DC Circuits, Batteries, Generators and Motors

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PART 1: DC CIRCUITS - TABLE OF CONTENTS

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INDUCTANCE

Experiments investigating the unique behavioral characteristics of inductance led to the invention of the transformer.

EO 1.1   **DESCRIBE how current flow, magnetic field, and stored energy in an inductor relate to one another.**

EO 1.2   **DESCRIBE how an inductor opposes a change in current flow.**

EO 1.3   **Given a circuit containing inductors, CALCULATE total inductance for series and parallel circuits.**

EO 1.4   **Given an inductive resistive circuit, CALCULATE the time constant for the circuit.**

Inductors

An inductor is a circuit element that will store electrical energy in the form of a magnetic field. It is usually a coil of wire wrapped around a core of permeable material. The magnetic field is generated when current is flowing through the wire. If two circuits are arranged as in Figure 1, a magnetic field is generated around Wire A, but there is no electromotive force (EMF) induced into Wire B because there is no relative motion between the magnetic field and Wire B.

If we now open the switch, the current stops flowing in Wire A, and the magnetic field collapses. As the field collapses, it moves relative to Wire B. When this occurs, an EMF is induced in Wire B.
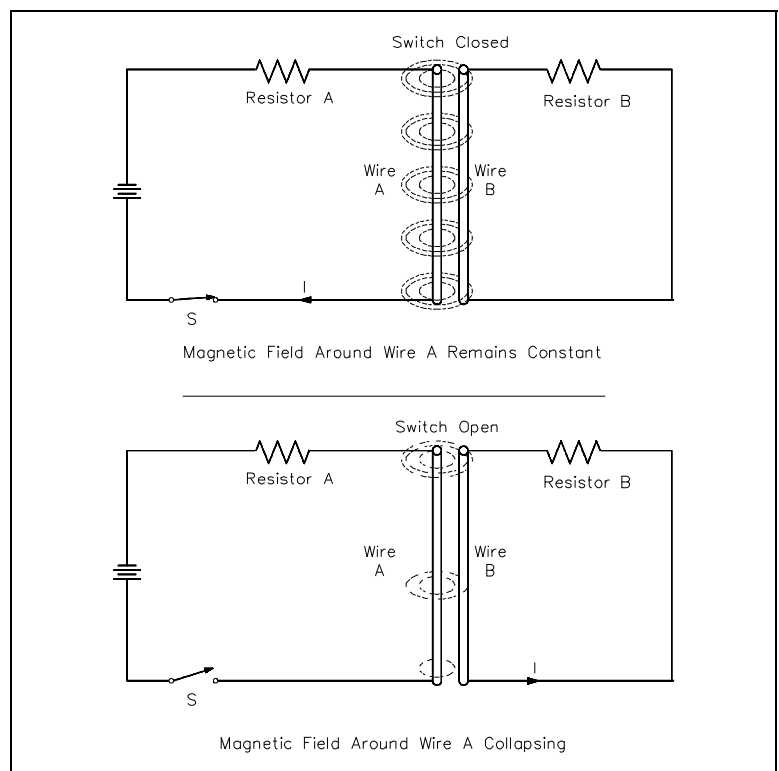

Figure 1   Induced EMF

This is an example of Faraday's Law, which states that a voltage is induced in a conductor when that conductor is moved through a magnetic field, or when the magnetic field moves past the conductor. When the EMF is induced in Wire B, a current will flow whose magnetic field opposes the change in the magnetic field that produced it.

For this reason, an induced EMF is sometimes called counter EMF or CEMF. This is an example of Lenz's Law, which states that the induced EMF opposes the EMF that caused it.

The three requirements for inducing an EMF are:

1. a conductor,

2. a magnetic field, and

3. relative motion between the two.

The faster the conductor moves, or the faster the magnetic field collapses or expands, the greater the induced EMF. The induction can also be increased by coiling the wire in either Circuit A or Circuit B, or both, as shown in Figure 2.
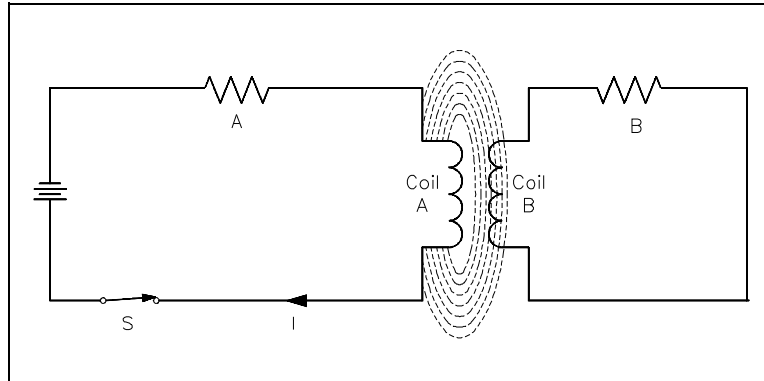
Figure 2 Induced EMF in Coils

Self-induced EMF is another phenomenon of induction. The circuit shown in Figure 3 contains a coil of wire called an inductor (L). As current flows through the circuit, a large magnetic field is set up around the coil. Since the current is not changing, there is no EMF produced. If we open the switch, the field around the inductor collapses. This collapsing magnetic field produces a voltage in the coil. This is called self-induced EMF.
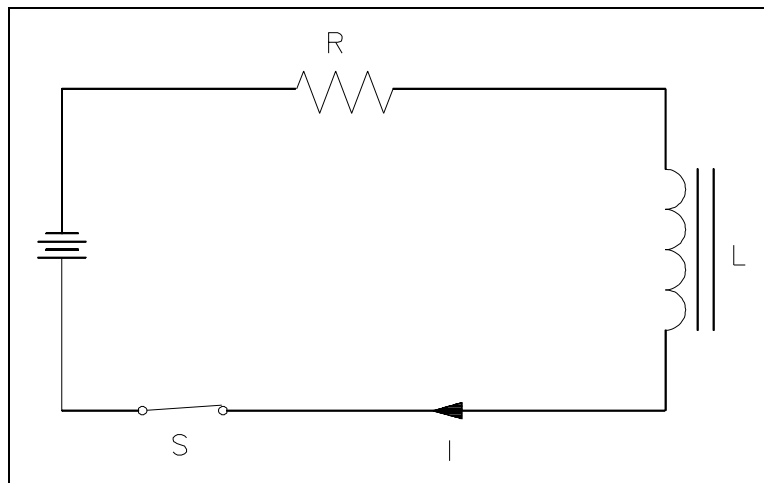
Figure 3 Self-Induced EMF

The polarity of self-induced EMF is given to us by Lenz's Law. The polarity is in the direction that opposes the change in the magnetic field that induced the EMF. The result is that the current caused by the induced EMF tends to maintain the same current that existed in the circuit before the switch was opened. It is commonly said that an inductor tends to oppose a change in current flow.

The induced EMF, or counter EMF, is proportional to the time rate of change of the current. The proportionality constant is called the "inductance" (L). Inductance is a measure of an inductor's ability to induce CEMF. It is measured in henries (H). An inductor has an inductance of one henry if one amp per second change in current produces one volt of CEMF, as shown in Equation (3-1).

$$\text{CEMF} \;=\; -L\,\frac{\Delta I}{\Delta t} \tag{3-1}$$

where

CEMF = induced voltage (volts)

L = inductance (henries)

$\dfrac{\Delta I}{\Delta t}$ = time rate of change of current (amp/sec)

The minus sign shows that the CEMF is opposite in polarity to the applied voltage.

Example: A 4-henry inductor is in series with a variable resistor. The resistance is increased so that the current drops from 6 amps to 2 amps in 2 seconds. What is the CEMF induced?

$$\text{CEMF} = -L\,\frac{\Delta I}{\Delta t}$$

$$= -4\left(\frac{2A - 6A}{2}\right)$$
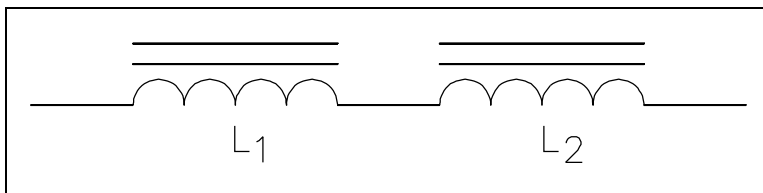
$$= -4(-2)$$

$$\text{CEMF} = +8 \text{ volts}$$

Figure 4 Inductors in Series

Inductors in series are combined like resistors in series. Equivalent inductance (L_{eq}) of two inductors in series (Figure 4) is given by Equation (3-2).

$$L_{eq} = L_1 + L_2 + ... L_n \tag{3-2}$$

Inductors in parallel are combined like resistors in parallel as given by Equation (3-3).

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots \frac{1}{L_N} \qquad (3\text{-}3)$$

When only two inductors are in parallel, as shown in Figure 5, Equation (3-3) may be simplified as given in Equation (3-4). As shown in Equation (3-4), this is valid when there are only two inductors in parallel.

Figure 5 Inductors in Parallel

$$\frac{1}{L_{eq}} = \frac{L_1 L_2}{L_1 + L_2} \qquad\qquad (3\text{-}4)$$
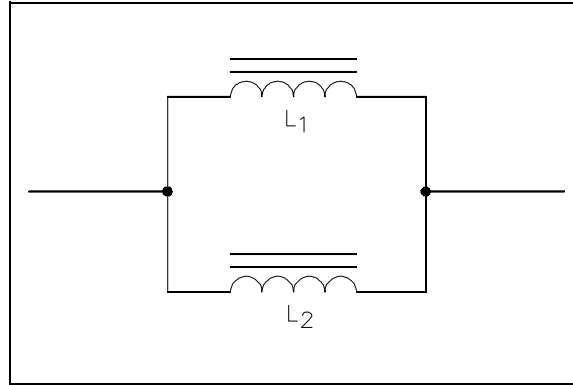
Inductors will store energy in the form of a magnetic field. Circuits containing inductors will behave differently from a simple resistance circuit. In circuits with elements that store energy, it is common for current and voltage to exhibit exponential increase and decay (Figure 6).
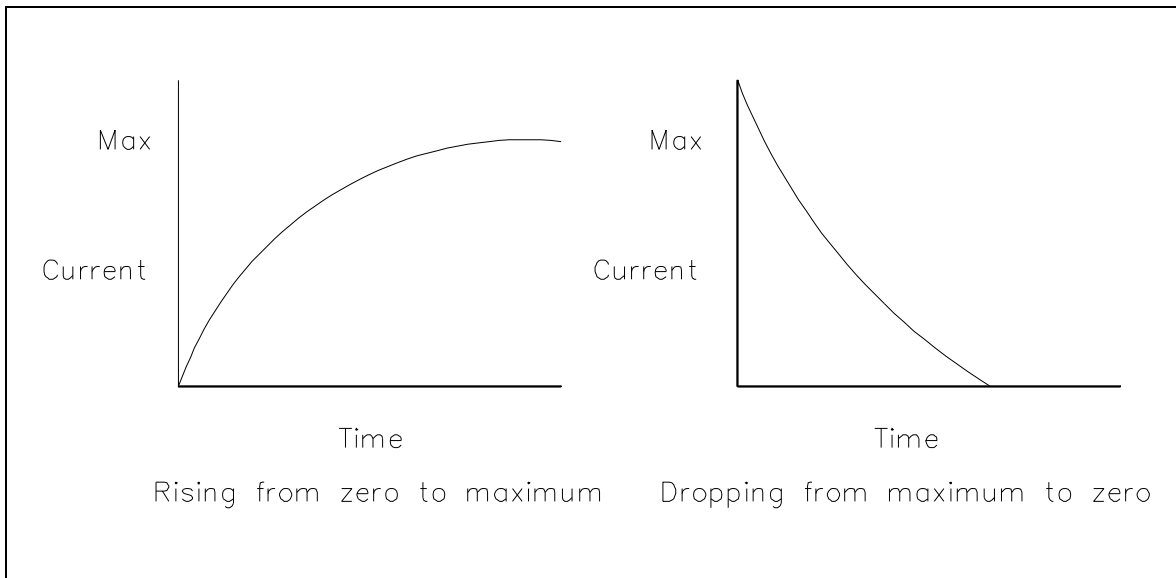

Figure 6 DC Current Through an Inductor

The relationship between values of current reached and the time it takes to reach them is called a time constant. The time constant for an inductor is defined as the time required for the current either to increase to 63.2 percent of its maximum value or to decrease by 63.2 percent of its maximum value (Figure 7).
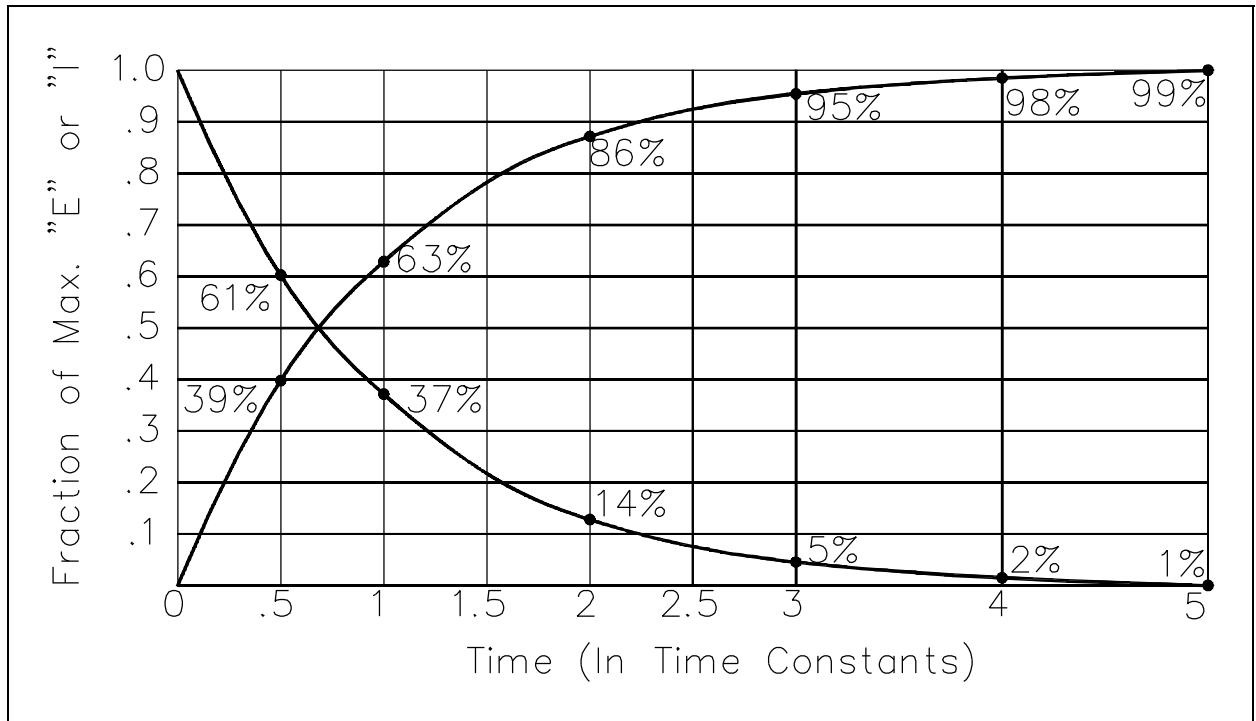

Figure 7 Time Constant

The value of the time constant is directly proportional to the inductance and inversely proportional to the resistance. If these two values are known, the time constant can be found using Equation (3-5).

$$T_L = \frac{L}{R} \tag{3-5}$$

where

T_L = time constant (seconds)
L = inductance (henries)
R = resistance (ohms)

The voltage drop across an inductor is directly proportional to the product of the inductance and the time rate of change of current through the inductor, as shown in Equation (3-6).

$$V_L \quad = \quad L \frac{\Delta I}{\Delta t} \qquad\qquad (3\text{-}6)$$

where

V_L =   voltage drop across the inductor (volts)

L =   inductance (henries)

$\dfrac{\Delta I}{\Delta t}$ =   time rate of change of current (amp/sec)

After five time constants, circuit parameters normally reach their final value. Circuits that contain both inductors and resistors are called RL circuits. The following example will illustrate how an RL circuit reacts to changes in the circuit (Figure 8).

