

DIRECT CURRENT GENERATORS

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INTRODUCTION

A generator is a machine that converts mechanical energy into electrical energy by using the principle of magnetic induction. This principle is explained as follows:

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 RIGHT-HAND RULE FOR GENERATORS is used. This rule is explained in the following manner.

Extend the thumb, forefinger, and middle finger of your right hand at right angles to one another. Point your thumb in the direction the conductor is being moved. Point your forefinger in the direction of magnetic flux (from north to south). Your middle finger will then point in the direction of current flow in an external circuit to which the voltage is applied.

THE ELEMENTARY GENERATOR

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 (fig. 1-2) 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 emf.

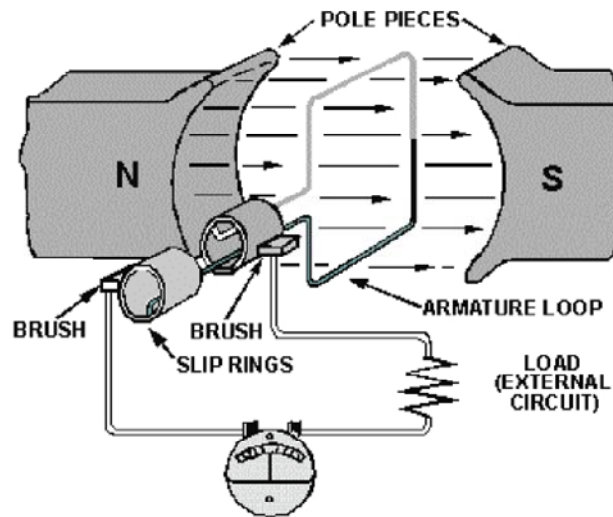


Figure 1-2.—The elementary generator.

The 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 (fig. 1-3). 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° the armature loop is perpendicular to the magnetic field. The black and white 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 (0°) to position B (90°), the conductors cut through more and more lines of flux, at a continually increasing angle. At 90° they are cutting through a maximum number of lines of flux and at maximum angle. The result is that between 0° and 90° , the induced emf in the conductors builds up from zero to a maximum value. Observe that from 0° to 90° , the black conductor cuts DOWN through the field. At the same time the white 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 90° (position B) to 180° (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 90° to 180° , the induced voltage will decrease to zero in the same manner that it increased during the rotation from 0° to 90° . The meter again reads zero. From 0° to 180° 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 180° (position C), through 270° (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 black conductor cuts UP through the field while the white conductor cuts DOWN 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 1-3.

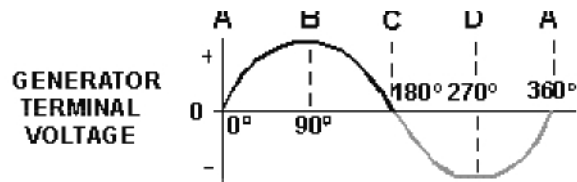
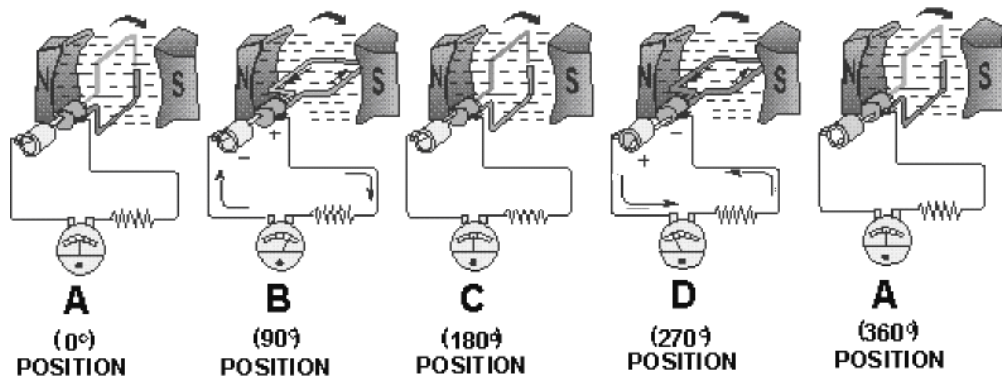


Figure 1-3.—Output voltage of an elementary generator during one revolution.

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 1-4. 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 as shown in the graph of figure 1-4. This action is known as commutation. Commutation is described in detail later in this chapter.

