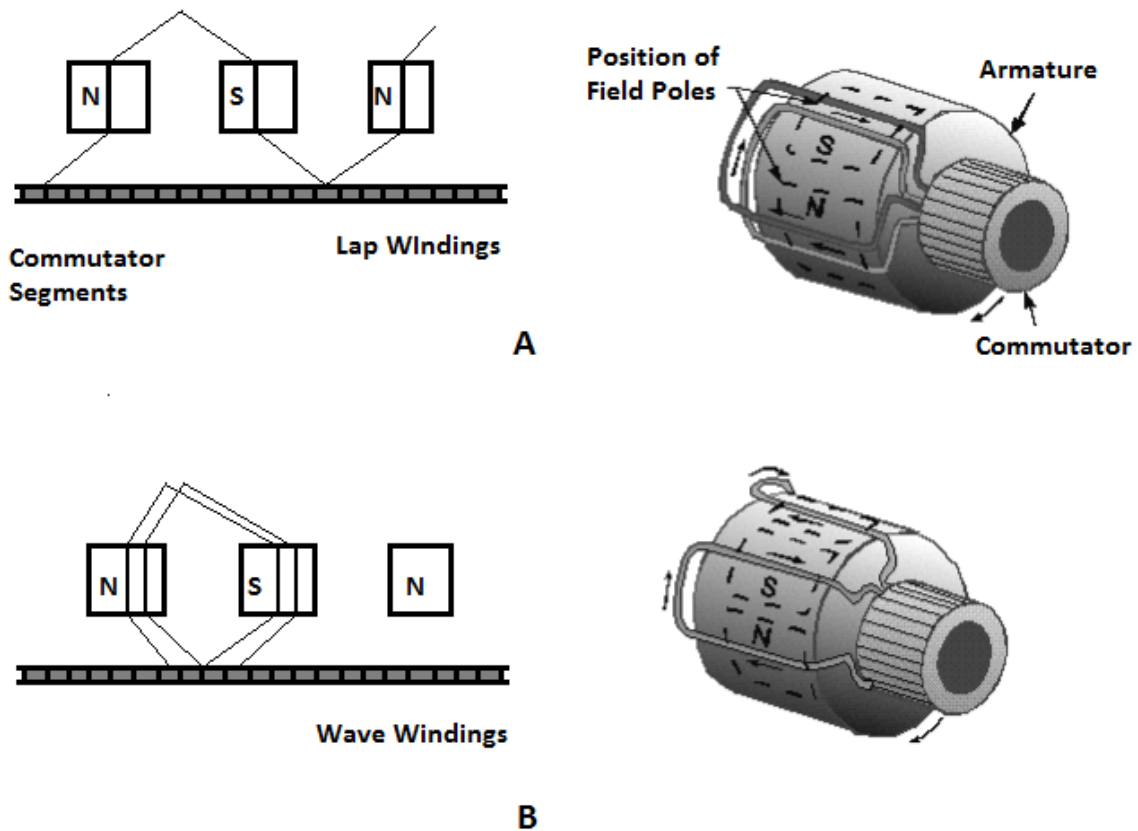
Types of Drum-Type Armatures

Figure 14

Figure 14, view B, shows a wave winding on a drum-type armature. This type of winding is used in DC generators employed in high-voltage applications. Notice that the two ends of each coil are connected to commutator segments separated by the distance between poles. This configuration allows the series addition of the voltages in all the windings between brushes. This type of winding only requires one pair of brushes. In practice, a practical generator may have several pairs to improve commutation.

Field Excitation

When a DC voltage is applied to the field windings of a DC generator, current flows through the windings and sets up a steady magnetic field. This is called *field excitation*.

This excitation voltage can be produced by the generator itself or it can be supplied by an outside source, such as a battery. A generator that supplies its own field excitation is called a *self-excited generator*. Self-excitation is possible only if the field pole pieces have retained a slight amount of permanent magnetism, called *residual magnetism*. When the generator starts rotating, the weak residual magnetism causes a small voltage to be generated in the armature. This small voltage applied to the field coils causes a small field current. Although small, this field current strengthens the magnetic field and allows the armature to generate a higher voltage. The higher voltage increases the field strength, and so on. This process continues until the output voltage reaches the rated output of the generator.

Classification of Generators

Self-excited generators are classed according to the type of field connection they use. There are three general types of field connections — *series-wound*, *shunt-wound* (parallel), and *compound-wound*. Compound-wound generators are further classified as cumulative-compound and differential-compound. These last two classifications are not discussed in this chapter.

Series-Wound Generator
In the series-wound generator, shown in Figure 15, the field windings are connected in series with the armature. Current that flows in the armature flows through the external circuit and through the field windings. The external circuit connected to the generator is called the load circuit.
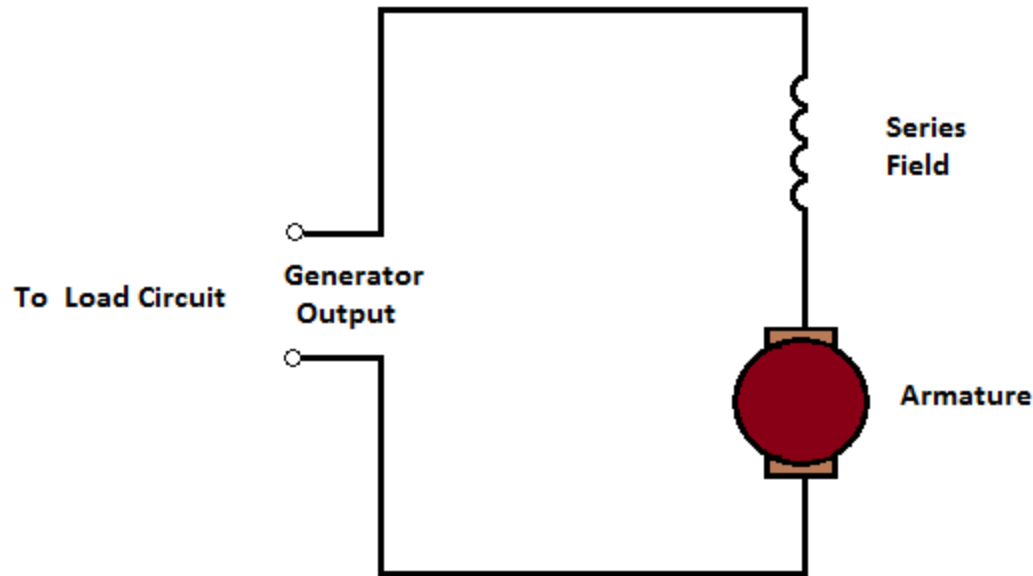
Series Wound Generator

Figure 15

A series-wound generator uses very low resistance field coils, which consist of a few turns of large diameter wire. The voltage output increases as the load circuit starts drawing more current. Under low-load current conditions, the current that flows in the load and through the generator is small. Since small current means that a small magnetic field is set up by the field poles, only a small voltage is induced in the armature. If the resistance of the load decreases, the load current increases. Under this condition, more current flows through the field. This increases the magnetic field and increases the output voltage. A series-wound DC generator has the characteristic that the output voltage varies with load current. This is undesirable in most applications. For this reason, this type of generator is rarely used in everyday practice.

The series-wound generator has provided an easy method to introduce you to the subject of self-excited generators.