1. Initially, the switch is in Position 1, and no current flows through the inductor.

2. When we move the switch to Position 2, the battery attempts to force a current of $10v/100\Omega$ = 0.1A through the inductor. But as current begins to flow, the inductor generates a magnetic field. As the field increases, a counter EMF is induced that opposes the battery voltage. As a steady state is reached, the counter EMF goes to zero exponentially.

3. When the switch is returned to Position 1, the magnetic field collapses, inducing an EMF that tends to maintain current flow in the same direction through the inductor. Its polarity will be opposite to that induced when the switch was placed in Position 2.
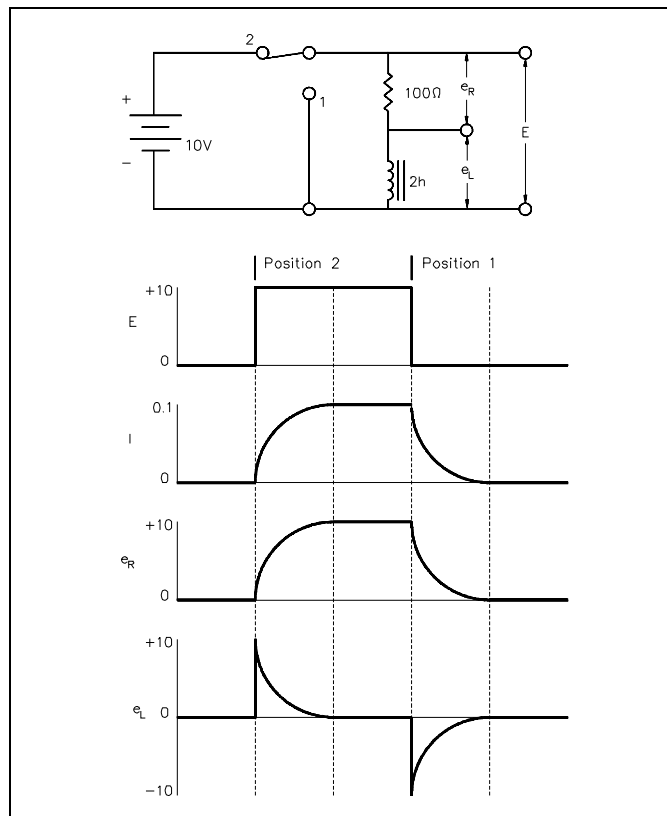

Figure 8   Voltage Applied to an Inductor

The example that follows shows how a circuit with an inductor in parallel with a resistor reacts to changes in the circuit. Inductors have some small resistance, and this is shown schematically as a 1Ω resistor (Figure 9).

1. While the switch is closed, a current of 20 v/1Ω = 20 amps flows through the inductor. This causes a very large magnetic field around the inductor.

2. When we open the switch, there is no longer a current through the inductor. As the magnetic field begins to collapse, a voltage is induced in the inductor. The change in applied voltage is instantaneous; the counter EMF is of exactly the right magnitude to prevent the current from changing initially. In order to maintain the current at 20 amps flowing through the inductor, the self-induced voltage in the inductor must be enough to push 20 amps through the 101Ω of resistance. The CEMF = (101)(20) = 2020 volts.

3. With the switch open, the circuit looks like a series RL circuit without a battery. The CEMF induced falls off, as does the current, with a time constant T_L of:
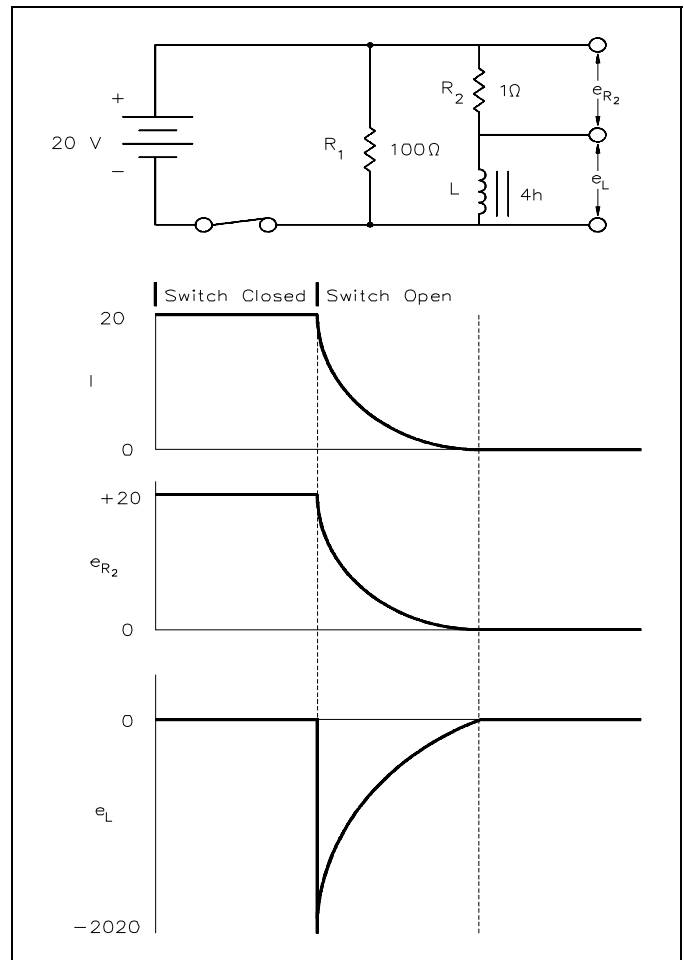
Figure 9 Inductor and Resistor in Parallel

$$T_L = \frac{L}{R}.$$

$$T_L = \frac{4H}{101\Omega} = 0.039 \text{ sec}$$

Summary

The important information on inductors is summarized below.

Inductance Summary

- When an inductor has a DC current flowing through it, the inductor will store energy in the form of a magnetic field.

- An inductor will oppose a change in current flow by the CEMF induced when the field collapses or expands.

- Inductors in series are combined like resistors in series.

- Inductors in parallel are combined like resistors in parallel.

- The time constant for an inductor is defined as the required time for the current either to increase to 63.2 percent of its maximum value or to decrease by 63.2 percent of its maximum value.

CAPACITANCE

Because of the effect of capacitance, an electrical circuit can store energy, even after being de-energized.

EO 1.5   **DESCRIBE the construction of a capacitor.**

EO 1.6   **DESCRIBE how a capacitor stores energy.**

EO 1.7   **DESCRIBE how a capacitor opposes a change in voltage.**

EO 1.8   **Given a circuit containing capacitors, CALCULATE total capacitance for series and parallel circuits.**

EO 1.9   **Given a circuit containing capacitors and resistors, CALCULATE the time constant of the circuit.**

Capacitor

Electrical devices that are constructed of two metal plates separated by an insulating material, called a *dielectric*, are known as capacitors (Figure 10a). Schematic symbols shown in Figures 10b and 10c apply to all capacitors.
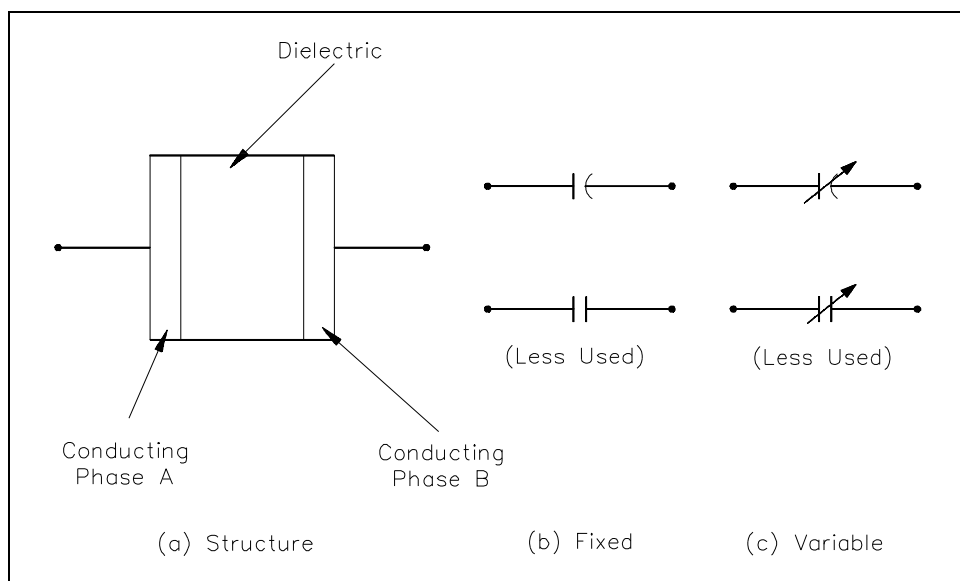

Figure 10   Capacitor and Symbols

The two conductor plates of the capacitor, shown in Figure 11a, are electrically neutral, because there are as many positive as negative charges on each plate. The capacitor, therefore, has no charge.

Now, we connect a battery across the plates (Figure 11b). When the switch is closed (Figure 11c), the negative charges on Plate A are attracted to the positive side of the battery, while the positive charges on Plate B are attracted to the negative side of the battery. This movement of charges will continue until the difference in charge between Plate A and Plate B is equal to the voltage of the battery. This is now a "charged capacitor." Capacitors store energy as an electric field between the two plates.
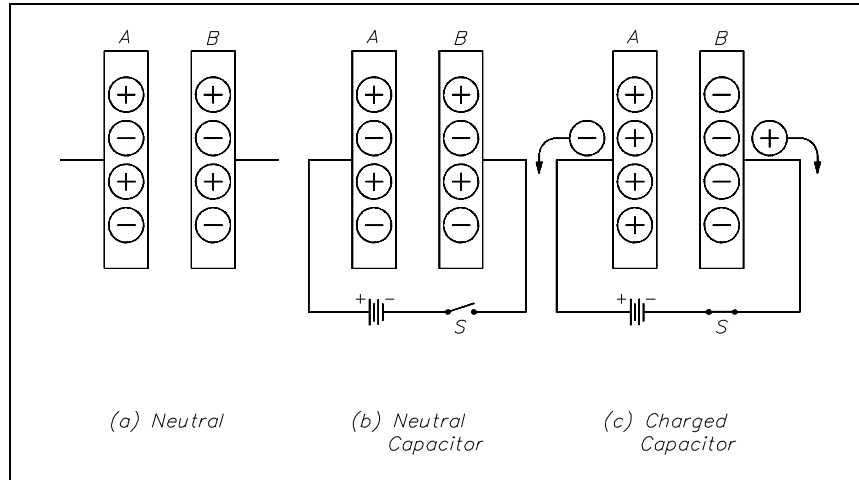
Figure 11   Charging a Capacitor

Because very few of the charges can cross between the plates, the capacitor will remain in the charged state even if the battery is removed. Because the charges on the opposing plates are attracted by one another, they will tend to oppose any changes in charge. In this manner, a capacitor will oppose any change in voltage felt across it.

If we place a conductor across the plates, electrons will find a path back to Plate A, and the charges will be neutralized again. This is now a "discharged" capacitor (Figure 12).

Figure 12   Discharging a Capacitor

Capacitance

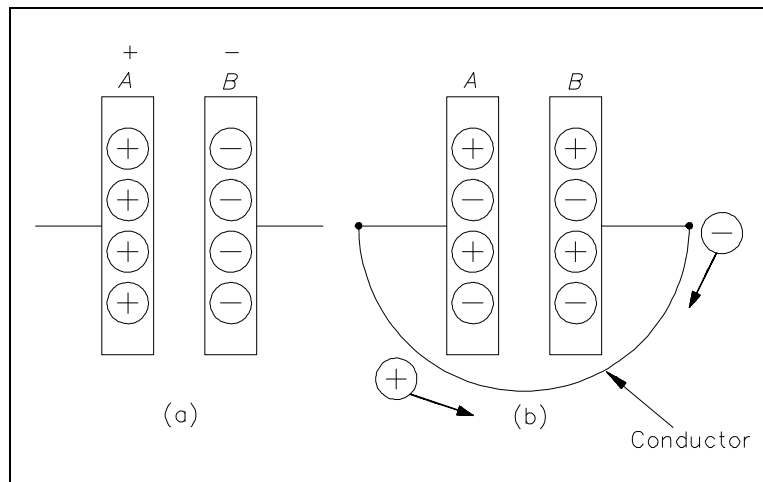Capacitance is the ability to store an electrical charge. Capacitance is equal to the amount of charge that can be stored divided by the applied voltage, as shown in Equation (3-7).

$$C = \frac{Q}{V} \tag{3-7}$$

where

$\quad$ C $\;=\;$ capacitance (F)
$\quad$ Q $\;=\;$ amount of charge (C)
$\quad$ V $\;=\;$ voltage (V)

The unit of capacitance is the farad (F). A farad is the capacitance that will store one coulomb of charge when one volt is applied across the plates of the capacitor.

The dielectric constant (K) describes the ability of the dielectric to store electrical energy. Air is used as a reference and is given a dielectric constant of 1. Therefore, the dielectric constant is unitless. Some other dielectric materials are paper, teflon, bakelite, mica, and ceramic.

The capacitance of a capacitor depends on three things.

$\qquad$ 1.$\qquad$ Area of conductor plates

$\qquad$ 2.$\qquad$ Separation between the plates

$\qquad$ 3.$\qquad$ Dielectric constant of insulation material

Equation (3-8) illustrates the formula to find the capacitance of a capacitor with two parallel plates.

$$C = K \frac{A}{d} \; (8.85 \times 10^{-12}) \tag{3-8}$$

where

C	=	capacitance
K	=	dielectric constant
A	=	area
d	=	distance between the plates
8.85×10^{-12}	=	constant of proportionality

Example 1:   Find the capacitance of a capacitor that stores 8 C of charge at 4 V.

$$C = \frac{Q}{V}$$

$$C = \frac{8}{4}$$

$$C = 2F$$

Example 2:   What is the charge taken on by a 5F capacitor at 2 volts?

$$Q = C\ V$$

$$Q = (5F)\,(2V)$$

$$Q = 10C$$

Example 3:   What is the capacitance if the area of a two plate mica capacitor is 0.0050 m^2 and the separation between the plates is 0.04 m?   The dielectric constant for mica is 7.

$$C = K\ \frac{A}{d}\ (8.85\ x\ 10^{-12})$$

$$C = 7\ \frac{0.0050}{0.04}\ (8.85\ x\ 10^{-12})$$

$$C = 7.74\ x\ 10^{-12}F$$

$$C = 7.74\ pF$$

Types of Capacitors

All commercial capacitors are named according to their dielectrics. The most common are air, mica, paper, and ceramic capacitors, plus the electrolytic type. These types of capacitors are compared in Table 1.