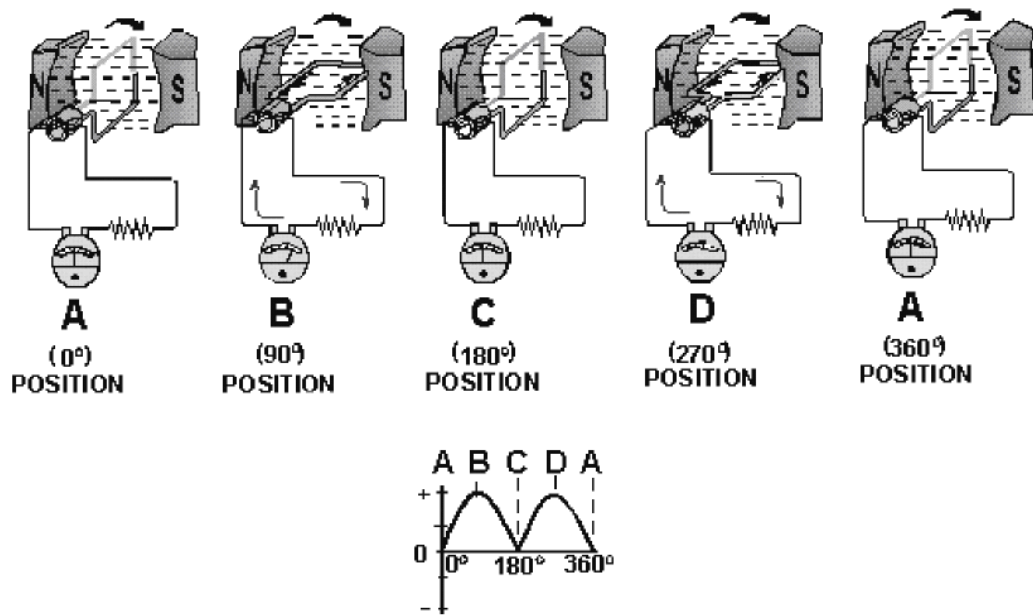


Figure 1-4.—Effects of commutation.

For the remainder of this discussion, refer to figure 1-4, 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 positive brush, through the meter and the load, and back through the negative 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 black side to the white side in position B and from the white side to the black 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 fig. 1-5). The coil is rotated in a clockwise direction from the position shown. The voltage induced in the white coil, **DECREASES FOR THE NEXT 90°** of rotation (from maximum to zero). The voltage induced in the black 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 90° instead of every 180°. This allows the brush to switch from the white coil to the black coil at the instant the voltages in the two coils are equal. The brush remains in contact with the black coil as its induced voltage increases to maximum, level B in the graph. It then decreases to level A, 90° later. At this point, the brush will contact the white coil again.

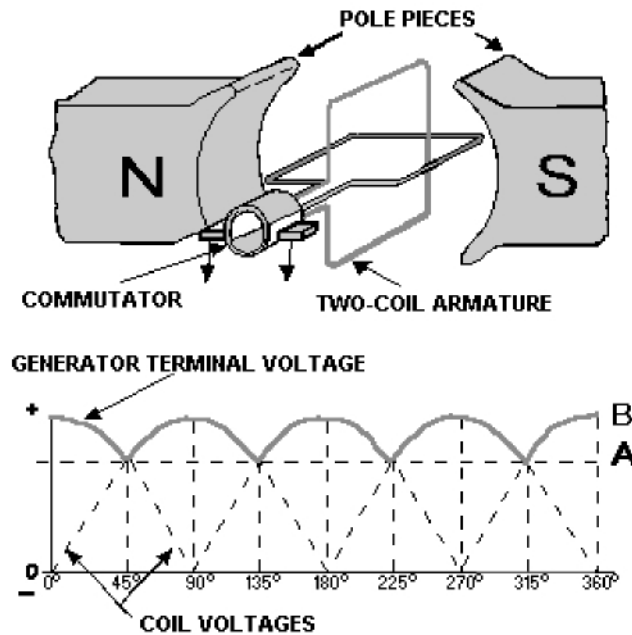


Figure 1-5.—Effects of additional coils.

The graph in figure 1-5 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.

NOTE: 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 figure 1-4 and 1-5. 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 1-6. 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.