Shunt-Wound Generators
In a shunt-wound generator, like the one shown in Figure 16, the field coils consist of many turns of small wire. They are connected in parallel with the load. In other words, they are connected across the output voltage of the armature.
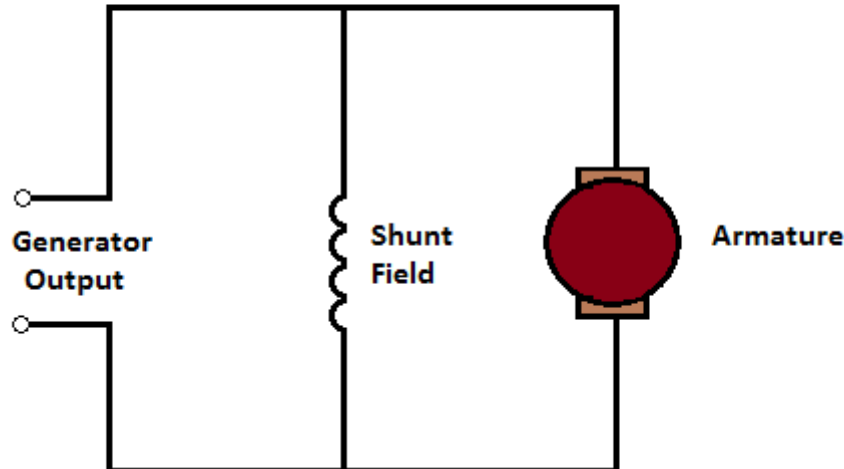
Shunt-Wound Generator

Figure 16

Current in the field windings of a shunt-wound generator is independent of the load current (currents in parallel branches are independent of each other). Since field current, and therefore field strength, is not affected by load current, the output voltage remains more nearly constant than does the output voltage of the series-wound generator.

In actual use, the output voltage in a DC shunt-wound generator varies inversely as load current varies. The output voltage decreases as load current increases because the voltage drop across the armature resistance increases ($E = IR$).

In a series-wound generator, output voltage varies directly with load current. In the shunt-wound generator, output voltage varies inversely with load current. A combination of the two types can overcome the disadvantages of both. This combination of windings is called the compound-wound DC generator.

Compound-Wound Generators
Compound-wound generators have a series-field winding in addition to a shunt-field winding, as shown in Figure 17. The shunt and series windings are wound on the same pole pieces.
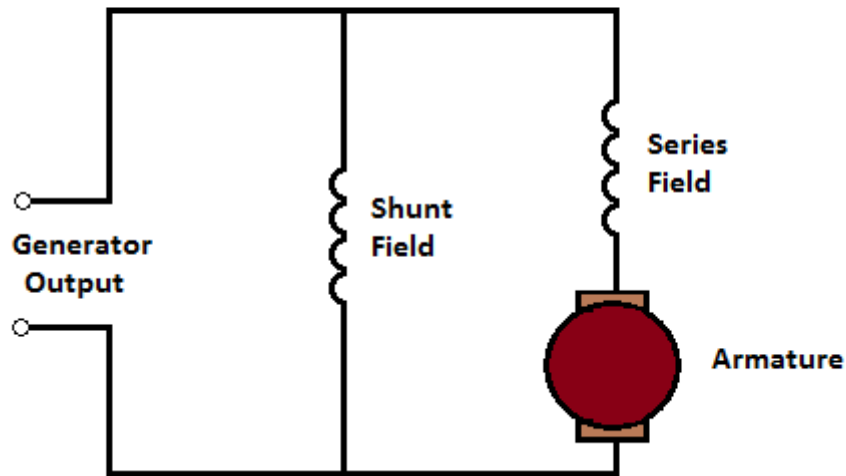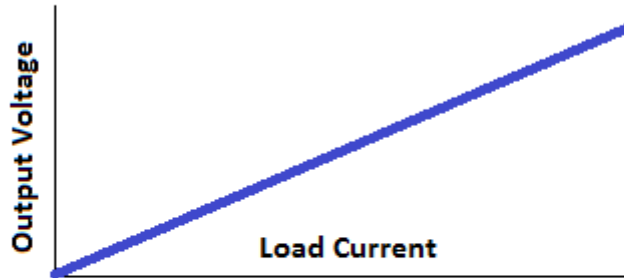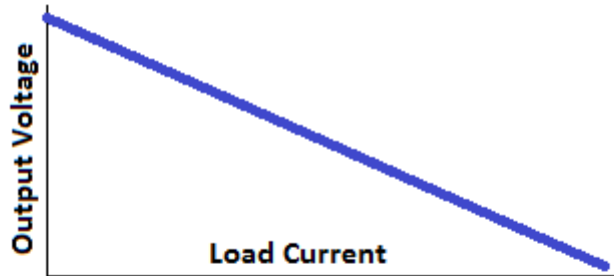
Compound-Wound Generator

Figure 17

In the compound-wound generator when load current increases, the armature voltage decreases just as in the shunt-wound generator. This causes the voltage applied to the shunt-field winding to decrease, which results in a decrease in the magnetic field. This same increase in load current, since it flows through the series winding, causes an increase in the magnetic field produced by that winding.

By proportioning the two fields so that the decrease in the shunt field is just compensated by the increase in the series field, the output voltage remains constant. This is shown in Figure 18, which shows the voltage characteristics of the series-, shunt-, and compound-wound generators. As you can see, by proportioning the effects of the two fields (series and shunt), a compound-wound generator provides a constant output voltage under varying load conditions. Actual curves are seldom, if ever, as perfect as shown.