TABLE 1
Types of Capacitors

Dielectric	Construction	Capacitance Range
Air	Meshed plates	10 - 400 pF
Mica	Stacked Sheets	10 - 5000 pF
Paper	Rolled foil	0.001 - 1 μF
Ceramic	Tubular	0.5 - 1600 pF
Disk	Tubular	0.002 - 0.1 μF
Electrolytic	Aluminum	5 - 1000 μF
Tantalum	Aluminum	0.01 - 300 μF

Capacitors in Series and Parallel

Capacitors in series are combined like resistors in parallel. The total capacitance, C_T, of capacitors connected in series (Figure 13), is shown in Equation (3-9).
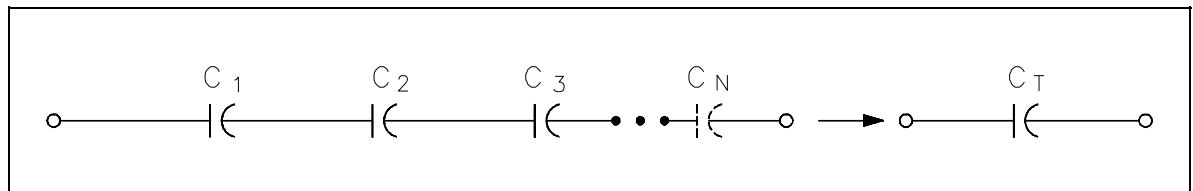

Figure 13 Capacitors Connected in Series

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ . \ . \ . \ \frac{1}{C_N} \tag{3-9}$$

When only two capacitors are in series, Equation (3-9) may be simplified as given in Equation (3-10). As shown in Equation (3-10), this is valid when there are only two capacitors in series.

$$C_T \ = \ \frac{C_1 C_2}{C_1 \ + \ C_2} \tag{3-10}$$

When all the capacitors in series are the same value, the total capacitance can be found by dividing the capacitor's value by the number of capacitors in series as given in Equation (3-11).

$$C_T \ = \ \frac{C}{N} \tag{3-11}$$

where

    C = value of any capacitor in series

    N = the number of capacitors in series with the same value.

Capacitors in parallel are combined like resistors in series. When capacitors are connected in parallel (Figure 14), the total capacitance, C_T, is the sum of the individual capacitances as given in Equation (3-12).
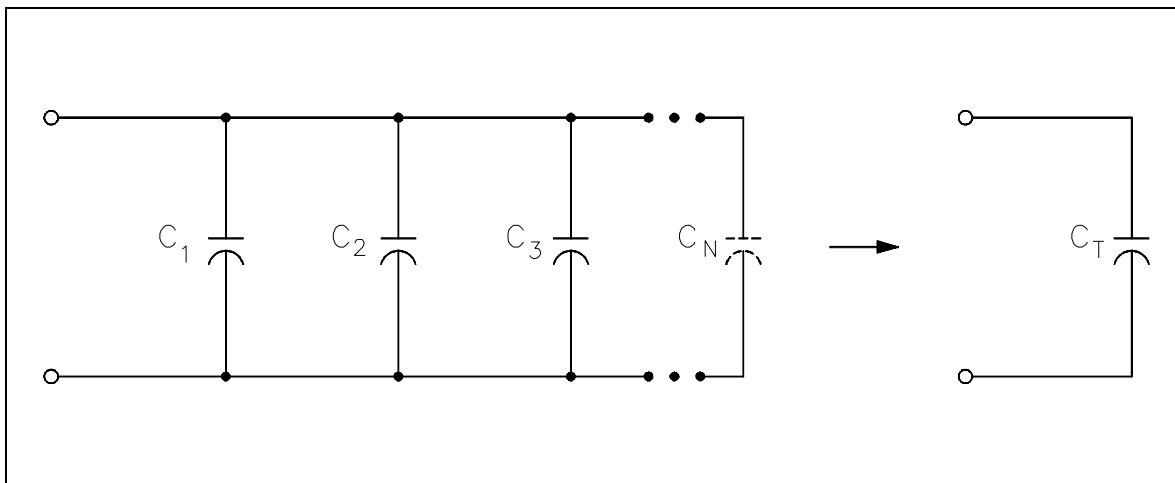
$$C_T = C_1 + C_2 + C_3 + ... + C_N \tag{3-12}$$

Figure 14 Capacitors Connected in Parallel

Example 1: Find the total capacitance of 3μF, 6μF, and 12μF capacitors connected in series (Figure 15).

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$= \frac{1}{3} + \frac{1}{6} + \frac{1}{12}$$

$$= \frac{4}{12} + \frac{2}{12} + \frac{1}{12}$$

$$= \frac{7}{12}$$

$$C_T = \frac{12}{7} = 1.7\mu f$$
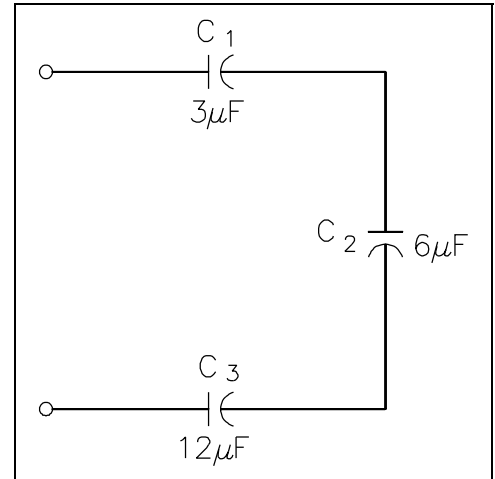
Figure 15 Example 1 - Capacitors Connected in Series

Example 2: Find the total capacitance and working voltage of two capacitors in series, when both have a value of 150 μF, 120 V (Figure 16).

$$C_T = \frac{C}{N}$$

$$= \frac{150}{2}$$

$$C_T = 75\mu f$$

Total voltage that can be applied across a group of capacitors in series is equal to the sum of the working voltages of the individual capacitors.
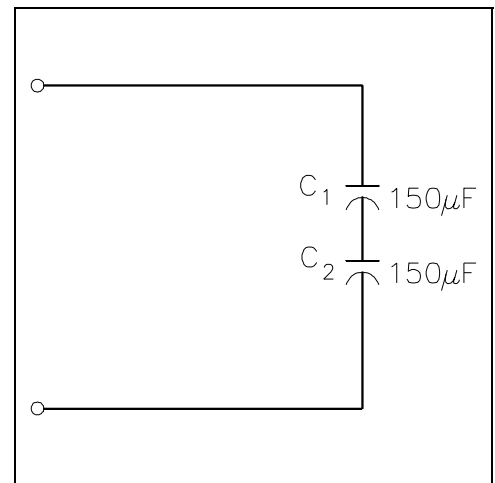
working voltage = 120 V + 120 V = 240 volts

Figure 16 Example 2 - Capacitors Connected in Series

Example 3:   Find the total capacitance of three capacitors in parallel, if the values are 15 µF-50 V, 10 µF-100 V, and 3 µF-150 V (Figure 17).   What would be the working voltage?

$$C_T = C_1 + C_2 + C_3$$

$$= 15\mu F + 10\mu F + 3\mu F$$

$$C_T = 28\mu F$$

The working voltage of a group of capacitors in parallel is only as high as the lowest working voltage of an individual capacitor.   Therefore, the working voltage of this combination is only 50 volts.
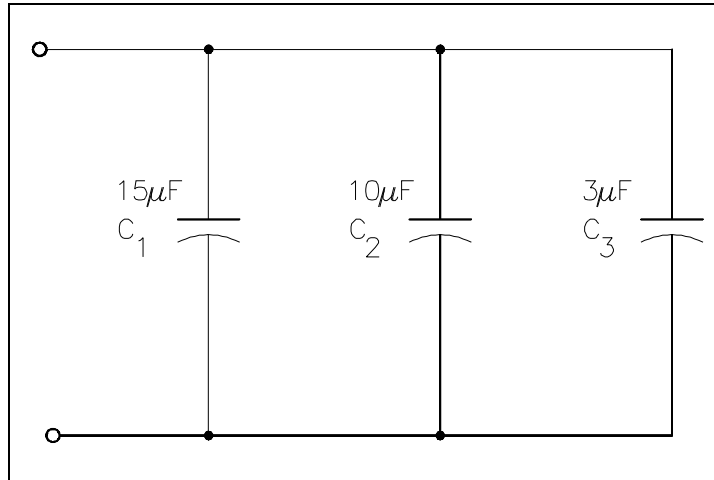
Figure 17 Example 3 - Capacitors Connected in Parallel

Capacitive Time Constant

When a capacitor is connected to a DC voltage source, it charges very rapidly. If no resistance was present in the charging circuit, the capacitor would become charged almost instantaneously. Resistance in a circuit will cause a delay in the time for charging a capacitor. The exact time required to charge a capacitor depends on the resistance (R) and the capacitance (C) in the charging circuit. Equation (3-13) illustrates this relationship.

$$T_C = RC \tag{3-13}$$

where

T_C = capacitive time constant (sec)
R = resistance (ohms)
C = capacitance (farad)

The capacitive time constant is the time required for the capacitor to charge to 63.2 percent of its fully charged voltage. In the following time constants, the capacitor will charge an additional 63.2 percent of the remaining voltage. The capacitor is considered fully charged after a period of five time constants (Figure 18).

Figure 18 Capacitive Time Constant for Charging Capacitor

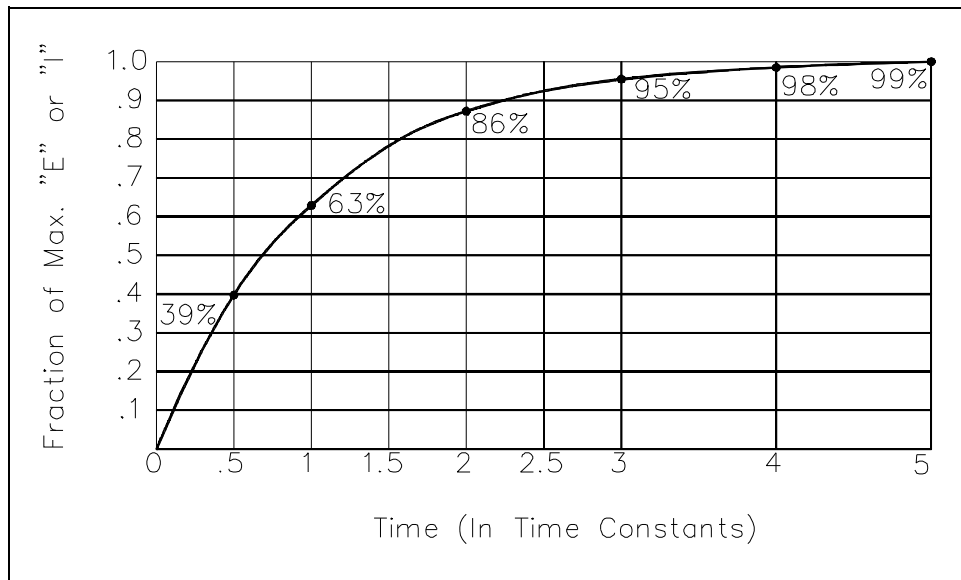The capacitive time constant also shows that it requires five time constants for the voltage across a discharging capacitor to drop to its minimum value (Figure 19).
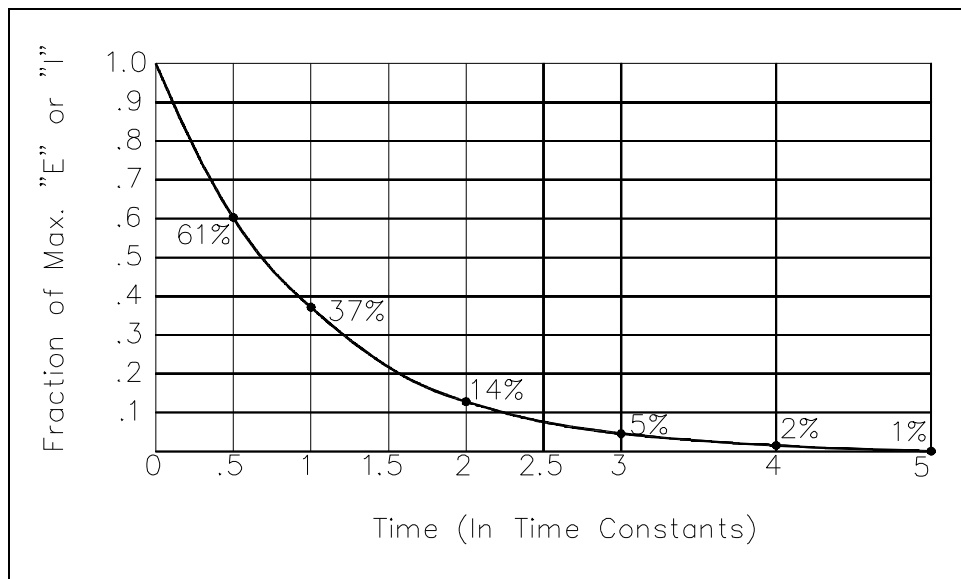
Figure 19 Capacitive Time Constant for Discharging Capacitor

Example: Find the time constant of a 100 µF capacitor in series with a 100Ω resistor (Figure 20).

$$T_C = RC$$

$$T_C = (100\,\Omega)(100\,\mu F)$$

$$T_C = 0.01 \text{ seconds}$$
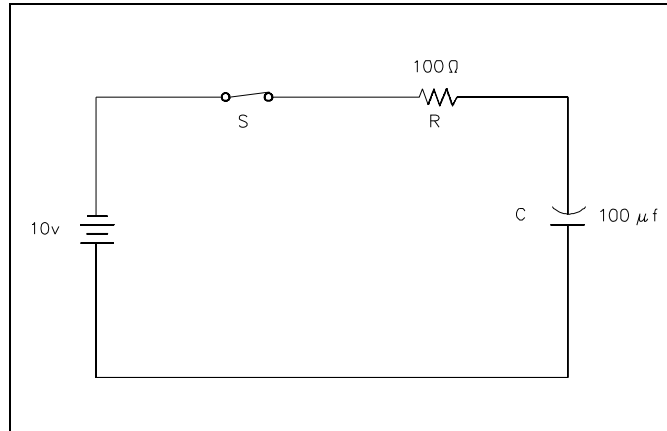
Figure 20 Example - Capacitive Time Constant

Summary

The important information on capacitors is summarized below.

Capacitance Summary

- A capacitor is constructed of two conductors (plates) separated by a dielectric.

- A capacitor will store energy in the form of an electric field caused by the attraction of the positively-charged particles in one plate to the negatively-charged particles in the other plate.

- The attraction of charges in the opposite plates of a capacitor opposes a change in voltage across the capacitor.

- Capacitors in series are combined like resistors in parallel.

- Capacitors in parallel are combined like resistors in series.

- The capacitive time constant is the time required for the capacitor to charge (or discharge) to 63.2 percent of its fully charged voltage.

PART 2: BATTERIES - TABLE OF CONTENTS

PART 2: BATTERIES - TABLE OF CONTENTS (Cont.)

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- Kidwell, Walter, <u>Electrical Instruments and Measurements</u>, McGraw-Hill.

BATTERY TERMINOLOGY

Batteries are used for a wide variety of services throughout technology today. To begin to study battery operation and characteristics, a few terms that are used with batteries must be understood.

EO 1.1   DEFINE the following terms as they relate to batteries and voltaic cells:
   a.   Voltaic cell
   b.   Battery
   c.   Electrode
   d.   Electrolyte
   e.   Specific gravity
   f.   Ampere-Hour

Voltaic Cell

The term *voltaic cell* is defined as a combination of materials used to convert chemical energy into electrical energy. A voltaic or chemical cell consists of two electrodes made of different types of metals or metallic compounds placed in an electrolyte solution.

Battery

A *battery* is a group of two or more connected voltaic cells.

Electrode

An *electrode* is a metallic compound, or metal, which has an abundance of electrons (negative electrode) or an abundance of positive charges (positive electrode).

Electrolyte

An *electrolyte* is a solution which is capable of conducting an electric current. The electrolyte of a cell may be a liquid or a paste. If the electrolyte is a paste, the cell is referred to as a dry cell; if the electrolyte is a solution, it is called a wet cell.