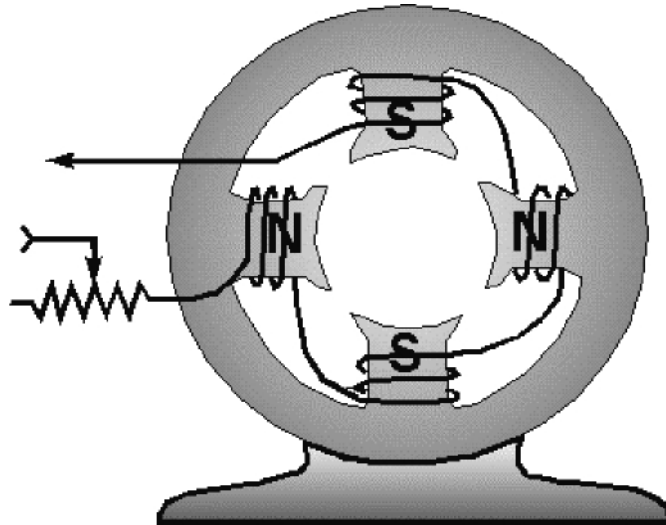


Figure 1-6.—Four-pole generator (without armature).

Q9. How can field strength be varied in a practical dc generator?

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 1-7, 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.

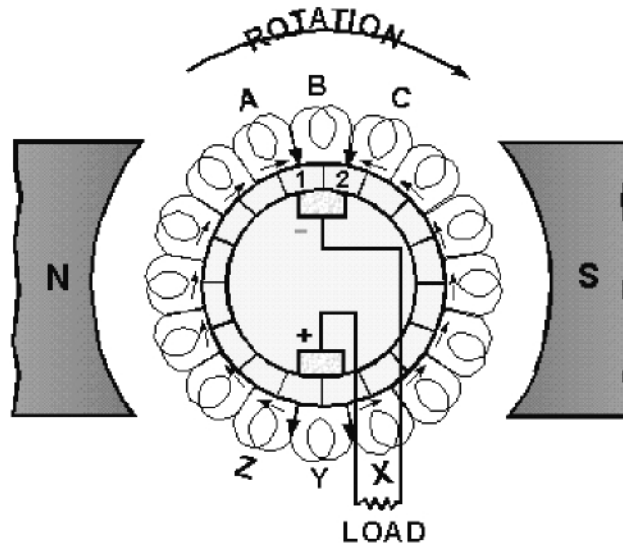


Figure 1-7.—Commutation of a dc generator.

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:

1. I^2R , or copper loss in the winding
2. Eddy current loss in the core
3. 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 CUPPER 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 1-11, view A, shows the eddy currents induced in an armature core that is a solid piece of soft iron. Figure 1-11, 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.

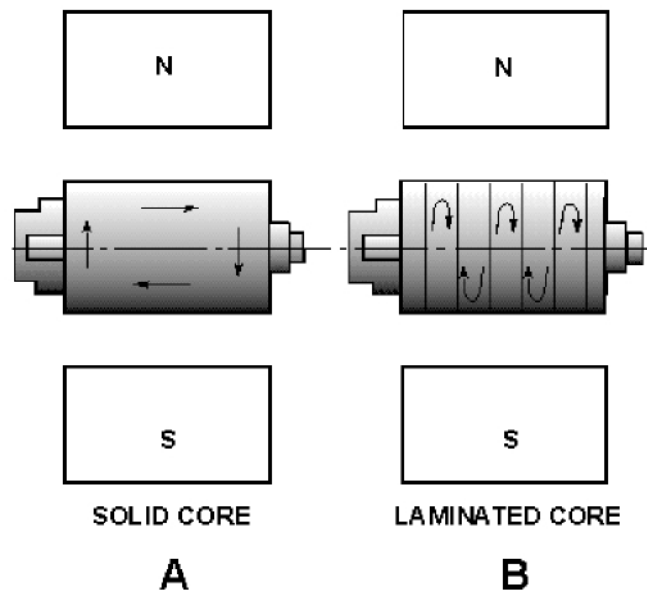


Figure 1-11.—Eddy currents in dc generator armature cores.

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.

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 1-15, 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.

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 1-16, 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.