A. Shunt-Wound DC Generator

Output Voltage

Load Current

B. Series-Wound DC Generator

Output Voltage

Load Current

C. Compound-Wound DC Generator

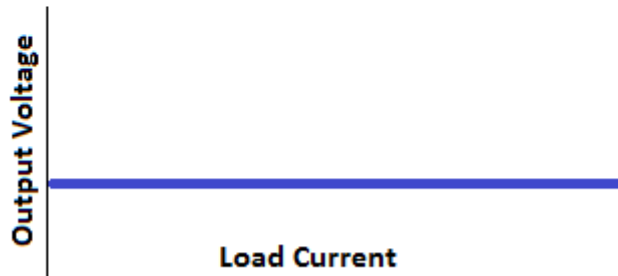**Output Voltage**

Load Current

Figure 18

Generator Construction

Figure 19 shows the entire generator with the component parts installed. The cutaway drawing helps you to see the physical relationship of the components to each other.
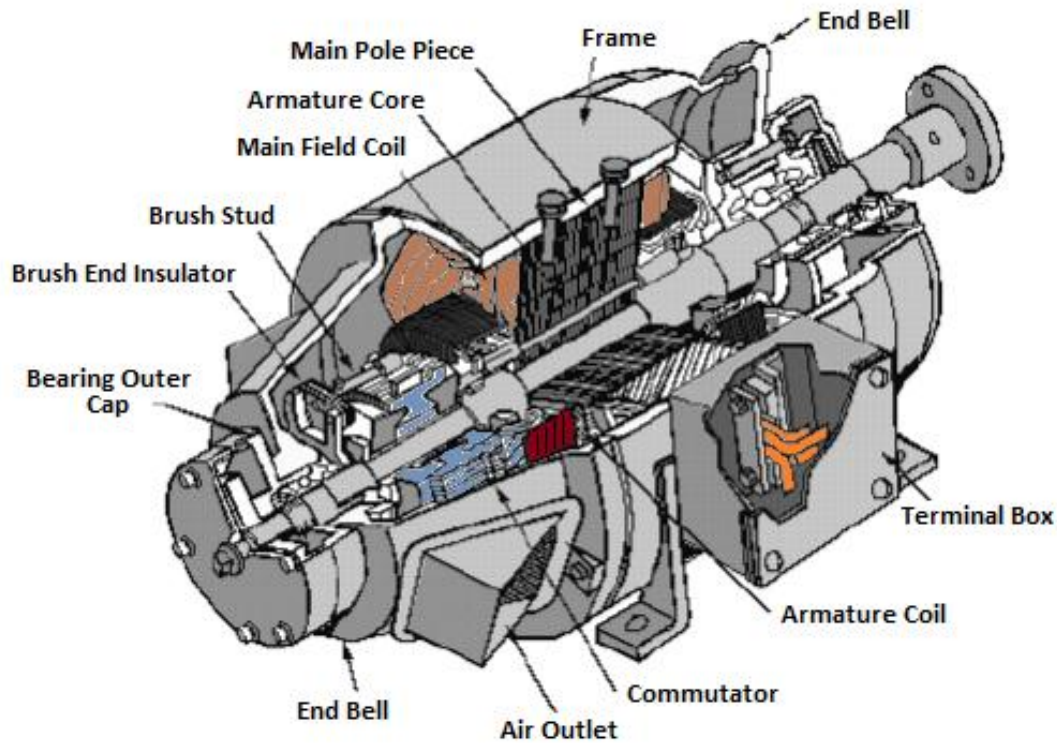
Construction of a DC Generator

Figure 19

Voltage Regulation

The regulation of a generator refers to the *voltage change* that takes place when the load changes. It is usually expressed as the change in voltage from a no-load condition to a full-load condition, and is expressed as a percentage of full-load. It is expressed in the following formula:

$$\textbf{Percent Regulation} = \frac{\textbf{E}_{\textbf{NL}} - \textbf{E}_{\textbf{FL}}}{\textbf{E}_{\textbf{FL}}} * \textbf{100}$$

Where,
E_{NL} = No-load terminal voltage and
E_{FL} = Full-load terminal voltage of the generator.

For example, calculate the percent of regulation of a generator with a no-load voltage of 462 volts and a full-load voltage of 440 volts.

The percent of regulation is,

$$\text{Percent Regulation} = \frac{462 - 440}{440} * 100$$

Percent Regulation = 0.05 * 100 = 5%

The lower the percent of regulation, the better the generator. In the above example, the 5% regulation represented a 22-volt change from no load to full load. A 1% change would represent a change of 4.4 volts, which, of course, would be better.

Voltage Control

Voltage control is either manual or automatic. In most cases the process involves changing the resistance of the field circuit. By changing the field circuit resistance, the field current is controlled.

Controlling the field current permits control of the output voltage. The major difference between the various voltage control systems is merely the method by which the field circuit resistance and the current are controlled.

Voltage regulation should not be confused with *voltage control*. As described previously, voltage regulation is an internal action occurring within the generator whenever the load changes. Voltage control is an imposed action, usually through an external adjustment, for the purpose of increasing or decreasing terminal voltage.

Manual Voltage Control
The hand-operated field rheostat, shown in Figure 20, is a typical example of manual voltage control. The field rheostat is connected in series with the shunt field circuit. This provides the simplest method of controlling the terminal voltage of a DC generator.
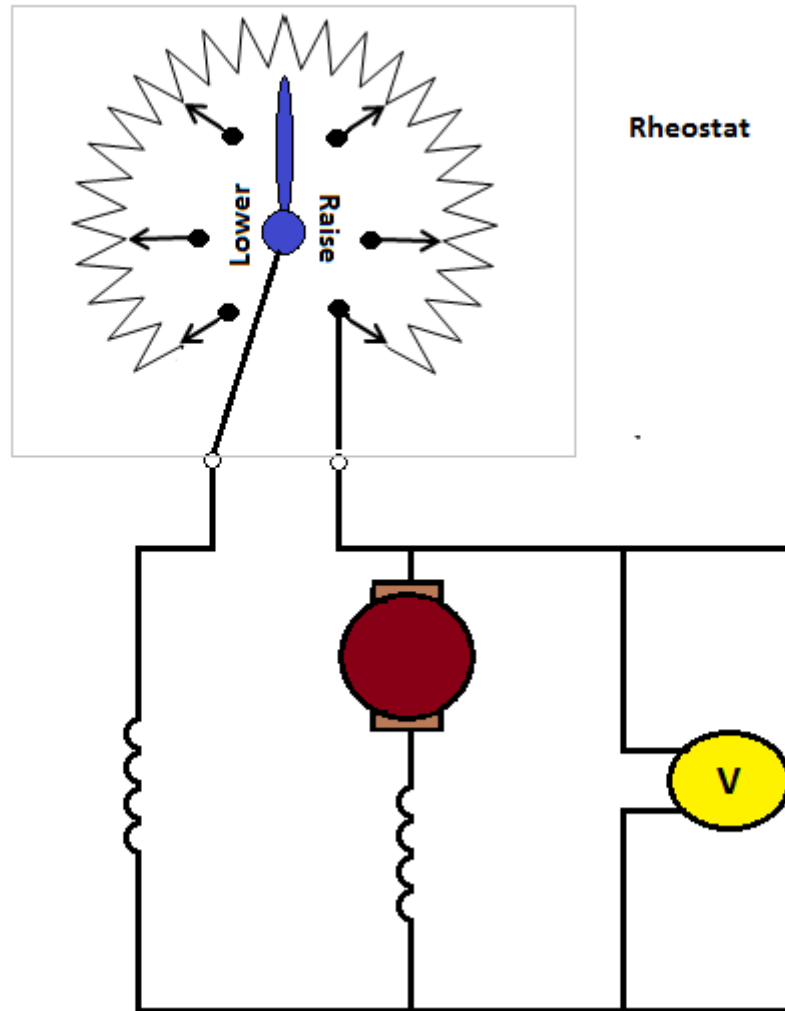
Hand-Operated Rheostat

Figure 20

This type of field rheostat contains tapped resistors with leads to a multi-terminal switch. The arm of the switch may be rotated to make contact with the various resistor taps. This varies the amount of resistance in the field circuit. Rotating the arm in the direction of the LOWER arrow (counterclockwise) increases the resistance and lowers the output voltage. Rotating the arm in the direction of the RAISE arrow (clockwise) decreases the resistance and increases the output voltage.

Most field rheostats for generators use resistors of alloy wire. They have a high specific resistance and a low temperature coefficient. These alloys include copper, nickel, manganese, and chromium. They are marked under trade names such as Nichrome, Advance, Manganin, and so forth. Some very large generators use cast-iron grids in place of rheostats, and motor-operated switching mechanisms to provide voltage control.

Automatic Voltage Control

Automatic voltage control may be used where load current variations exceed the built-in ability of the generator to regulate itself. An automatic voltage control device "senses" changes in output voltage and causes a change in field resistance to keep output voltage constant.

The actual circuitry involved in automatic voltage control will not be covered in this chapter. Whichever control method is used, the range over which voltage can be changed is a design characteristic of the generator. The voltage can be controlled only within the design limits.