Specific Gravity

Specific gravity is defined as the ratio comparing the weight of any liquid to the weight of an equal volume of water. The specific gravity of pure water is 1.000. Lead-acid batteries use an electrolyte which contains sulfuric acid. Pure sulfuric acid has a specific gravity of 1.835, since it weighs 1.835 times as much as pure water per unit volume.

Since the electrolyte of a lead-acid battery consists of a mixture of water and sulfuric acid, the specific gravity of the electrolyte will fall between 1.000 and 1.835. Normally, the electrolyte for a battery is mixed such that the specific gravity is less than 1.350.

Specific gravity is measured with a hydrometer. A simple hydrometer consists of a glass float inside a glass tube, as shown in Figure 1. The hydrometer float is weighted at one end and sealed at both ends. A scale calibrated in specific gravity is positioned lengthwise along the body of the float. The float is placed inside the glass tube, and the fluid to be tested is drawn into the tube. As the fluid is drawn into the tube, the hydrometer float will sink to a certain level in the fluid. The extent to which the hydrometer float protrudes above the level of the fluid depends on the specific gravity of the fluid. The reading on the float scale at the surface of the fluid is the specific gravity of the fluid.

Ampere-Hour

An *ampere-hour* is defined as a current of one ampere flowing for one hour. If you multiply the current in amperes by the time of flow in hours, the result is the total number of ampere-hours. Ampere-hours are normally used to indicate the amount of energy a storage battery can deliver.
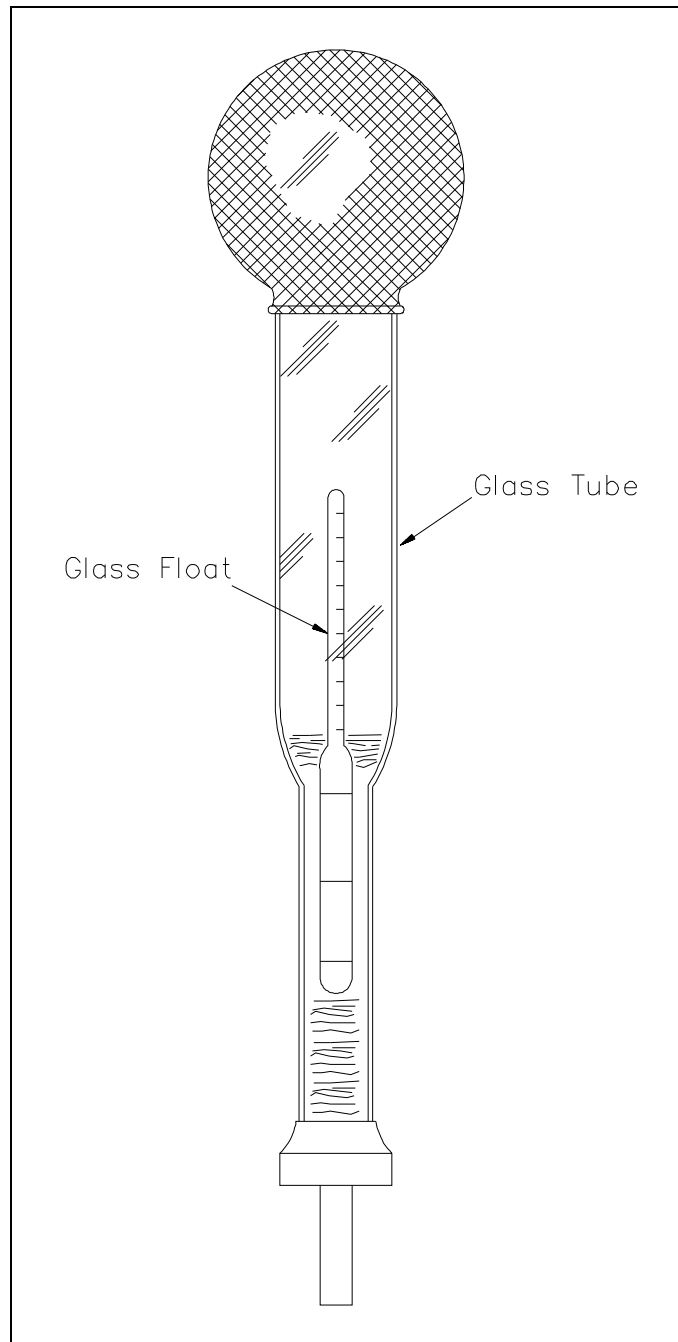
Figure 1 Simple Hydrometer

Summary

Battery terms are summarized below.

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Battery Terminology Summary

- A voltaic cell is a combination of materials used to convert chemical energy into electrical energy.

- A battery is a group of two or more connected voltaic cells.

- An electrode is a metallic compound, or metal, which has an abundance of electrons (negative electrode) or an abundance of positive charges (positive electrode).

- An electrolyte is a solution which is capable of conducting an electric current.

- Specific gravity is defined as the ratio comparing the weight of any liquid to the weight of an equal volume of water.

- An ampere-hour is defined as a current of one ampere flowing for one hour.

</div>

BATTERY THEORY

A battery converts chemical energy to electrical energy. This conversion enables electrical power to be stored.

EO 1.2   **STATE the purpose of a battery.**

EO 1.3   **DESCRIBE the operation of a simple voltaic cell.**

EO 1.4   **STATE the chemical equation for the reaction that occurs when a lead-acid battery is being charged or discharged.**

EO 1.5   **EXPLAIN the relationship between specific gravity and state of charge of a lead-acid battery.**

<u>Batteries</u>

The purpose of a battery is to store chemical energy and to convert this chemical energy into electrical energy when the need arises.

As described in previous chapters, a chemical cell (or voltaic cell) consists of two electrodes of different types of metals or metallic compounds and an electrolyte solution which is capable of conducting an electric current.

A good example of a voltaic cell is one that contains zinc and copper electrodes. The zinc electrode contains an abundance of negatively charged atoms, and the copper electrode contains an abundance of positively charged atoms. When these electrodes are immersed in an electrolyte, chemical action begins. The zinc electrode will accumulate a much larger negative charge because it dissolves into the electrolyte. The atoms, which leave the zinc electrode, are positively charged and are attracted by the negatively charged ions of the electrolyte; the atoms repel the positively charged ions of the electrolyte toward the copper electrode (Figure 2).
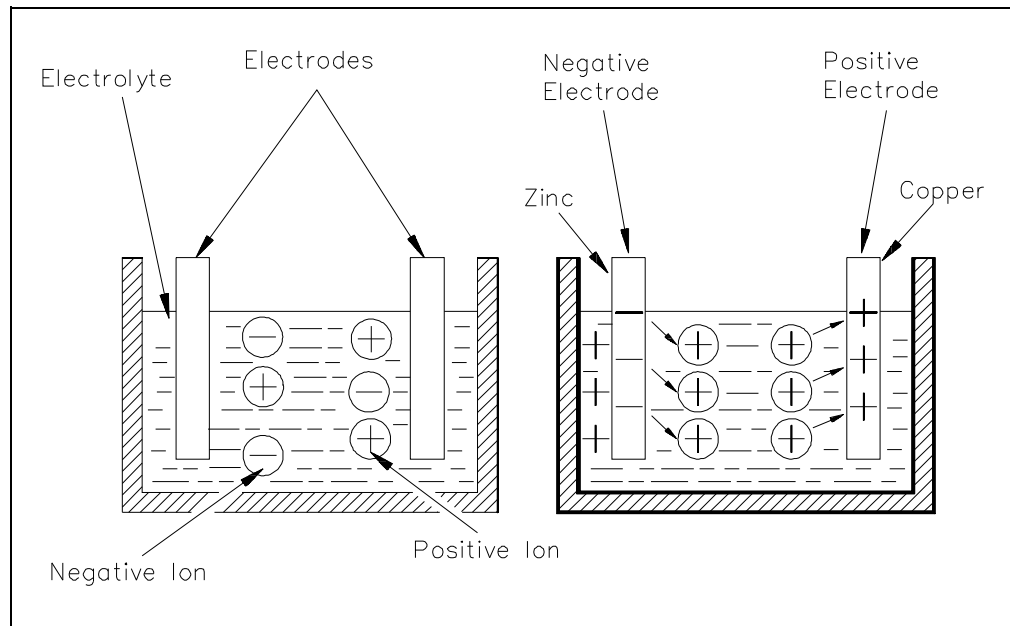
Figure 2 Basic Chemical Production of Electrical Power

This action causes electrons to be removed from the copper electrode, leaving it with an excess of positive charge. If a load is connected across the electrodes, the forces of attraction and repulsion will cause the free electrons in the negative zinc electrode to move through the connecting wire and load, and toward the positive copper electrode (Figure 3).

The potential difference that results allows the cell to function as a source of applied voltage.
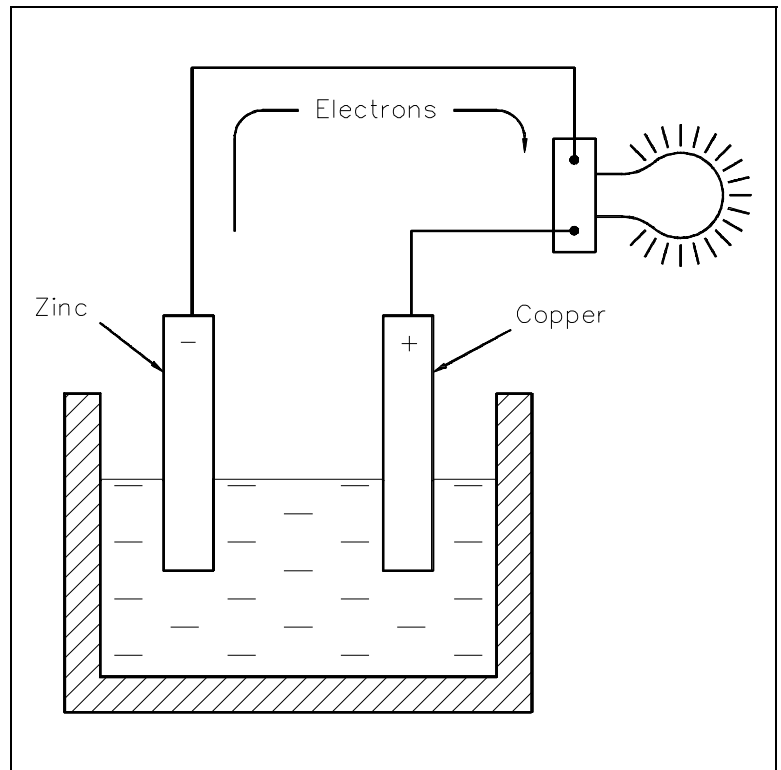
Figure 3 Electron Flow Through a Battery

Discharge and Charging of Lead-Acid Battery

In a lead-acid battery, two types of lead are acted upon electro-chemically by an electrolytic solution of diluted sulfuric acid (H_2SO_4). The positive plate consists of lead peroxide (PbO_2), and the negative plate is sponge lead (Pb), shown in Figure 4.
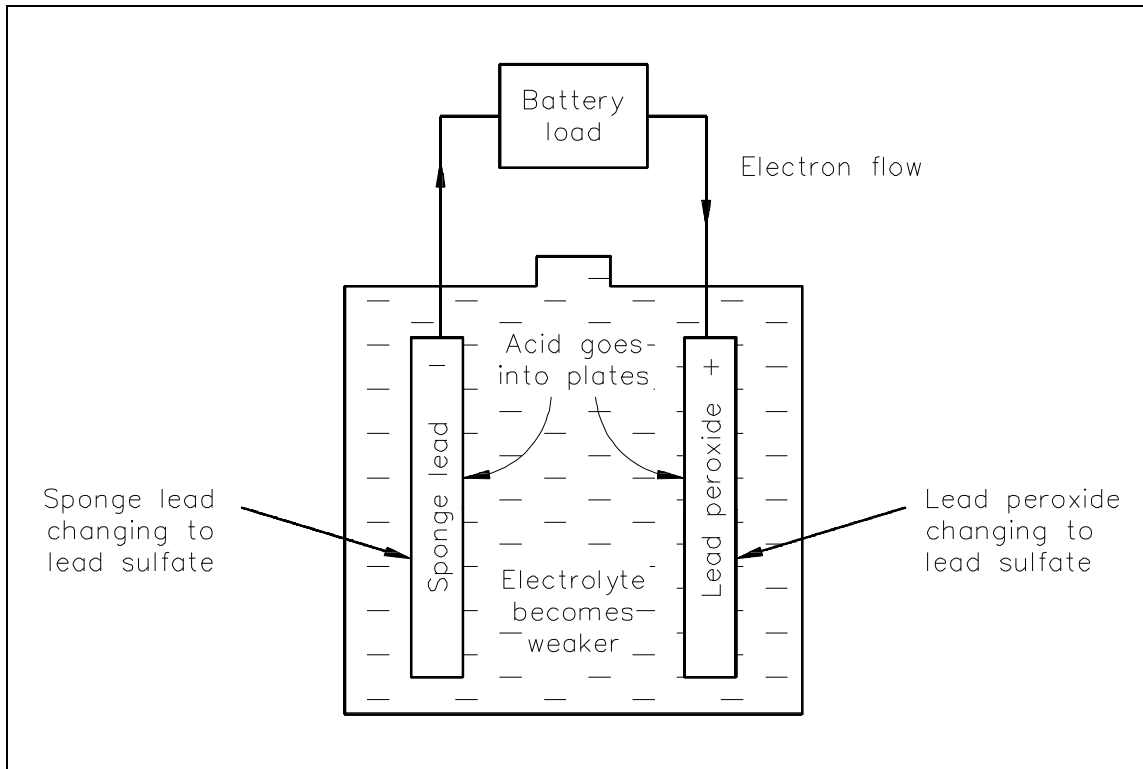
Figure 4 Chemical Action During Discharge

When a lead-acid battery is discharged, the electrolyte divides into H_2 and SO_4. The H_2 will combine with some of the oxygen that is formed on the positive plate to produce water (H_2O), and thereby reduces the amount of acid in the electrolyte. The sulfate (SO_4) combines with the lead (Pb) of both plates, forming lead sulphate ($PbSO_4$), as shown in Equation (4-1).