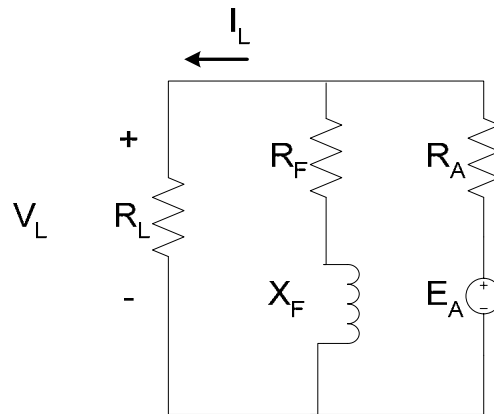


Figure 1-16.—Shunt-wound generator.

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 ($E = IR$).

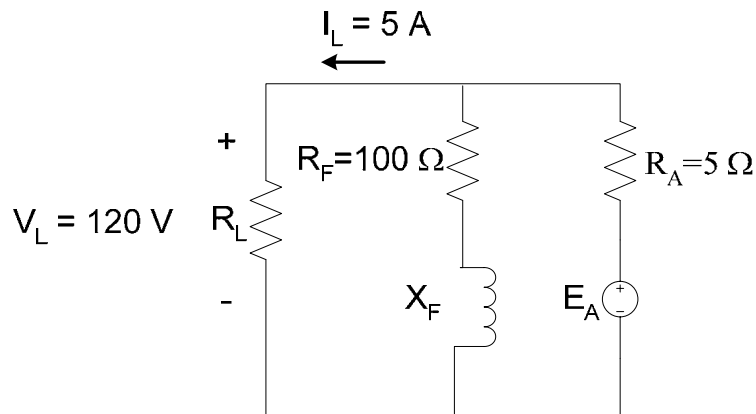
In a series-wound generator, output voltage varies directly with load current. In the shunt-wound generator, output voltage varies inversely with load current. A combination of the two types can overcome the disadvantages of both. This combination of windings is called the compound-wound dc generator.

Generated Voltage

Voltage generated in a DC machine is given by

$$E_A = k\phi N$$

Where E_A is the generated voltage, ϕ is a measure of magnetic flux, N is the shaft's speed in RPM and k is a constant related to the physical construction of the motor (i.e. number of poles, conductors and windings). The generated voltage (E_A) can be increased by increasing magnetic flux or the machine's speed of rotation. The terminal voltage produced by a DC generator is always less the generated voltage due to losses in the armature windings. This can be seen in the example below. The current through the field and armature are $I_F = V/R = 120 \text{ V} / 100 \Omega = 1.2 \text{ A}$ and $I_A = 5 \text{ A} + 1.2 \text{ A} = 6.2 \text{ A}$ respectively. The voltage lost in the armature winding is $V = IR = (6.2\text{A})(5 \Omega) = 31 \text{ V}$. This leads to a generated voltage of $E_A = 151 \text{ V}$ required to produce a terminal voltage of 120 V across the load.



Voltage Regulation

In order to control generator output voltage, a rheostat (variable resistor) can be added in series with the field winding. This variable resistance can be used to control the current flow through the field windings and thus the strength of the generated voltage.

A second method for controlling output voltage is to change the rate at which the armature is spinning. As the armature spins faster through the shunt coil's magnetic field, output voltage increases.

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:

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{fL})}{E_{fL}} \times 100$$

where E_{nL} is the no-load terminal voltage and E_{fL} is the full-load terminal voltage of the generator.

For example, to calculate the percent of regulation of a generator with a no-load voltage of 462

volts and a full-load voltage of 440 volts:

Given:

- No-load voltage 462 V
- Full-load voltage 440 V

$$\text{Percent of regulation} = \frac{(E_{nL} - E_{tL})}{E_{tL}} \times 100$$

$$\text{Percent of regulation} = \frac{(462\text{V} - 440\text{V})}{440\text{V}} \times 100$$

$$\text{Percent of regulation} = \frac{22\text{V}}{440\text{V}} \times 100$$

$$\text{Percent of regulation} = .05 \times 100$$

$$\text{Regulation} = 5\%$$

NOTE: 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 (1) manual or (2) 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.