Parallel Operation of Generators

When two or more generators are supplying a common load, they are said to be operating in parallel. The purpose of connecting generators in parallel is simply to provide more current than a single generator is capable of providing. The generators may be physically located quite a distance apart. However, they are connected to the common load through the power distribution system.

There are several reasons for operating generators in parallel. The number of generators used may be selected in accordance with the load demand. By operating each generator as nearly as possible to its rated capacity, maximum efficiency is achieved. A disabled or faulty generator may be taken off-line and replaced without interrupting normal operations.

Amplidynes

Amplidynes are special-purpose DC generators. They supply large DC currents, precisely controlled, to the large DC motors used to drive heavy physical loads, such as gun turrets and missile launchers.

The amplidyne is really a motor and a generator. It consists of a constant-speed AC motor (the prime mover) mechanically coupled to a DC generator, which is wired to function as a high-gain amplifier (an amplifier is a device in which a small input voltage can control a large current source). For instance, in a normal DC generator, a small DC voltage applied to the field windings is able to control the output of the generator. In a typical generator, a change in voltage from 0-volt DC to 3-volts DC applied to the field winding may cause the generator output to vary from 0-volt DC to 300-volts DC. If the 3-volts applied to the field winding is considered an input, and the 300 volts taken from the brushes is an output, there is a gain of 100. Gain is expressed as the ratio of output to input:

$$\textbf{Gain} = \frac{\textbf{Output}}{\textbf{Input}}$$

In this case 300 V ÷ 3 V = 100. This means that the 3 volts output is 100 times larger than the input. The following paragraphs explain how gain is achieved in a typical DC generator and how the modifications making the generator an amplidyne increase the gain to as high as 10,000.

The schematic diagram in Figure 21 shows a separately excited DC generator. Because of the 10-volt controlling voltage, 10 amperes of current will flow through the ohm field winding. This draws 100 watts of input power (P = V*I).
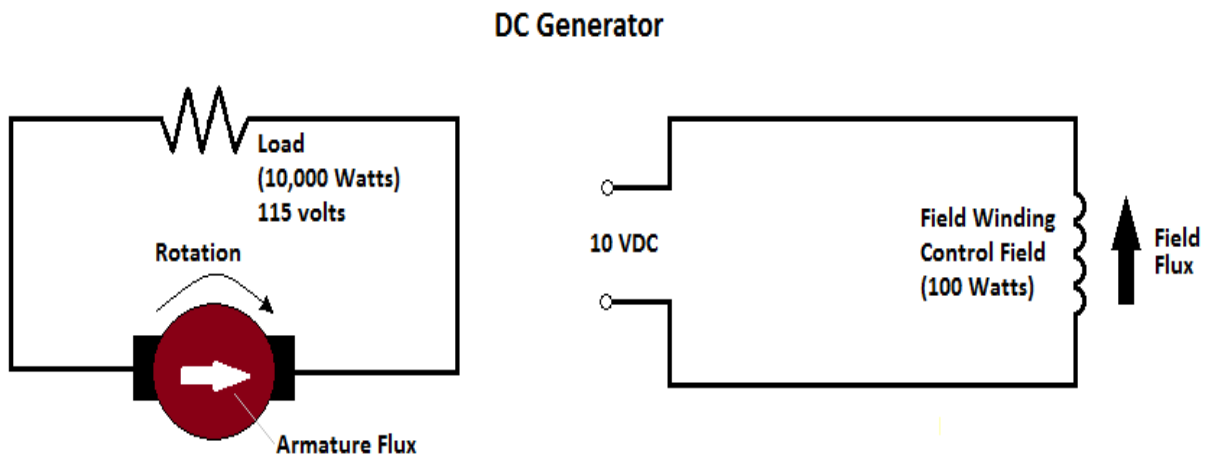
DC Generator

Figure 21

Assume that the characteristics of this generator enable it to produce approximately 87 amperes of armature current at 115 volts at the output terminals. This represents an output power of approximately 10,000 watts (P = V*I). You can see that the power gain of this generator is 100. In effect, 100 watts controls 10,000 watts.

An amplidyne is a special type of DC generator. The following changes, for explanation purposes, will convert the typical DC generator above into an amplidyne. The first step is to short the brushes together, as shown in Figure 22. This removes nearly all of the resistance in the armature circuit.
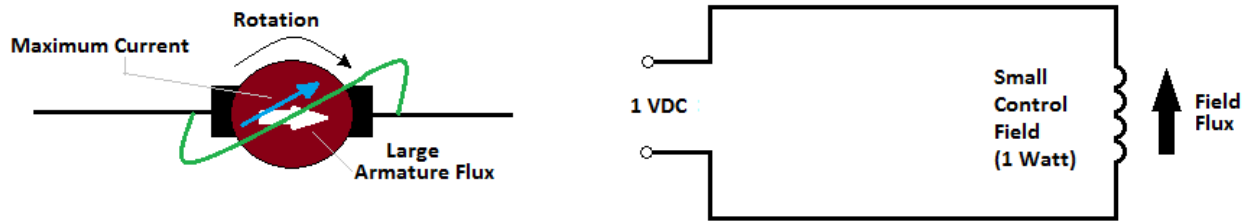
Brushes Shorted in a DC Generator

Figure 22

Because of the very low resistance in the armature circuit, a much lower control-field flux produces full-load armature current (full-load current in the armature is still about 87 amperes). The smaller control field now requires a control voltage of only 1 volt and an input power of 1 watt (1 volt across 1 ohm causes 1 ampere of current, which produces 1 watt of input power). The next step is to add another set of brushes. These now become the output brushes of the amplidyne. They are placed against the commutator in a position perpendicular to the original brushes, as shown in Figure 23. The previously shorted brushes are now called the "quadrature" brushes. This is because they are in quadrature (perpendicular) to the output brushes. The output brushes are in line with the armature flux. Therefore, they pick off the voltage induced in the armature windings at this point. The voltage at the output will be the same as in the original generator, 115 volts in our example.

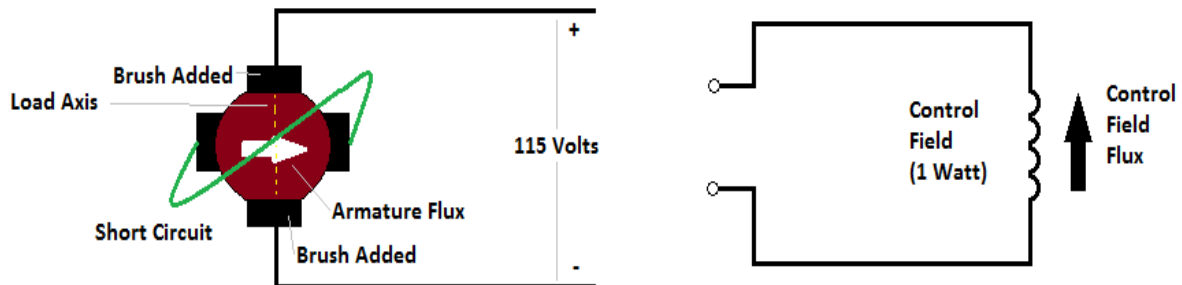**Amplidyne Load Brushes**

Figure 23

As you have seen, the original generator produced a 10,000-watt output with a 100-watt input. The amplidyne produces the same 10,000-watt output with only a one watt input. This represents a gain of 10,000. The gain of the original generator has been greatly increased.