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{\text{discharge}} 2PbSO_4 + 2H_2O \qquad (4\text{-}1)$$

As a lead-acid battery is charged in the reverse direction, the action described in the discharge is reversed. The lead sulphate ($PbSO_4$) is driven out and back into the electrolyte (H_2SO_4). The return of acid to the electrolyte will reduce the sulphate in the plates and increase the specific gravity. This will continue to happen until all of the acid is driven from the plates and back into the electrolyte, as shown in Equation (4-2) and Figure 5.
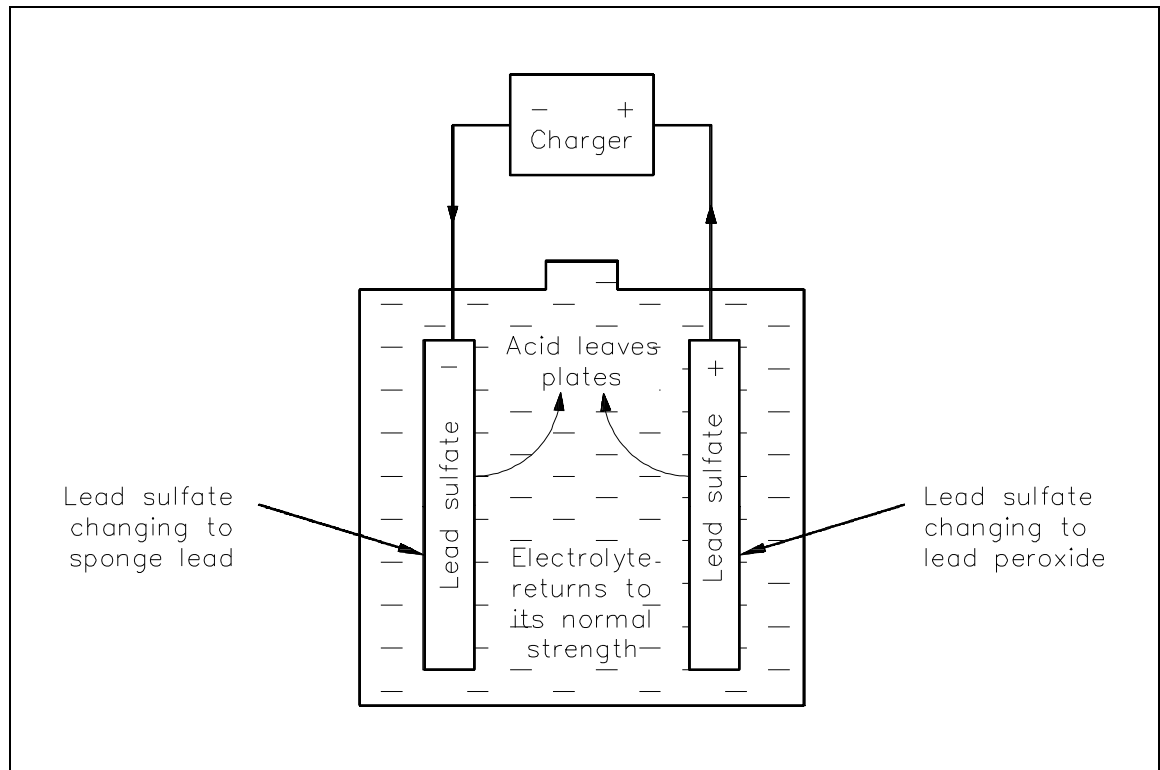
Figure 5 Chemical Action During Charging

$$PbO_2 + Pb + 2H_2SO_4 \overset{\text{charge}}{\leftarrow} 2PbSO_4 + 2H_2O \qquad (4\text{-}2)$$
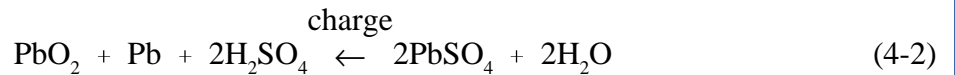
As a lead-acid battery charge nears completion, hydrogen (H_2) gas is liberated at the negative plate, and oxygen (O_2) gas is liberated at the positive plate. This action occurs since the charging current is usually greater than the current necessary to reduce the remaining amount of lead sulfate on the plates. The excess current ionizes the water (H_2O) in the electrolyte. Since hydrogen is highly explosive, it is necessary to provide adequate ventilation to the battery whenever charging is in progress. Also, no smoking, electric sparks, or open flames are allowed near a charging battery.

The decrease in specific gravity on discharge is proportional to the ampere-hours discharged. While charging a lead-acid battery, the rise in specific gravity is not uniform, or proportional, to the amount of ampere-hours charged (Figure 6).
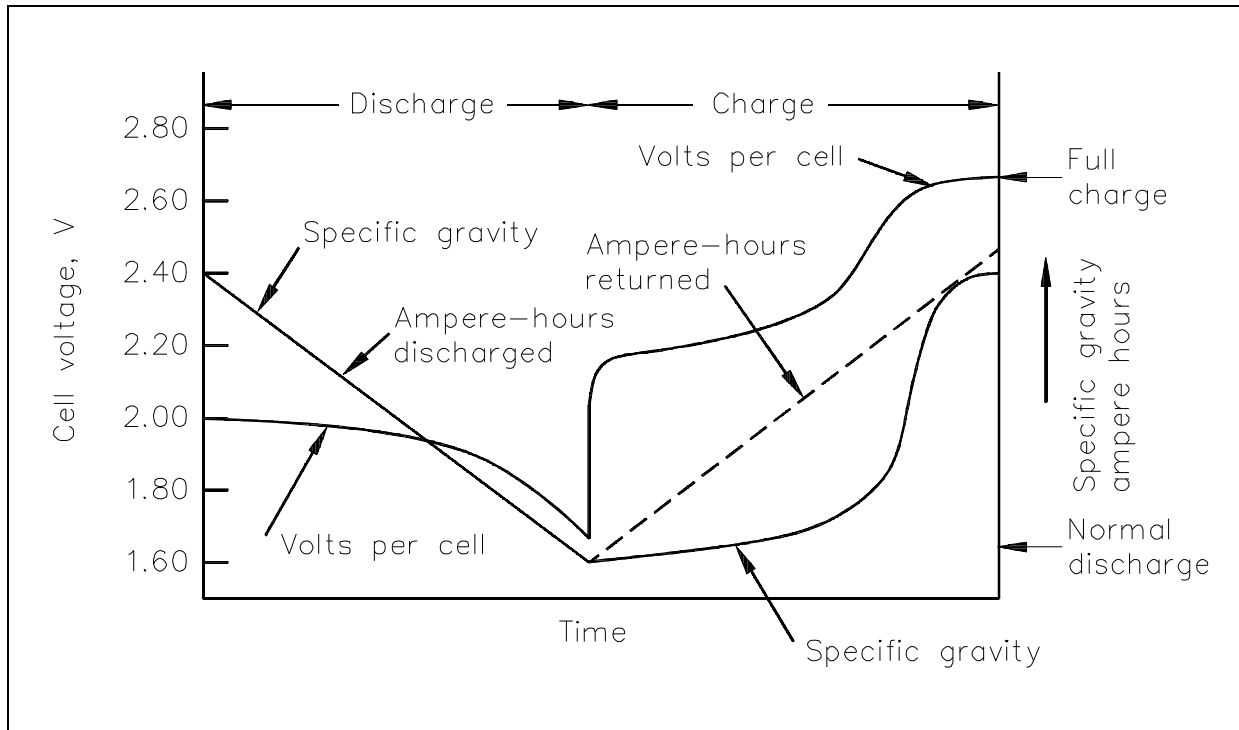
Figure 6 Voltage and Specific Gravity During Charge and Discharge

The electrolyte in a lead-acid battery plays a direct role in the chemical reaction. The specific gravity decreases as the battery discharges and increases to its normal, original value as it is charged. Since specific gravity of a lead-acid battery decreases proportionally during discharge, the value of specific gravity at any given time is an approximate indication of the battery's state of charge. To determine the state of charge, compare the specific gravity, as read using a hydrometer, with the full charge value and the manufacturer's published specific gravity drop, which is the decrease from full to nominal charge value.

Example: A lead-acid battery reads 1.175 specific gravity. Its average full charge specific gravity is 1.260 and has a normal gravity drop of 120 points (or.120) at an 8 hour discharge rate.

Solution:

Fully charged - 1.260
Present charge - 1.175

The battery is 85 points below its fully charged state. It is therefore about 85/120, or 71%, discharged.

Summary

Battery theory is summarized below.

<div style="border:1px solid black; padding:1em;">

Battery Theory Summary

- The purpose of a battery is to store chemical energy and to convert this chemical energy into electrical energy when the need arises.

- A voltaic cell develops a potential difference when electrodes of two different metals are immersed in an electrolyte. One electrode accumulates a positive charge. The potential difference is due to the difference in charge between the two electrodes.

- The chemical equation for a lead-acid battery during discharge is:

$$PbO_2 + Pb + 2H_2SO_4 \xrightarrow{\text{discharge}} 2PbSO_4 + 2H_2O.$$
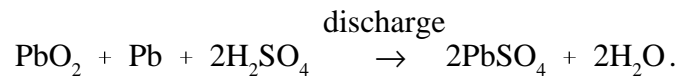
- The chemical equation for a lead-acid battery during charge is:

$$PbO_2 + Pb + 2H_2SO_4 \xleftarrow{\text{charge}} 2PbSO_4 + 2H_2O.$$
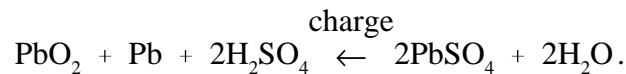
- When a lead-acid battery is discharged, electrolyte and the active material on the plates of the battery are consumed to produce water and lead sulphate.

- When a lead-acid battery is charged, electrical energy is added to the battery, causing the water and lead sulphate to be consumed and produce electrolyte and active material.

- Since specific gravity of a lead-acid battery decreases proportionally during discharge, the value of specific gravity at any given time is an approximate indication of the battery's state of charge.

</div>

BATTERY OPERATIONS

Once the basic theory behind the operation of batteries is understood, we can apply these concepts to better understand the way batteries are utilized.

EO 1.6   **DESCRIBE the relationship between total battery voltage and cell voltage for a series-connected battery.**

EO 1.7   **STATE the advantage of connecting a battery in parallel with respect to current-carrying capability.**

EO 1.8   **STATE the difference between primary and secondary cells with respect to recharge capability.**

Series Cells

When several cells are connected in series (Figure 7), the total voltage output of the battery is equal to the sum of the individual cell voltages. In the example of the battery in Figure 7, the four 1.5V cells provide a total of 6 volts. When we connect cells in series, the positive terminal of one cell is connected to the negative terminal of the next cell. The current flow through a battery connected in series is the same as for one cell.
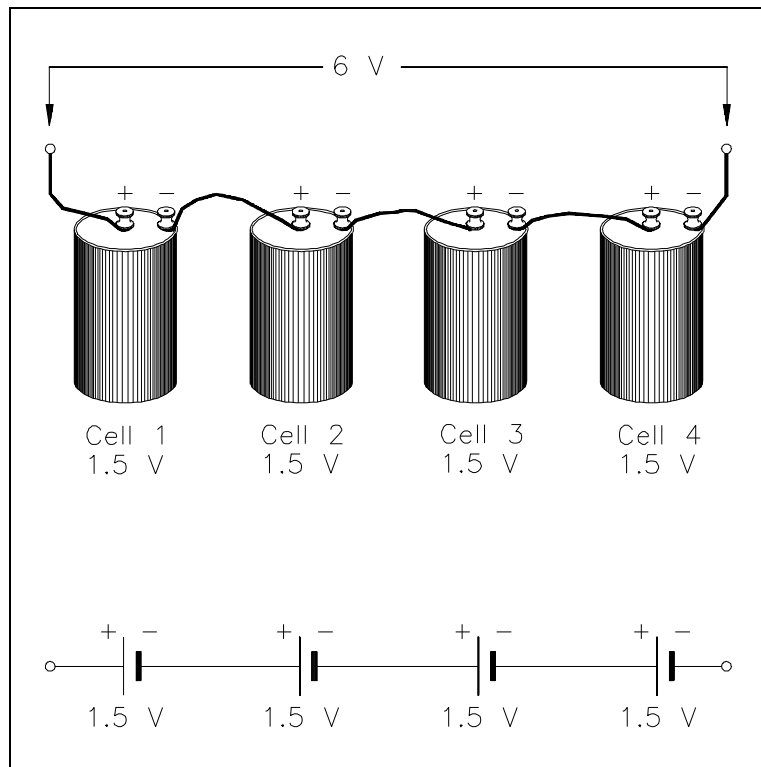
Figure 7 Cells Connected in Series

Parallel Cells

Cells connected in parallel (Figure 8), give the battery a greater current capacity. When cells are connected in parallel, all the positive terminals are connected together, and all the negative terminals are connected together. The total voltage output of a battery connected in parallel is the same as that of a single cell. Cells connected in parallel have the same effect as increasing the size of the electrodes and electrolyte in a single cell. The advantage of connecting cells in parallel is that it will increase the current-carrying capability of the battery.
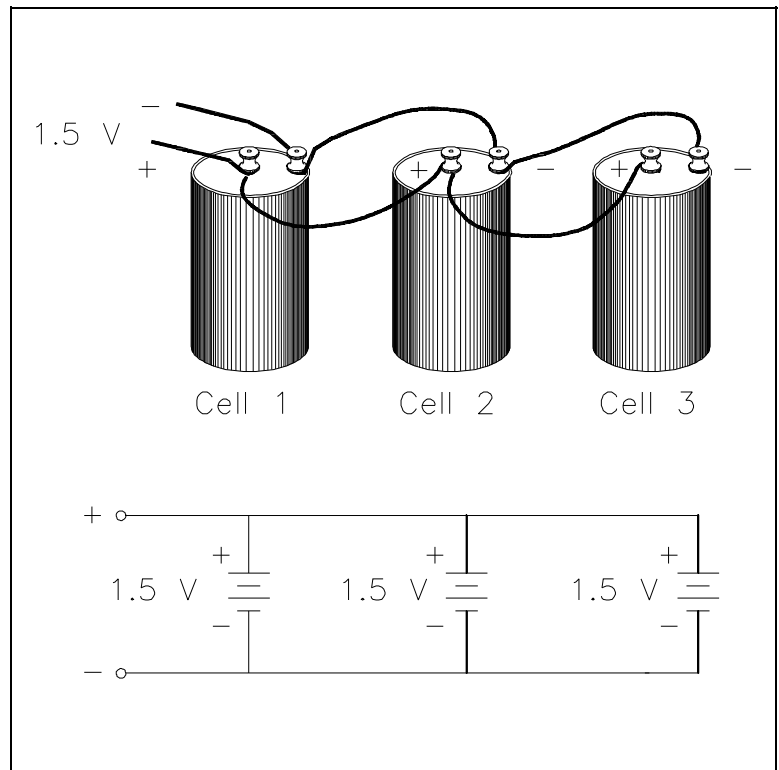
Figure 8 Cells Connected in Parallel

Primary Cell

Cells that cannot be returned to good condition, or recharged after their voltage output has dropped to a value that is not usable, are called *primary cells*. Dry cells that are used in flashlights and transistor radios (e.g., AA cells, C cells) are examples of primary cells.

Secondary Cells

Cells that can be recharged to nearly their original condition are called *secondary cells*. The most common example of a secondary, or rechargeable cell, is the lead-acid automobile battery.

Capacity

The capacity of a storage battery determines how long the storage battery will operate at a certain discharge rate and is rated in ampere-hours. For example, a 120 ampere-hour battery must be recharged after 12 hours if the discharge rate is 10 amps.

Internal Resistance

Internal resistance in a chemical cell is due mainly to the resistance of the electrolyte between electrodes (Figure 9).

Any current in the battery must flow through the internal resistance. The internal resistance is in series with the voltage of the battery, causing an internal voltage drop (Figure 10).