Efficiency and Power

Some losses occur during the conversion from mechanical energy to electrical energy in a DC shunt generator. These losses are due to both mechanical effects (friction, drag) and electrical effects (resistance). The power lost can be computed given using following equation.

$$P_{out} = P_{in} - P_{lost}$$

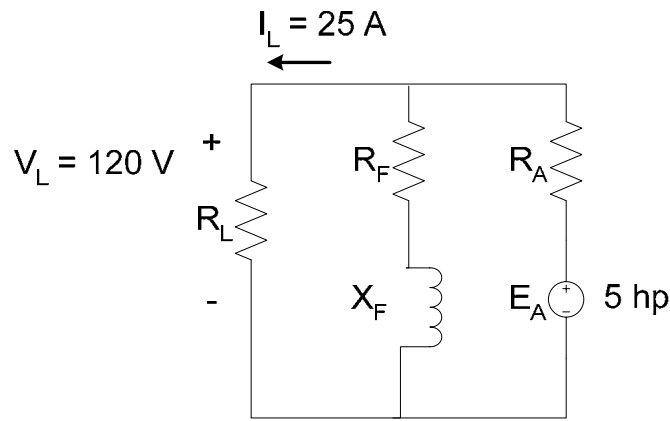
The percent efficiency of a motor is given by the following equation.

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

Mechanical power is frequently stated in horsepower. To convert from horsepower to watts, use
 $1 \text{ horsepower} = 746 \text{ watt}$

Example Problem

A 5 hp gasoline motor is used to turn a DC shunt generator that delivers 120 V and 25 A to a load. Find the total power lost in the generator. Determine the generator's efficiency.



$$\text{Power Generated} = V * I = 120 \text{ V} * 25 \text{ A} = 3000 \text{ W}$$

$$\text{Power Supplied} = 5 \text{ hp} = 5 * 746 \text{ W} / 1 \text{ hp} = 3730 \text{ W}$$

$$\text{Power Lost} = \text{Power Supplied} - \text{Power Generated} = 3730 \text{ W} - 3000 \text{ W} = 730 \text{ W}$$

$$\text{Power Efficiency} = 100 * 3000 / 3730 = 80.4\%$$

GENERATOR CONSTRUCTION

Figure 1-19, views A through E, shows the component parts of dc generators. Figure 1-20 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.

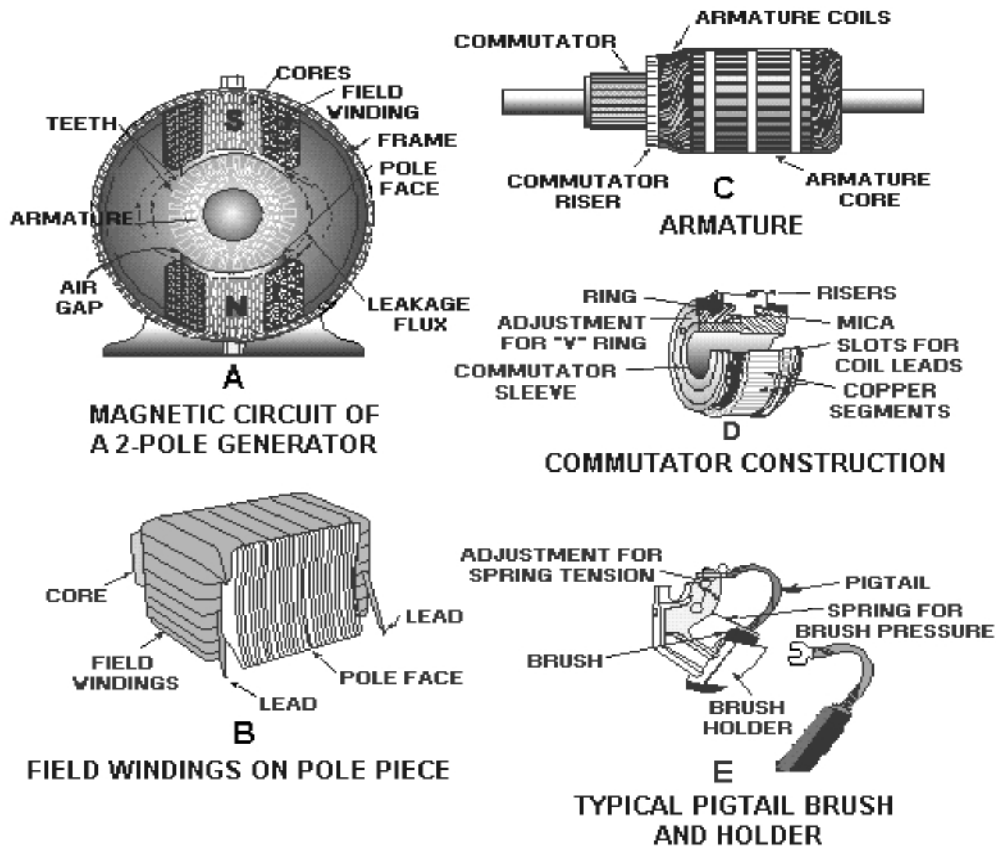


Figure 1-19.—Components of a dc generator.