As previously stated, an amplidyne is used to provide large DC currents. The primary use of an amplidyne is in the positioning of heavy loads through the use of synchro/servo systems.

Assume that a very large turning force is required to rotate a heavy object, such as an antenna, to a very precise position. A low-power, relatively weak voltage representing the amount of antenna rotation required can be used to control the field winding of an amplidyne. Because of the amplidyne's ability to amplify, its output can be used to drive a powerful motor, which turns the heavy object (antenna). When the source of the input voltage senses the correct movement of the object, it drops the voltage to zero. The field is no longer strong enough to allow an output voltage to be developed, so the motor ceases to drive the object (antenna).

The above is an oversimplification and is not meant to describe a functioning system. The intent is to show a typical sequence of events between the demand for movement and the movement itself. It is meant to strengthen the idea that with the amplidyne, something large and heavy can be controlled very precisely by something very small, almost insignificant.

Safety Precautions

Before leaving the subject of DC generators, let's talk safety. You must always observe safety precautions when working around electrical equipment to avoid injury to personnel and damage to equipment. Electrical equipment frequently has accessories that require separate sources of power. Lighting fixtures, heaters, externally powered temperature detectors, and alarm systems are examples of accessories whose terminals must be de-energized. When working on DC generators, you must check to ensure that all such circuits have been de-energized and tagged before you attempt any maintenance or repair work. You must also use the greatest care when working on or near the output terminals of DC generators.

Chapter 2
Direct Current Motors

The DC motor is a mechanical workhorse that can be used in many different ways. Many large pieces of equipment depend on a DC motor for their power to move. The speed and direction of rotation of a DC motor are easily controlled. This makes it especially useful for operating equipment, such as winches and cranes, which must move in different directions and at varying speeds.

Principles of Operation

The operation of a DC motor is based on the following principle:

> A current-carrying conductor placed in a magnetic field, perpendicular to the lines of flux, tends to move in a direction perpendicular to the magnetic lines of flux.

There is a definite relationship between the direction of the magnetic field, the direction of current in the conductor, and the direction in which the conductor tends to move. This relationship is best explained by using the *right-hand rule for motors* (Figure 24).
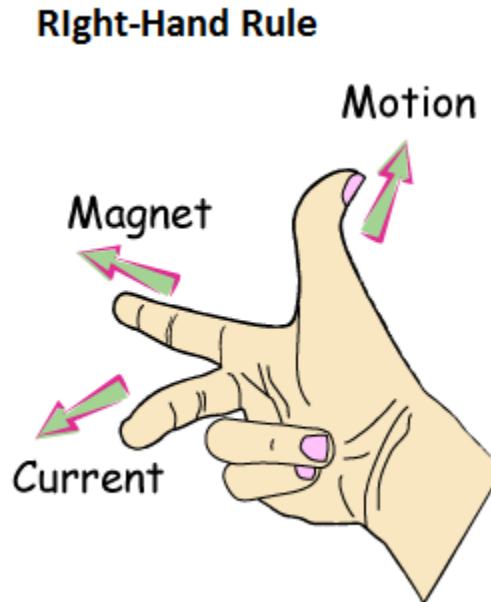
RIght-Hand Rule

Figure 24

To find the direction of motion of a conductor, extend the thumb, forefinger, and middle finger of your right hand so they are at right angles to each other. If the forefinger is pointed in the direction of magnetic flux (north to south) and the middle finger is pointed in the direction of current flow in the conductor, the thumb will point in the direction the conductor will move.

Stated very simply, a DC motor rotates as a result of two magnetic fields interacting with each other. The armature of a DC motor acts like an electromagnet when current flows through its coils. Since the armature is located within the magnetic field of the field poles, these two magnetic fields interact. Like magnetic poles repel each other, and unlike magnetic poles attract each other. As in the DC generator, the DC motor has field poles that are stationary and an armature that turns on bearings in the space between the field poles. The armature of a DC motor has windings on it just like the armature of a DC generator.

These windings are also connected to commutator segments. A DC motor consists of the same components as a DC generator. In fact, most DC generators can be made to act as motors, and vice versa.

Look at the simple DC motor shown in Figure 25. It has two field poles, one a north pole and one a south pole. The magnetic lines of force extend across the opening between the poles from north to south.
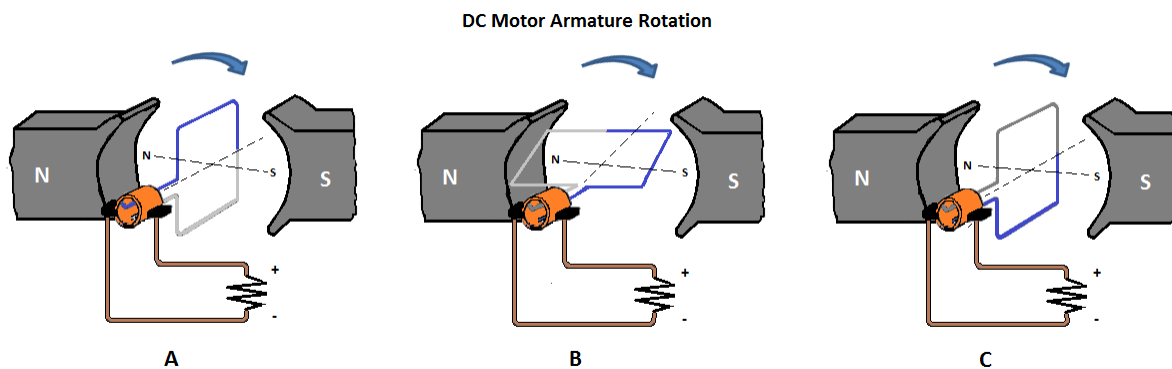

Figure 25

The armature in this simple DC motor is a single loop of wire, just as in the simple armature you studied at the beginning of the chapter on DC generators. The loop of wire in the DC motor, however, has current flowing through it from an external source. This current causes a magnetic field to be produced.

This field is indicated by the dotted line through the loops. The loop (armature) field is both attracted and repelled by the field from the field poles. Since the current through the loop goes around in the direction of the arrows, the north pole of the armature is at the upper left, and the south pole of the armature is at the lower right, as shown in Figure 25, (view A). Of course, as the loop (armature) turns, these magnetic poles turn with it. Now, as shown in the illustrations, the north armature pole is repelled from the north field pole and attracted to the right by the south field pole. Likewise, the south armature pole is repelled from the south field pole and is attracted to the left by the north field pole. This action causes the armature to turn in a clockwise direction, as shown in Figure 25 (view B).

After the loop has turned far enough so that its north pole is exactly opposite the south field pole, the brushes advance to the next segments. This changes the direction of current flow through the armature loop. Also, it changes the polarity of the armature field, as shown in Figure 25 (view C). The magnetic fields again repel and attract each other, and the armature continues to turn.

In this simple motor, the momentum of the rotating armature carries the armature past the position where the unlike poles are exactly lined up. However, if these fields are exactly lined up when the armature current is turned on, there is no momentum to start the armature moving. In this case, the motor would not rotate. It would be necessary to give a motor like this a spin to start it. This disadvantage does not exist when there are more turns on the armature, because there is more than one armature field. No two armature fields could be exactly aligned with the field from the field poles at the same time.