With no current flow, the voltage drop is zero; thus, the full battery voltage is developed across the output terminals (V_B). If a load is placed on the battery, load resistance (R_L) is in series with internal resistance (R_i).
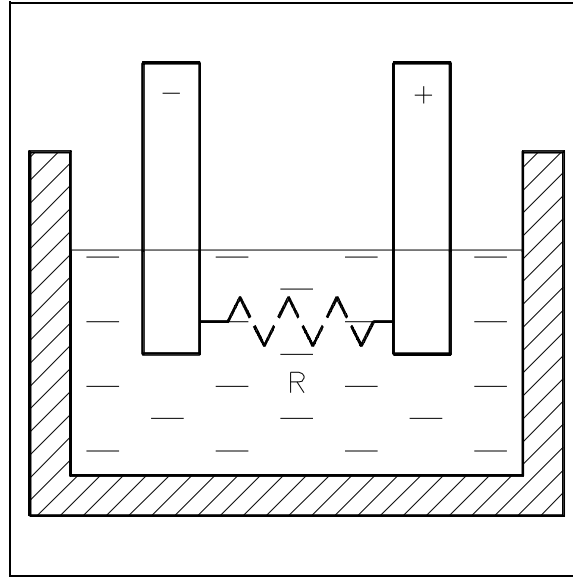
Figure 9 Internal Resistance in a Chemical Cell
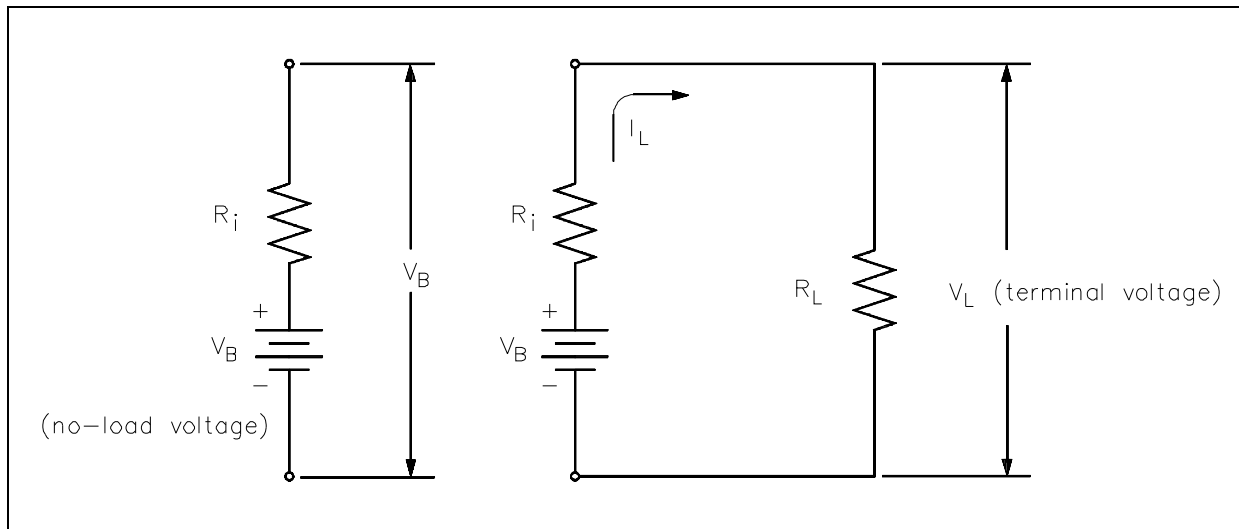
Figure 10 Internal Voltage Drop

When current flows in the circuit (I_L), the internal voltage drop ($I_L R_i$) drops the terminal voltage of the battery as shown in Equation (4-3). Thus, internal resistance reduces both the current and voltage available to the load.

$$V_L = V_B - I_L R_i \qquad\qquad (4\text{-}3)$$

Shelf Life

The *shelf life* of a battery is the time which a battery may be stored and not lose more than 10 percent of its original capacity.

Charge and Discharge

The *charge* of a battery may refer to as one of two things: (1) the relative state of capacity of the battery, or (2) the actual act of applying current flow in the reverse direction to return the battery to a fully-charged state.

Discharge, simply stated, is the act of drawing current from a battery.

Summary

Battery operations are summarized below.

Battery Operations Summary

- The output voltage of a battery connected in series is equal to the sum of the cell voltages.

- A battery that is connected in parallel has the advantage of a greater current-carrying capability.

- Secondary cells can be recharged; primary cells cannot be recharged.

- The unit for battery capacity is the ampere-hour.

- Internal resistance in a battery will decrease the battery voltage when a load is placed on the battery.

- Shelf life is a term that is used to measure the time that a battery may sit idle and not lose more than 10 percent of its charge.

- The charge of a battery may refer to one of two things: (1) the relative state of capacity of the battery, or (2) the actual act of applying current flow in the reverse direction to restore the battery to a fully-charged condition.

- Discharge refers to the act of drawing current from a battery.

TYPES OF BATTERIES

The lead-acid battery is the most common type of battery in use today. There are other types of storage batteries, each having certain advantages.

EO 1.9   **STATE the advantage of each of the following types of batteries:**
       a.   **Carbon-zinc cell**
       b.   **Alkaline cell**
       c.   **Nickel-cadmium cell**
       d.   **Edison cell**
       e.   **Mercury cell**

Wet and Dry Cells

Wet and dry cells are classified by the type of electrolyte the battery uses. The electrolyte of a cell may be a liquid or a paste. If the electrolyte is a paste, the cell is referred to as a dry cell. If the electrolyte is a solution, the cell is called a wet cell.

Carbon-Zinc Cell

The carbon-zinc cell is one of the oldest and most widely used types of dry cells. The carbon in the battery is in the form of a rod in the center of the cell which acts as the positive terminal. The case is made from zinc and acts as the negative electrode. The electrolyte for this type of cell is a chemical paste-like mixture which is housed between the carbon electrode and the zinc case. The cell is then sealed to prevent any of the liquid in the paste from evaporating.

The advantage of a carbon-zinc battery is that it is durable and very inexpensive to produce. The cell voltage for this type of cell is about 1.5 volts.

Alkaline Cell

The alkaline cell is so called because it has an alkaline electrolyte of potassium hydroxide. The negative electrode is made from zinc, and the positive electrode is made of manganese dioxide. The typical alkaline cell generates 1.5 volts. The alkaline cell has the advantage of an extended life over that of a carbon-zinc cell of the same size; however, it is usually more expensive.

Nickel-Cadmium Cell

The nickel-cadmium cell is a secondary cell, and the electrolyte is potassium hydroxide. The negative electrode is made of nickel hydroxide, and the positive electrode is made of cadmium hydroxide. The nominal voltage of a nickel-cadmium cell is 1.25 volts. The nickel-cadmium battery has the advantage of being a dry cell that is a true storage battery with a reversible chemical reaction (i.e., it can be recharged). The nickel-cadmium battery is a rugged, dependable battery. It gives dependable service under extreme conditions of temperature, shock, and vibration. Due to its dependability, it is ideally suited for use in portable communications equipment.

Edison Cell

In an edison cell the positive plate consists of nickel and nickel hydrate, and the negative plate is made of iron. The electrolyte is an alkaline. Typical voltage output is 1.4 volts, and it should be recharged when it reaches 1.0 volts. The edison cell has the advantage of being a lighter and more rugged secondary cell than a lead-acid storage battery.

Mercury Cell

Mercury cells come in two types; one is a flat cell that is shaped like a button, while the other is a cylindrical cell that looks like a regular flashlight battery. Each cell produces about 1.35 volts. These cells are very rugged and have a relatively long shelf life. The mercury cell has the advantage of maintaining a fairly constant output under varying load conditions. For this reason, they are used in products such as electric watches, hearing aids, cameras, and test instruments.

Summary

Battery types are summarized below.

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Battery Types Summary

- If the electrolyte is a paste, the cell is referred to as a dry cell. If the electrolyte is a solution, the cell is called a wet cell.

- The advantage of a carbon-zinc battery is that it is durable and very inexpensive to produce.

- The alkaline cell has the advantage of an extended life over that of a carbon-zinc cell of the same size.

- The nickel-cadmium battery has the advantage of being a dry cell that is a true storage battery with a reversible chemical reaction.

- The edison cell has the advantage of being a lighter and more rugged secondary cell than a lead-acid storage battery.

- The mercury cell has the advantage of maintaining a fairly constant output under varying load conditions.

</div>

BATTERY HAZARDS

Because batteries store large amounts of energy, there are certain hazards that are associated with battery operation. These hazards must be fully understood to ensure safe operation of batteries.

EO 1.10   **EXPLAIN the adverse effects of a shorted cell.**

EO 1.11   **EXPLAIN how gas generation is minimized for a lead-acid battery.**

EO 1.12   **EXPLAIN how heat is generated in a lead-acid battery.**

Shorted Cell

Cell short circuits can be caused by several conditions, which include the following: faulty separators; lead particles or other metals forming a circuit between the positive and negative plates; buckling of the plates; or excessive sediments in the bottom of the jar. The primary cause of some of these occurrences is overcharging and overdischarging of the battery, which causes sediment to build up due to flaking of active material and buckling of cell plates.

Overcharging and overdischarging should be avoided at all costs. Short circuits cause a great reduction in battery capacity. With each shorted cell, battery capacity is reduced by a percentage equal to one over the total number of cells.

Gas Generation

A lead-acid battery cannot absorb all the energy from the charging source when the battery is nearing the completion of the charge. This excess energy dissociates water by way of electrolysis into hydrogen and oxygen. Oxygen is produced by the positive plate, and hydrogen is produced by the negative plate. This process is known as gassing.

Gassing is first noticed when cell voltage reaches 2.30-2.35 volts per cell and increases as the charge progresses. At full charge, the amount of hydrogen produced is about one cubic foot per cell for each 63 ampere-hours input. If gassing occurs and the gases are allowed to collect, an explosive mixture of hydrogen and oxygen can be readily produced. It is necessary, therefore, to ensure that the area is well ventilated and that it remains free of any open flames or spark-producing equipment.

As long as battery voltage is greater than 2.30 volts per cell, gassing will occur and cannot be prevented entirely. To reduce the amount of gassing, charging voltages above 2.30 volts per cell should be minimized (e.g., 13.8 volts for a 12 volt battery).

Battery Temperature

The operating temperature of a battery should preferably be maintained in the nominal band of 60-80°F. Whenever the battery is charged, the current flowing through the battery will cause heat to be generated by the electrolysis of water. The current flowing through the battery (I) will also cause heat to be generated (P) during charge and discharge as it passes through the internal resistance (R_i), as illustrated using the formula for power in Equation (4-4).

$$P = I^2 R_i \qquad (4\text{-}4)$$

Higher temperatures will give some additional capacity, but they will eventually reduce the life of the battery. Very high temperatures, 125°F and higher, can actually do damage to the battery and cause early failure.

Low temperatures will lower battery capacity but also prolong battery life under floating (i.e., slightly charging) operation or storage. Extremely low temperatures can freeze the electrolyte, but only if the battery is low in specific gravity.

Summary

Battery hazards are summarized below.

Battery Hazards Summary

- Short circuits cause a great reduction in battery capacity.

- To prevent short circuits in a battery, overcharging and overdischarging should be avoided at all costs.

- The adverse effect of gassing is that if gassing occurs and the gases are allowed to collect, an explosive mixture of hydrogen and oxygen can be readily produced.

- To reduce the amount of gassing, charging voltages above 2.30 volts per cell should be minimized.

- Whenever the battery is charged, the current flowing through the battery will cause heat to be generated by the electrolysis of water and by I^2R_i power generation.

- Higher temperatures will give some additional capacity, but they will eventually reduce the life of the battery. Very high temperatures, 125°F and higher, can actually do damage to the battery and cause early failure.

PART 3: DC GENERATORS - TABLE OF CONTENTS

PART 3: DC GENERATORS - TABLE OF CONTENTS (Cont.)

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DC EQUIPMENT TERMINOLOGY

Direct current devices are used frequently in today's technology. Before the construction and operation of these devices can be introduced, a few common terms must be understood.

EO 1.1 **DEFINE terminal voltage as it applies to DC generators.**

EO 1.2 **DEFINE counter-electromotive force (CEMF) as it applies to a DC machine.**

EO 1.3 **DESCRIBE the effects of commutation in a DC generator.**

Terminal Voltage

Terminal voltage, as applied to DC generators, is defined as the voltage that can be measured at the output of the generator.

Counter-Electromotive Force (CEMF)

In a generator using a rotating armature, the conductors cut the magnetic lines of force in the magnetic field. Voltage is induced in the armature conductors. This induced voltage opposes the applied voltage; it counteracts some of the applied voltage, which reduces the current flow through the armature. This induced voltage acts counter to applied voltage; therefore, it is called *counter-electromotive force* (CEMF).

Applied Voltage

Applied voltage is defined as the voltage that is delivered across the load. This voltage should be the same as terminal voltage; however, various circuit faults and losses may reduce the terminal voltage.

Commutation

Commutation is the positioning of the DC generator brushes so that the commutator segments change brushes at the same time the armature current changes direction. More simply stated, commutation is the mechanical conversion from AC to DC at the brushes of a DC machine, as shown in Figure 1.

Figure 1 AC to DC Conversion with a Commutator

In a DC generator, commutation provides for the conversion of AC to a DC output that is generated in the armature windings. Commutation will be discussed in greater detail in subsequent chapters.

Summary

DC equipment terms are summarized below.

DC Equipment Terminology Summary

- Terminal voltage, as applied to DC generators, is defined as the voltage that can be measured at the output of the generator.

- Counter-electromotive force (CEMF) is defined as the induced voltage that acts to counter the applied voltage in a DC motor or a DC generator.

- Applied voltage is defined as the voltage that is delivered across the load.

- Commutation is the positioning of the DC generator brushes so that the commutator segments change brushes at the same time the armature current changes direction.
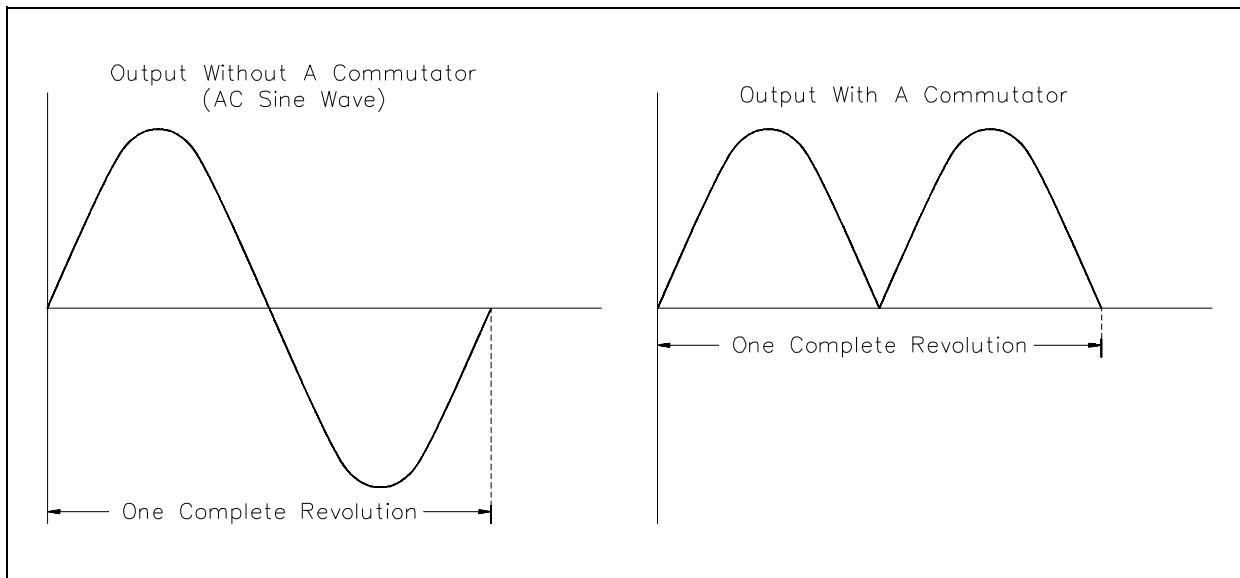
- In a DC generator, commutation provides for the conversion of AC to a DC output that is generated in the armature windings.

DC EQUIPMENT CONSTRUCTION

Direct current machines are energy transfer devices. These machines can function as either a motor or a generator. DC motors and generators have the same basic construction, differing primarily in the energy conversion. To better understand the operation and construction of DC machines, a few basic terms must be understood.

EO 1.4   **STATE the purpose of each of the following components of a DC machine:**
         a.   **Armature**
         b.   **Rotor**
         c.   **Stator**
         d.   **Field**

Armature

The purpose of the *armature* is to provide the energy conversion in a DC machine (refer to Figure 2).