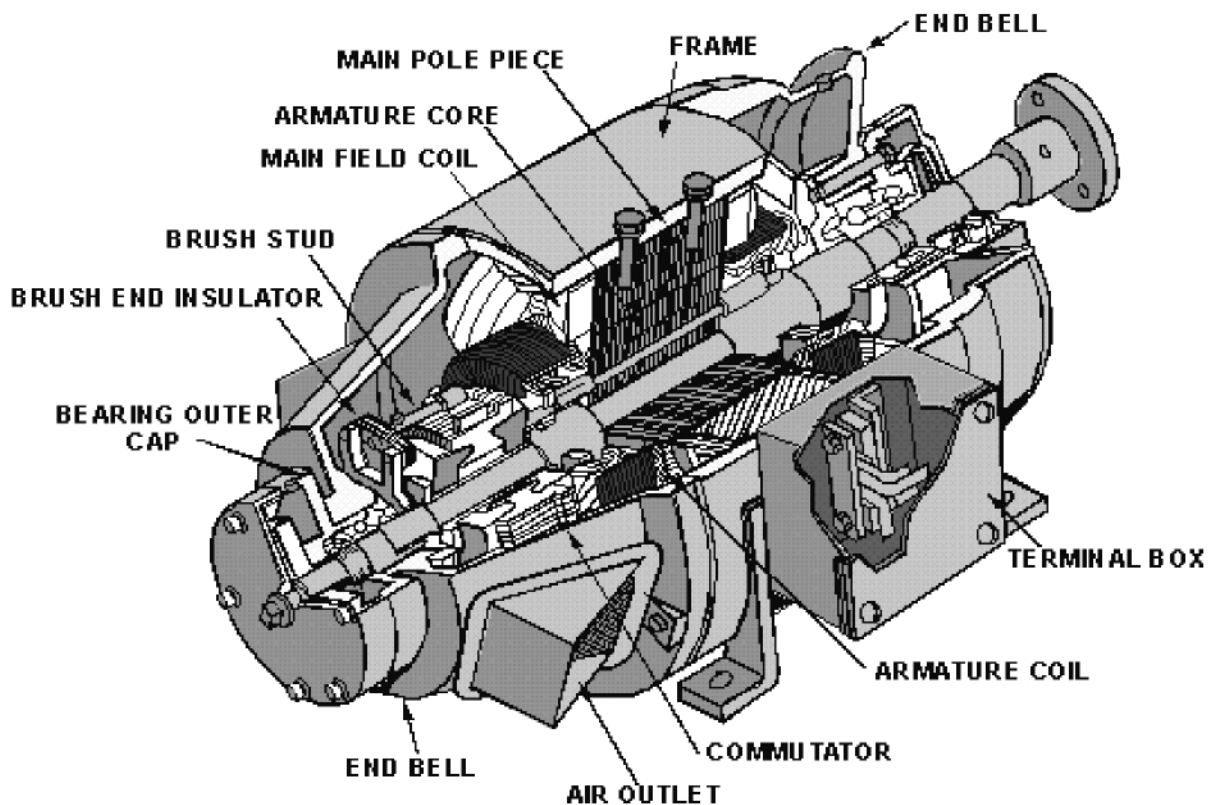


Figure 1-20.—Construction of a dc generator (cutaway drawing).

Definitions

Stator – outer, stationary portion of the machine.

Rotor – rotating portion of the machine which revolves inside the stator.

Field Winding – wire coil with the sole purpose of providing a magnetic field.

Armature – portion of the machine where energy conversion occurs (rotor for DC machines).

Commutator – conducting segments mounted on the machine's shaft and insulated from one another.

Brushes – devices used to maintain sliding contact with the commutator.