Counter EMF

While a DC motor is running, it acts somewhat like a DC generator. There is a magnetic field from the field poles, and a loop of wire is turning and cutting this magnetic field. For the moment, disregard the fact that there is current flowing through the loop of wire from the battery. As the loop sides cut the magnetic field, a voltage is induced in them, the same as it was in the loop sides of the DC generator. This induced voltage causes current to flow in the loop. Now, consider the relative direction between this current and the current that causes the motor to run. First, check the direction the current flows as a result of the generator action taking place (view A of Figure 25).

Using the left hand, hold it so that the forefinger points in the direction of the magnetic field (north to south) and the thumb points in the direction that the blue side of the armature moves (up). Your middle finger then points out of the paper (toward you), showing the direction of current flow caused by the generator action in the blue half of the armature. This is in the direction opposite to that of the battery current. Since this generator-action voltage is opposite that of the battery, it is called *counter EMF*. The two currents are flowing in opposite directions. This proves that the battery voltage and the counter EMF are opposite in polarity.

At the beginning of this discussion, we disregarded armature current while explaining how counter EMF was generated. Then, we showed that normal armature current flowed opposite to the current created by the counter EMF. We talked about two opposite currents that flow at the same time. However, this is a bit oversimplified. Actually, only one current flows. Because the counter EMF can never become as large as the applied voltage, and because they are of opposite polarity as we have seen, the counter EMF effectively cancels part of the armature voltage. The

single current that flows is armature current, but it is greatly reduced because of the counter EMF.

In a DC motor, there is always a counter EMF developed. This counter EMF cannot be equal to or greater than the applied battery voltage; if it were, the motor would not run. The counter EMF is always a little less. However, the counter EMF opposes the applied voltage enough to keep the armature current from the battery to a fairly low value. If there were no such thing as counter EMF, much more current would flow through the armature, and the motor would run much faster. However, there is no way to avoid the counter EMF.

Motor Loads

Motors are used to turn mechanical devices, such as water pumps, grinding wheels, fan blades, and circular saws. For example, when a motor is turning a water pump, the water pump is the load. The water pump is the mechanical device that the motor must move. This is the definition of a motor load.

As with electrical loads, the mechanical load connected to a DC motor affects many electrical quantities. Such things as the power drawn from the line, amount of current, speed, efficiency, etc., are all partially controlled by the size of the load. The physical and electrical characteristics of the motor must be matched to the requirements of the load if the work is to be done without the possibility of damage to either the load or the motor.

Practical DC Motors

As you have seen, DC motors are electrically identical to DC generators. In fact, the same DC machine may be driven mechanically to generate a voltage, or it may be driven electrically to move a mechanical load. While this is not normally done, it does point out the similarities between the two machines.

Series DC Motor
In a series DC motor, the field is connected in series with the armature. The field is wound with a few turns of large wire, because it must carry full armature current. The circuit for a series DC motor is shown in Figure 26.
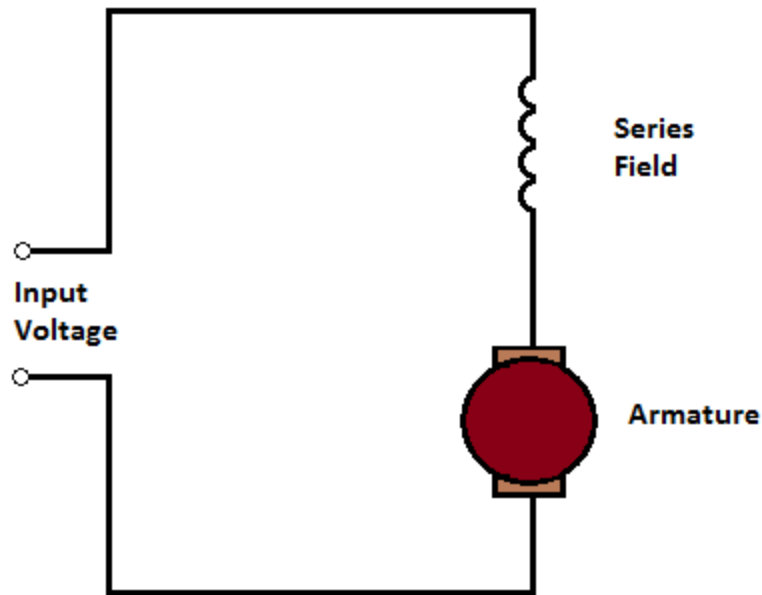
Series-Wound DC Motor

Figure 26

This type of motor develops a very large amount of turning force, called torque, from a standstill. Because of this characteristic, the series DC motor can be used to operate small electric appliances, portable electric tools, cranes, winches, hoists, and the like.

Another characteristic is that the speed varies widely between no-load and full-load. Series motors cannot be used where a relatively constant speed is required under conditions of varying load.

A major disadvantage of the series motor is related to the speed characteristic mentioned in the last paragraph. The speed of a series motor with no load connected to it increases to the point where the motor may become damaged. Usually, either the bearings are damaged or the windings fly out of the slots in the armature. There is a danger to both equipment and personnel. Some load must *always* be connected to a series motor before you turn it on. This precaution is primarily for large motors. Small motors, such as those used in electric hand drills, have enough internal friction to load themselves.

A final advantage of series motors is that they can be operated by using either an AC or DC power source. This will be covered in the chapter on AC motors.

Shunt Motor

A shunt motor is connected in the same way as a shunt generator. The field windings are connected in parallel (shunt) with the armature windings. The circuit for a shunt motor is shown in Figure 27.
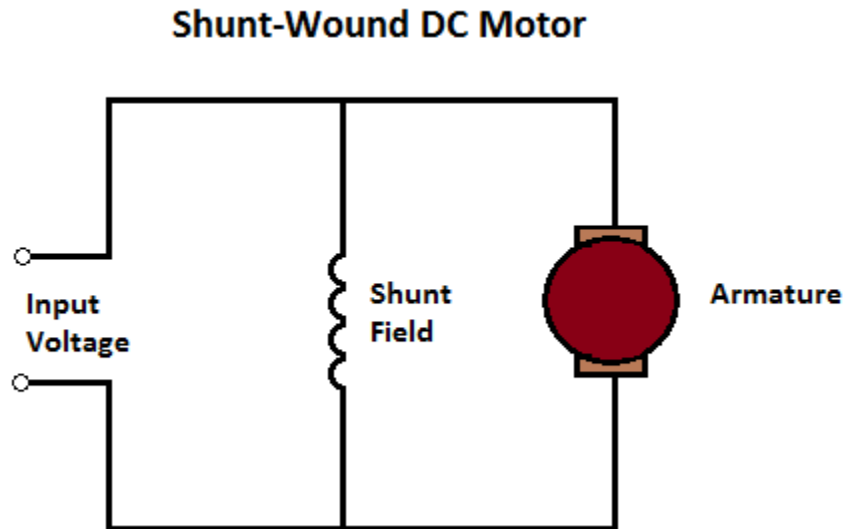
Shunt-Wound DC Motor

Figure 27

Once you adjust the speed of a DC shunt motor, the speed remains relatively constant even under changing load conditions. One reason for this is that the field flux remains constant. A constant voltage across the field makes the field independent of variations in the armature circuit.

If the load on the motor is increased, the motor tends to slow down. When this happens, the counter EMF generated in the armature decreases. This causes a corresponding decrease in the opposition to battery current flow through the armature. Armature current increases, causing the motor to speed up. The conditions that established the original speed are reestablished, and the original speed is maintained.