In a DC generator, the armature is rotated by an external mechanical force, such as a steam turbine. This rotation induces a voltage and current flow in the armature. Thus, the armature converts mechanical energy to electrical energy.

In a DC motor, the armature receives voltage from an outside electrical source and converts electrical energy into mechanical energy in the form of torque.

Figure 2 Basic DC Machine

Rotor

The purpose of the *rotor* is to provide the rotating element in a DC machine (refer to Figure 2). In a DC generator, the rotor is the component that is rotated by an external force. In a DC motor, the rotor is the component that turns a piece of equipment. In both types of DC machines, the rotor is the armature.

Stator

The *stator* is the part of a motor or generator that is stationary (refer to Figure 2). In DC machines, the purpose of the stator is to provide the magnetic field. The stator in Figure 2 is provided by a permanent magnet.

Field

The purpose of the *field* in a DC machine is to provide a magnetic field for producing either a voltage (generator) or a torque (motor) (refer to Figure 2). The field in a DC machine is produced by either a permanent magnet or an electromagnet. Normally, electromagnets are used because they have an increased magnetic strength, and the magnetic strength is more easily varied using external devices. In Figure 2, the field is provided by the stator.

Summary

The construction of DC equipment is summarized below.

DC Equipment Construction Summary

- The purpose of the armature is to provide the energy conversion in a DC machine.

- The purpose of the rotor is to provide the rotating element in a DC machine.

- In DC machines, the purpose of the stator is to provide the field.

- The purpose of the field in a DC machine is to provide a magnetic field for producing either a voltage or a torque.

DC GENERATOR THEORY

DC generators are widely used to produce a DC voltage. The amount of voltage produced depends on a variety of factors.

EO 1.5   **LIST the three conditions necessary to induce a voltage into a conductor.**

EO 1.6   **Using the left-hand rule of generators, DETERMINE the direction of the magnetic field, the motion of the conductor, or the direction of current induced into a conductor.**

EO 1.7   **DESCRIBE how terminal voltage of a DC generator is adjusted.**

EO 1.8   **STATE the basis behind each of the four DC generator ratings.**

EO 1.9   **LIST the four internal losses found in a DC generator.**

Voltage Production

Recall from Module 3, DC Circuits, that there are three conditions necessary to induce a voltage into a conductor.

1.   A magnetic field
2.   A conductor
3.   Relative motion between the two

A DC generator provides these three conditions to produce a DC voltage output.

Theory of Operation

A basic DC generator has four basic parts: (1) a magnetic field; (2) a single conductor, or loop; (3) a commutator; and (4) brushes (Figure 3). The magnetic field may be supplied by either a permanent magnet or an electromagnet. For now, we will use a permanent magnet to describe a basic DC generator.
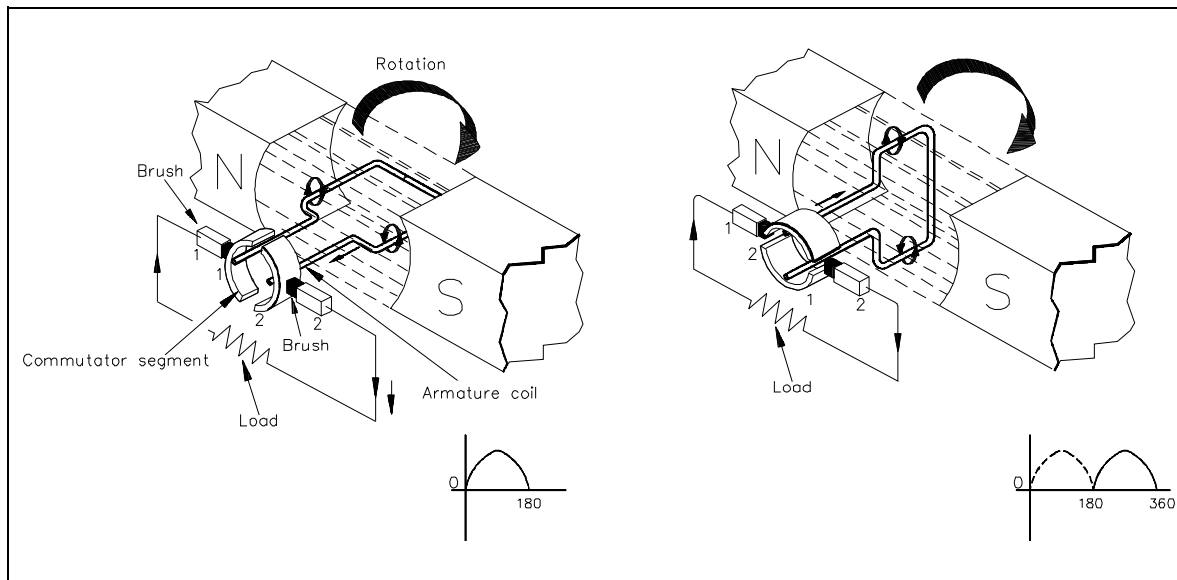
Figure 3   Basic Operation of a DC Generator

A single conductor, shaped in the form of a loop, is positioned between the magnetic poles. As long as the loop is stationary, the magnetic field has no effect (no relative motion). If we rotate the loop, the loop cuts through the magnetic field, and an EMF (voltage) is induced into the loop.

When we have relative motion between a magnetic field and a conductor in that magnetic field, and the direction of rotation is such that the conductor cuts the lines of flux, an EMF is induced into the conductor. The magnitude of the induced EMF depends on the field strength and the rate at which the flux lines are cut, as given in equation (5-1). The stronger the field or the more flux lines cut for a given period of time, the larger the induced EMF.

$$E_g = K\Phi N \qquad\qquad\qquad (5\text{-}1)$$

where

  E_g = generated voltage
  K = fixed constant
  Φ = magnetic flux strength
  N = speed in RPM

The direction of the induced current flow can be determined using the "left-hand rule" for generators. This rule states that if you point the index finger of your left hand in the direction of the magnetic field (from North to South) and point the thumb in the direction of motion of the conductor, the middle finger will point in the direction of current flow (Figure 4). In the generator shown in Figure 4, for example, the conductor closest to the N pole is traveling upward across the field; therefore, the current flow is to the right, lower corner. Applying the left-hand rule to both sides of the loop will show that current flows in a counter-clockwise direction in the loop.
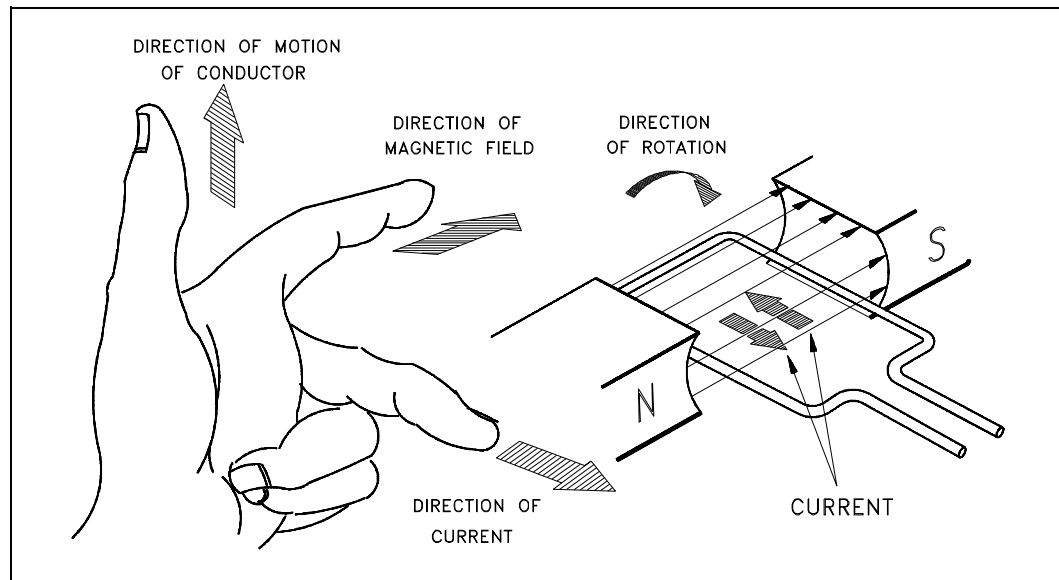
Figure 4 Left-Hand Rule for Generators

Commutator Action

The commutator converts the AC voltage generated in the rotating loop into a DC voltage. It also serves as a means of connecting the brushes to the rotating loop. The purpose of the brushes is to connect the generated voltage to an external circuit. In order to do this, each brush must make contact with one of the ends of the loop. Since the loop or armature rotates, a direct connection is impractical. Instead, the brushes are connected to the ends of the loop through the commutator.

Brush   Conducting Material   Insulating Material   Brush

The commutator is essentially two semicylindrical metal pieces separated by an insulating material.

The brushes are made of soft, conducting material that slides easily on the commutator.
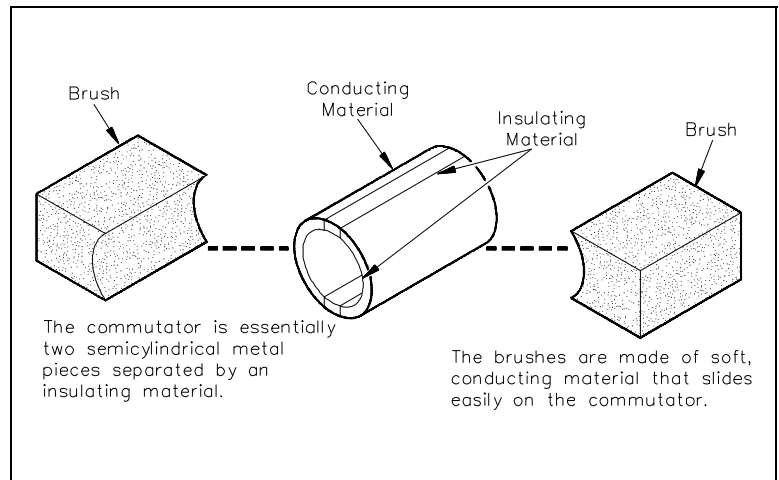
Figure 5 Commutator Segments and Brushes

In a simple one-loop generator, the commutator is made up of two semicylindrical pieces of a smooth conducting material, usually copper, separated by an insulating material, as shown in Figure 5. Each half of the commutator segments is permanently attached to one end of the rotating loop, and the commutator rotates with the loop. The brushes, usually made of carbon, rest against the commutator and slide along the commutator as it rotates. This is the means by which the brushes make contact with each end of the loop.

Each brush slides along one half of the commutator and then along the other half. The brushes are positioned on opposite sides of the commutator; they will pass from one commutator half to the other at the instant the loop reaches the point of rotation, at which point the voltage that was induced reverses the polarity. Every time the ends of the loop reverse polarity, the brushes switch from one commutator segment to the next. This means that one brush is always positive with respect to another. The voltage between the brushes fluctuates in amplitude (size or magnitude) between zero and some maximum value, but is always of the same polarity (Figure 6). In this manner, commutation is accomplished in a DC generator.
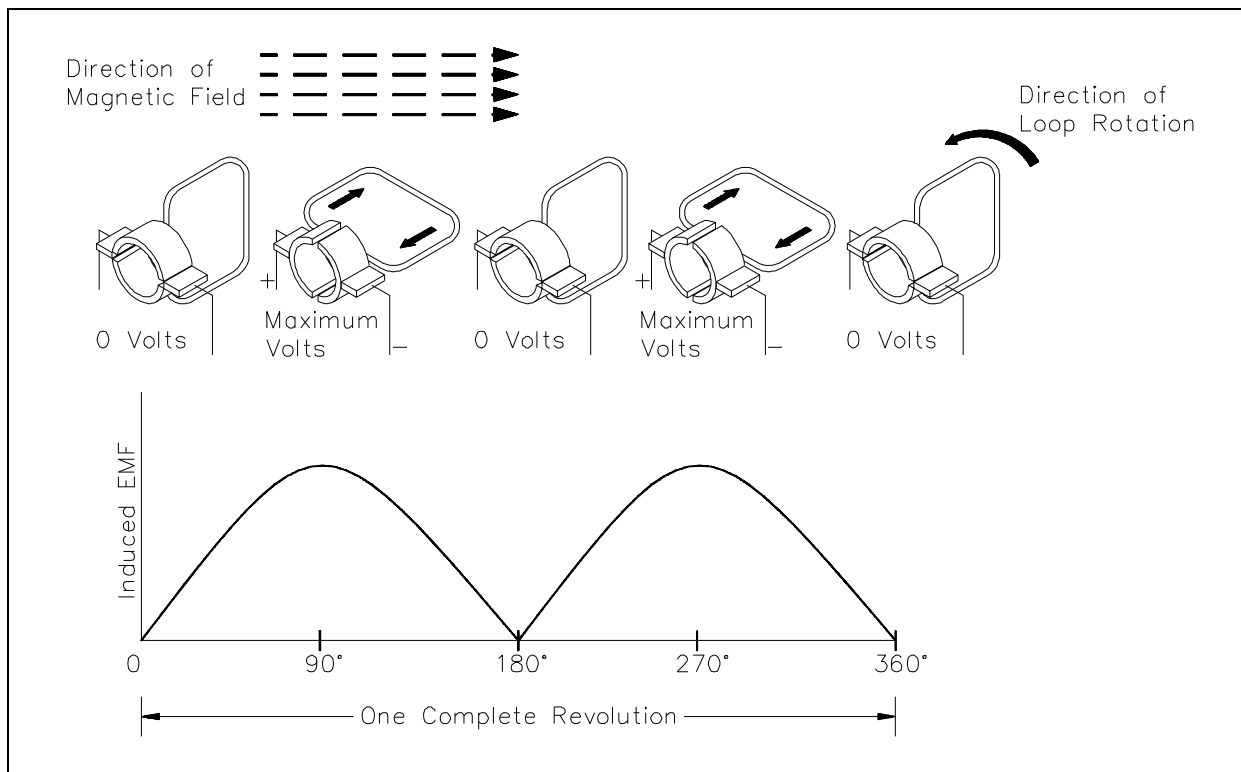
Figure 6 Commutation in a DC Generator

One important point to note is that, as the brushes pass from one segment to the other, there is an instant when the brushes contact both segments at the same time. The induced voltage at this point is zero. If the induced voltage at this point were not zero, extremely high currents would be produced due to the brushes shorting the ends of the loop together. The point at which the brushes contact both commutator segments, when the induced voltage is zero, is called the "neutral plane."

Field Excitation

The magnetic fields in DC generators are most commonly provided by electromagnets. A current must flow through the electromagnet conductors to produce a magnetic field. In order for a DC generator to operate properly, the magnetic field must always be in the same direction. Therefore, the current through the field winding must be direct current. This current is known as the *field excitation current* and can be supplied to the field winding in one of two ways. It can come from a separate DC source external to the generator (e.g., a separately excited generator) or it can come directly from the output of the generator, in which case it is called a *self-excited generator*.

In a self-excited generator, the field winding is connected directly to the generator output. The field may be connected in series with the output, in parallel with the output, or a combination of the two.

Separate excitation requires an external source, such as a battery or another DC source. It is generally more expensive than a self-excited generator. Separately excited generators are, therefore, used only where self-excitation is not satisfactory. They would be used in cases where the generator must respond quickly to an external control source or where the generated voltage must be varied over a wide range during normal operations.