Conversely, if the motor load is decreased, the motor tends to increase speed; counter EMF increases, armature current decreases, and the speed decreases. In each case, all of this happens so rapidly that any actual change in speed is slight. There is instantaneous tendency to change rather than a large fluctuation in speed.

Compound Motor

A compound motor has two field windings, as shown in Figure 28. One is a shunt field connected in parallel with the armature; the other is a series field that is connected in series with the armature. The shunt field gives this type of motor the constant speed advantage of a regular shunt motor. The series field gives it the advantage of being able to develop a large torque when the motor is started under a heavy load. It should not be a surprise that the compound motor has both shunt- and series-motor characteristics.
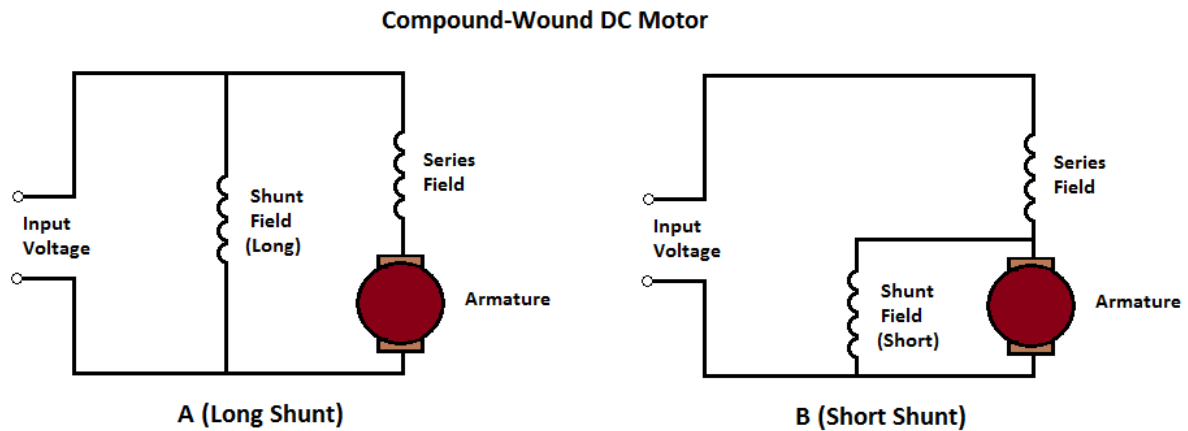
Compound-Wound DC Motor

Figure 28

When the shunt field is connected in parallel with the series field and armature, it is called a "long shunt" as shown in Figure 28, (view A). Otherwise, it is called a "short shunt", as shown in Figure 28, (view B).

Types of Armatures

As with DC generators, DC motors can be constructed using one of two types of armatures. A brief review of the Gramme-ring and drum-wound armatures is necessary to emphasize the similarities between DC generators and DC motors.

Gramme-Ring Armature
The Gramme-ring armature is constructed by winding an insulated wire around a soft-iron ring (Figure 29). Eight equally spaced connections are made to the winding. Each of these is connected to a commutator segment. The brushes touch only the top and bottom segments. There are two parallel paths for current to follow — one up the left side and one up the right side. These paths are completed through the top brush back to the positive lead of the battery.
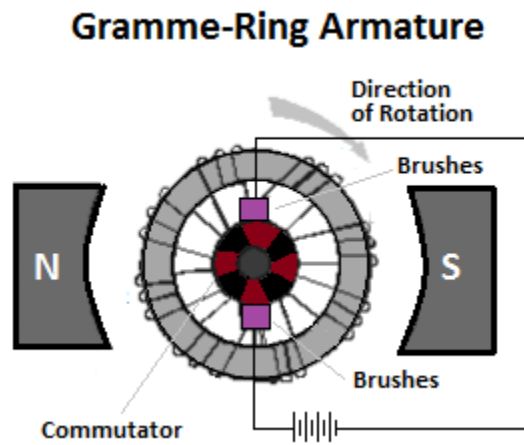

Figure 29

To check the direction of rotation of this armature, you should use the right-hand rule for motors. Hold your thumb, forefinger, and middle finger at right angles. Point your forefinger in the direction of field flux; in this case, from left to right. Now turn your wrist so that your middle finger points in the direction that the current flows in the winding on the outside of the ring. Note that current flows into the page (away from you) in the left-hand windings and out of the page (toward you) in the right-hand windings. Your thumb now points in the direction that the winding will move.

The Gramme-ring armature is seldom used in modern DC motors. The windings on the inside of the ring are shielded from magnetic flux, which causes this type of armature to be inefficient. The Gramme-ring armature is discussed primarily to help you better understand the drum-wound armature.

Drum-Wound Armature
The drum-wound armature is generally used in AC motors. It is identical to the drum winding discussed in the chapter on DC generators. If the drum-wound armature were cut in half, an end view at the cut would resemble the drawing in Figure 30, (view A), Figure 30, (view B) is a side view of the armature and pole pieces. Notice that the length of each conductor is positioned parallel to the faces of the pole pieces. Therefore, each conductor of the armature can cut the maximum flux of the motor field. The inefficiency of the Gramme-ring armature is overcome by this positioning.
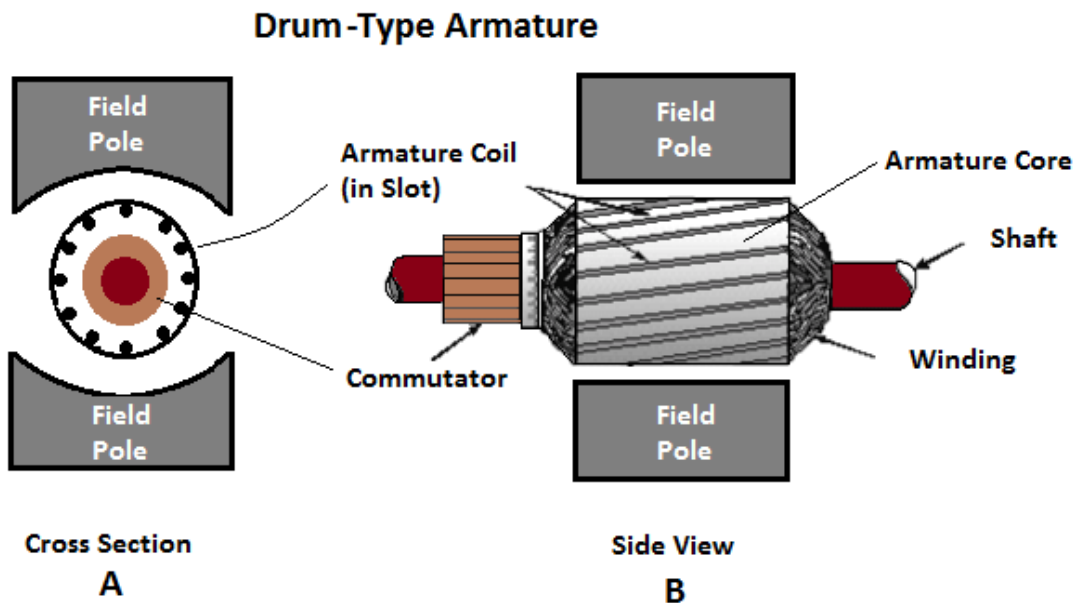
Drum-Type Armature

Cross Section
A

Side View
B

Figure 30

The direction of current flow is marked in each conductor in Figure 30, (view A) as though the armature were turning in a magnetic field. The dots show that current is flowing toward you on the left side, and the crosses show that the current is flowing away from you on the right side.

Strips of insulation are inserted in the slots to keep windings in place when the armature spins. These are shown as wedges in Figure 30, (view A).

Direction of Rotation

The direction of rotation of a DC motor depends on the direction of the magnetic field and the direction of current flow in the armature. If either the direction of the field or the direction of current flow through the armature is reversed, the rotation of the motor will reverse. However, if both of these factors are reversed at the same time, the motor will continue rotating in the same direction. In actual practice, the field excitation voltage is reversed in order to reverse motor direction.

Ordinarily, a motor is set up to do a particular job that requires a fixed direction of rotation. However, there are times when it is necessary to change the direction of rotation. Each of these must be able to move in both directions. Remember, the connections of either the armature or the field must be reversed, but not both. In such applications, the proper connections are brought out to a reversing switch.

Motor Speed

A motor whose speed can be controlled is called a variable-speed motor; DC motors are variable speed motors. The speed of a DC motor is changed by changing the current in the field or by changing the current in the armature.

When the field current is decreased, the field flux is reduced, and the counter EMF decreases. This permits more armature current. Therefore, the motor speeds up. When the field current is increased, the field flux is increased. More counter EMF is developed, which opposes the armature current. The armature current then decreases and the motor slows down.

When the voltage applied to the armature is decreased, the armature current is decreased, and the motor again slows down. When the armature voltage and current are both increased, the motor speeds up.

In a shunt motor, speed is usually controlled by a rheostat connected in series with the field windings, as shown in Figure 31. When the resistance of the rheostat is increased, the current through the field winding is decreased. The decreased flux momentarily decreases the counter EMF. The motor then speeds up, and the increase in counter EMF keeps the armature current the same. In a similar manner, a decrease in rheostat resistance increases the current flow through the field windings and causes the motor to slow down.
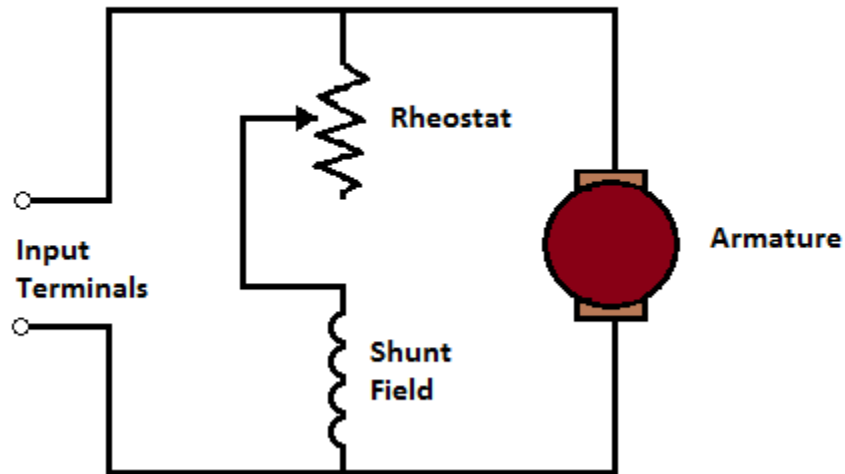
Controlling Motor Speed

Figure 31

In a series motor, the rheostat speed control may be connected either in parallel or in series with the armature windings. In either case, moving the rheostat in a direction that lowers the voltage across the armature lowers the current through the armature and slows the motor. Moving the rheostat in a direction that increases the voltage and current through the armature increases motor speed.

Armature Reaction

You will remember that the subject of armature reaction was covered previously. The reasons for armature reaction and the methods of compensating for its effects are basically the same for DC motors as for DC generators.

Figure 32 reiterates for you the distorting effect that the armature field has on the flux between the pole pieces. Notice, however, that the effect has shifted the neutral plane backward, against the direction of rotation. This is different from a DC generator, where the neutral plane shifted forward in the direction of rotation.
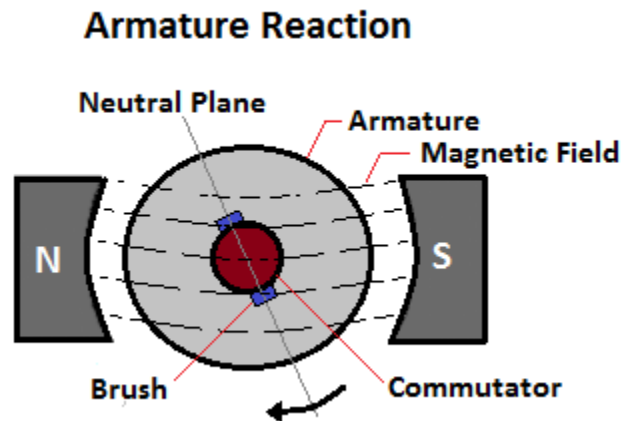
Armature Reaction

Figure 32

As before, the brushes must be shifted to the new neutral plane. As shown in Figure 9, the shift is counterclockwise. Again, the proper location is reached when there is no sparking from the brushes.

Compensating windings and interpoles cancel armature reaction in DC motors. Shifting brushes reduces sparking, but it also makes the field less effective. Canceling armature reaction eliminates the need to shift brushes in the first place.

Compensating windings and interpoles are as important in motors as they are in generators. Compensating windings are relatively expensive; therefore, most large DC motors depend on interpoles to correct armature reaction. Compensating windings are the same in motors as they are in generators.

Interpoles, however, are slightly different. The difference is that in a generator the interpole has the same polarity as the main pole *ahead* of it in the direction of rotation. In a motor the interpole has the same polarity as the main pole *following* it. The interpole coil in a motor is connected to carry the armature current the same as in a generator.

As the load varies, the interpole flux varies, and commutation is automatically corrected as the load changes. It is not necessary to shift the brushes when there is an increase or decrease in load. The brushes are located on the no-load neutral plane. They remain in that position for all conditions of load.

The DC motor is reversed by reversing the direction of the current in the armature. When the armature current is reversed, the current through the interpole is also reversed. Therefore, the interpole still has the proper polarity to provide automatic commutation.

Manual and Automatic Starters

Because the DC resistance of most motor armatures is low (0.05 to 0.5 ohm), and because the counter EMF does not exist until the armature begins to turn, it is necessary to use an external starting resistance in series with the armature of a DC motor to keep the initial armature current to a safe value. As the armature begins to turn, counter EMF increases; and, since the counter EMF opposes the applied voltage, the armature current is reduced. The external resistance in series with the armature is decreased or eliminated as the motor comes up to normal speed and full voltage is applied across the armature.

Controlling the starting resistance in a DC motor is accomplished either manually, by an operator, or by any of several automatic devices. The automatic devices are usually just switches controlled by motor speed sensors. Automatic starters are not covered in detail in this module.

Summary

This course has been a review of the DC generator and DC motor. The DC generator is the basic device to convert mechanical energy to electrical energy. A generator forces electric charge to flow through an external electrical circuit. The reverse conversion of electrical energy into mechanical energy is done by an electric motor, and motors and generators have many similarities. Many motors can be mechanically driven to generate electricity and frequently make acceptable generators.

From the basic DC generator came the discovery of a DC electric motor, the AC alternator, the AC synchronous motor, and the rotary converter.

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