Terminal Voltage

DC generator output voltage is dependent on three factors (recall equation 5-1): (1) the number of conductor loops in series in the armature, (2) armature speed, and (3) magnetic field strength. In order to change the generator output, one of these three factors must be varied. The number of conductors in the armature cannot be changed in a normally operating generator, and it is usually impractical to change the speed at which the armature rotates. The strength of the magnetic field, however, can be changed quite easily by varying

Figure 7 Varying Generator Terminal Voltage

the current through the field winding. This is the most widely used method for regulating the output voltage of a DC generator (Figure 7).
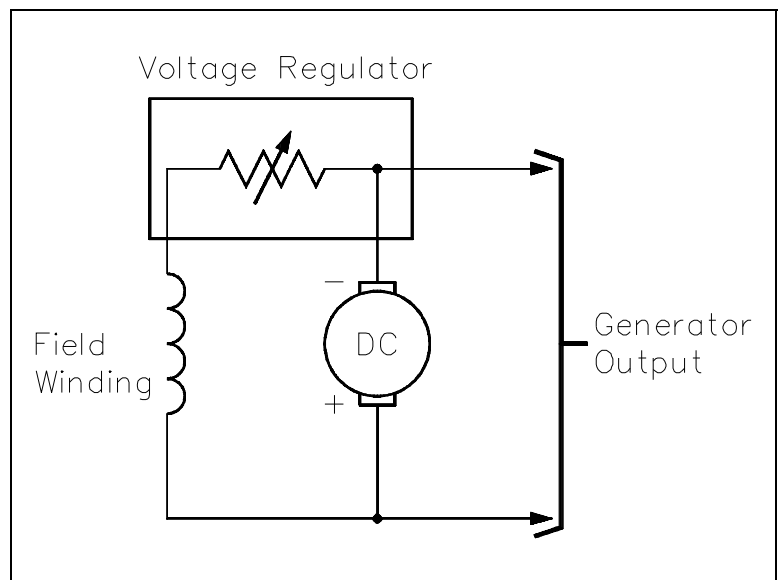
DC Generator Ratings

A DC generator contains four ratings.

Voltage: Voltage rating of a machine is based on the insulation type and design of the machine.

Current: The current rating is based on the size of the conductor and the amount of heat that can be dissipated in the generator.

Power: The power rating is based on the mechanical limitations of the device that is used to turn the generator and on the thermal limits of conductors, bearings, and other components of the generator.

Speed: Speed rating, at the upper limit, is determined by the speed at which mechanical damage is done to the machine. The lower speed rating is based on the limit for field current (as speed increases, a higher field current is necessary to produce the same voltage).

Internal Losses

There are four internal losses that contribute to lower efficiency of a DC generator.

- Copper losses
- Eddy-current losses
- Hysteresis losses
- Mechanical losses

Each of these is described in the paragraphs that follow.

Copper Losses

Copper loss is the power lost as heat in the windings; it is caused by the flow of current through the coils of the DC armature or DC field. This loss varies directly with the square of the current in the armature or field and the resistance of the armature or field coils.

Armature: $I_a^2 R_a$
Field: $I_f^2 R_f$

Eddy-Current Losses

As the armature rotates within the field, it cuts the lines of flux at the same time that the copper coils of wire that are wound on the armature cut the lines of flux. Since the armature is made of iron, an EMF is induced in the iron, which causes a current to flow. These circulating currents within the iron core are called *eddy-currents*.

To reduce eddy-currents, the armature and field cores are constructed from laminated (layered) steel sheets. The laminated sheets are insulated from one another so that current cannot flow from one sheet to the other.

Hysteresis Losses

Hysteresis losses occur when the armature rotates in a magnetic field. The magnetic domains of the armature are held in alignment with the field in varying numbers, dependent upon field strength. The magnetic domains rotate, with respect to the particles not held in alignment, by one complete turn during each rotation of the armature. This rotation of magnetic domains in the iron causes friction and heat. The heat produced by this friction is called magnetic hysteresis loss.

To reduce hysteresis losses, most DC armatures are constructed of heat-treated silicon steel, which has an inherently low hysteresis loss. After the heat-treated silicon steel is formed to the desired shape, the laminations are heated to a dull red and then allowed to cool. This process, known as annealing, reduces hysteresis losses to a very low value.

Mechanical Losses

Rotational or *mechanical losses* can be caused by bearing friction, brush friction on the commutator, or air friction (called windage), which is caused by the air turbulence due to armature rotation. Careful maintenance can be instrumental in keeping bearing friction to a minimum. Clean bearings and proper lubrication are essential to the reduction of bearing friction. Brush friction is reduced by assuring proper brush seating, using proper brushes, and maintaining proper brush tension. A smooth and clean commutator also aids in the reduction of brush friction.

Summary

DC generator theory is summarized below.

DC Generator Theory Summary

- The three conditions necessary to induce a voltage into a conductor are:
  - Magnetic field
  - Conductor
  - Relative motion between the two

- The left-hand rule states that if you point the index finger of the left hand in the direction of the magnetic field and point the thumb in the direction of motion of the conductor, the middle finger will point in the direction of current flow.

- The terminal voltage of a DC generator is adjusted by varying the field strength.
- The voltage rating of a DC generator is based on the insulation type and design of the machine.

- The current rating of a DC generator is based on the size of the conductor and the amount of heat that can be dissipated in the generator.

- The power rating of a DC generator is based on the mechanical limitation of the device that is used to turn the generator.

- The upper speed rating of a DC generator is determined by the speed at which mechanical damage is done to the machine. The lower speed rating is based on the limit for field current.

- There are four internal losses that contribute to lower efficiency of a DC generator.
  - Copper losses
  - Eddy-current losses
  - Hysteresis losses
  - Mechanical losses

DC GENERATOR CONSTRUCTION

A DC generator may be constructed in a variety of ways depending upon the relationship and location of each of the fields. Each type of construction contains certain advantages.

EO 1.10   **DESCRIBE the differences in construction between a shunt-wound and a series-wound DC generator with respect to the relationship between the field and the armature.**

EO 1.11   **DESCRIBE the relationship between the shunt and series fields for cumulatively-compounded and differentially-compounded DC generators.**

EO 1.12   **DESCRIBE the voltage-vs-load current characteristics for a flat-compounded, over-compounded, and under-compounded DC generator.**

<u>Shunt-Wound DC Generators</u>

When the field winding of a generator is connected in parallel with the generator armature, the generator is called a shunt-wound generator (Figure 8).

The excitation current in a shunt-wound generator is dependent upon the output voltage and the field resistance. Normally, field excitation is maintained between 0.5 and 5 percent of the total current output of the generator.
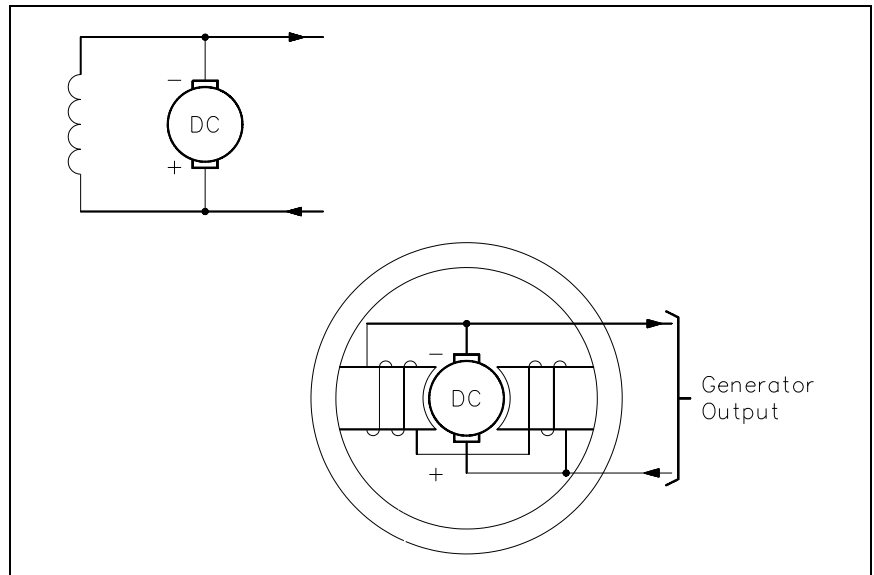

Figure 8 Shunt-Wound DC Generator

The shunt-wound generator, running at a constant speed under varying load conditions, has a much more stable voltage output than does a series-wound generator. Some change in output voltage does take place. This change is caused by the fact that, as the load current increases, the voltage drop (I_aR_a) across the armature coil increases, causing output voltage to decrease. As a result, the current through the field decreases, reducing the magnetic field and causing voltage to decrease even more. If load current is much higher than the design of the generator, the drop in output voltage is severe. For load current within the design range of the generator, the drop in output voltage is minimal (Figure 9).
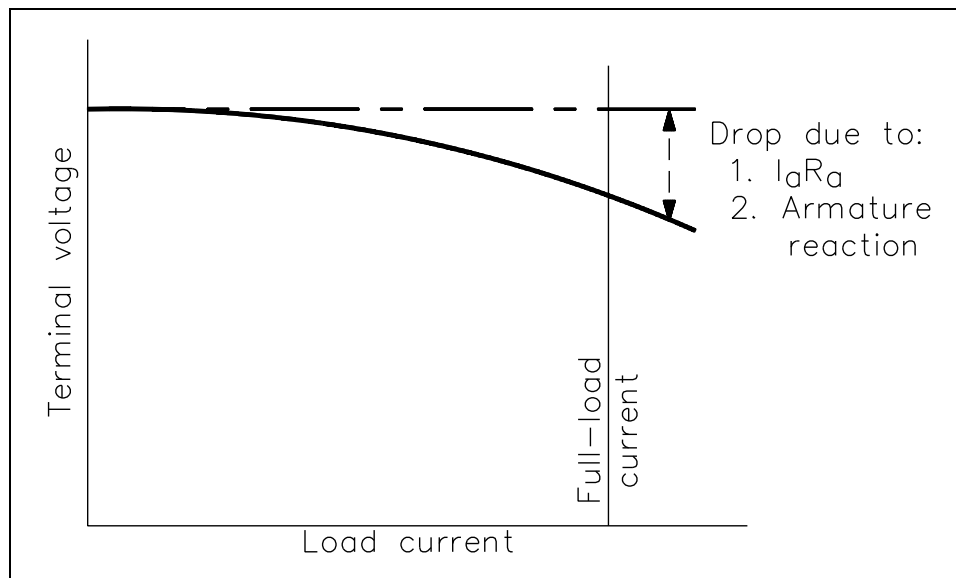

Figure 9 Output Voltage-vs-Load Current for Shunt-Wound DC Generator

Series-Wound
DC Generators

When the field winding of a DC generator is connected in series with the armature, the generator is called a series-wound generator (Figure 10).

The excitation current in a series-wound generator is the same as the current the generator delivers to the load. If the load has a high resistance and only draws a small amount of current, the excitation current is also small. Therefore, the magnetic field of the series field winding is weak, making the generated voltage low.

Figure 10 Series-Wound DC Generator

Conversely, if the load draws a large current, the excitation current is also high. Therefore, the magnetic field of the series field winding is very strong, and the generated voltage is high.
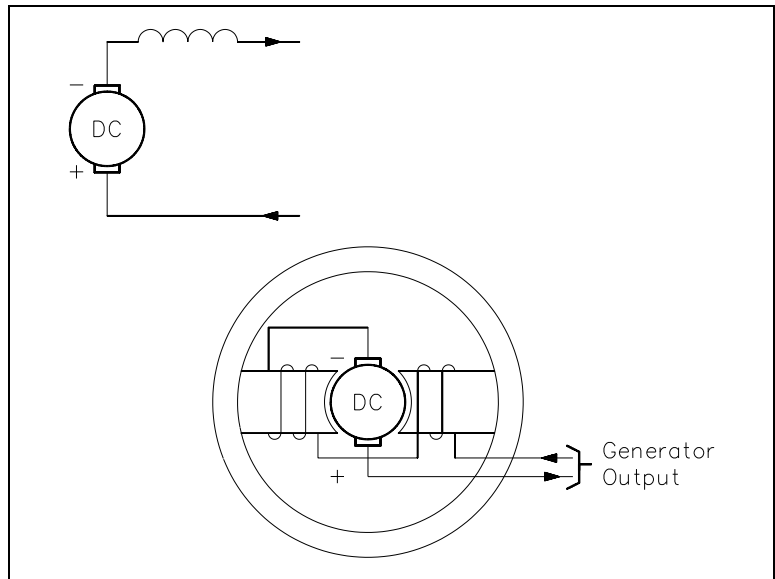
As you can see in Figure 11, in a series generator, changes in load current drastically affect the generator output voltage. A series generator has poor voltage regulation, and, as a result, series generators are not used for fluctuating loads. As is the case for the shunt-wound generator, a series-wound generator also exhibits some losses due to the resistance of the windings and armature reaction. These losses cause a lower terminal voltage than that for an ideal magnetization curve.

Figure 11 Output Voltage-vs-Load Current for Series-Wound DC Generator

Compound Generators

Series-wound and shunt-wound generators have a disadvantage in that changes in load current cause changes in generator output voltage. Many applications in which generators are used require a more stable output voltage than can be supplied by a series-wound or shunt-wound generator. One means of supplying a stable output voltage is by using a compound generator.

The compound generator has a field winding in parallel with the generator armature (the same as a shunt-wound generator) and a field

Figure 12 Compounded DC Generator

winding in series with the generator armature (the same as a series-wound generator) (Figure 12).

The two windings of the compounded generator are made such that their magnetic fields will either aid or oppose one another.

If the two fields are wound so that their flux fields oppose one another, the generator is said to be *differentially-compounded*. Due to the nature of this type of generator, it is used only in special cases and will not be discussed further in this text.

If the two fields of a compound generator are wound so that their magnetic fields aid one another, the generator is said to be *cumulatively-compounded*. As the load current increases, the current through the series field winding increases, increasing the overall magnetic field strength and causing an increase in the output voltage of the generator. With proper design, the increase in the magnetic field strength of the series winding will compensate for the decrease in shunt field strength. Therefore, the overall strength of the combined magnetic fields remains almost unchanged, so the output voltage will remain constant. In reality, the two fields cannot be made so that their magnetic field strengths compensate for each other completely. There will be some change in output voltage from the no-load to full-load conditions.
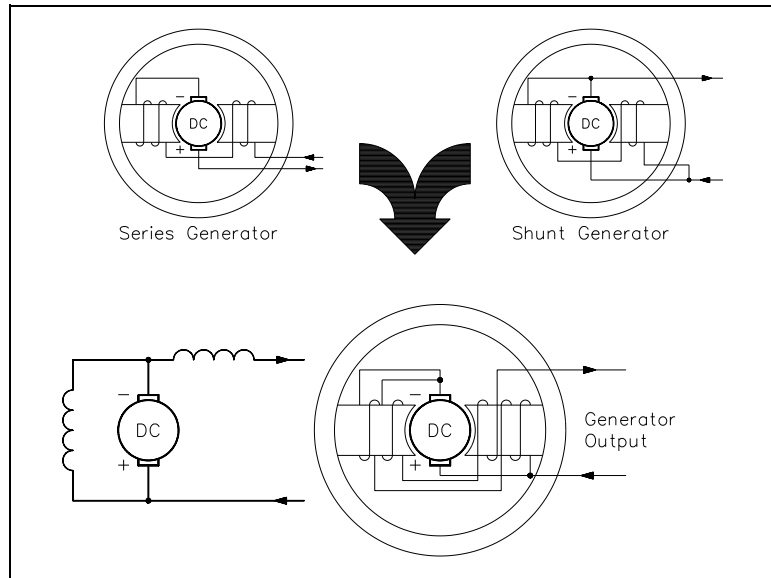
In practical compounded generators, the change in output voltage from no-load to full-load is less than 5 percent. A generator with this characteristic is said to be *flat-compounded* (Figure 13).
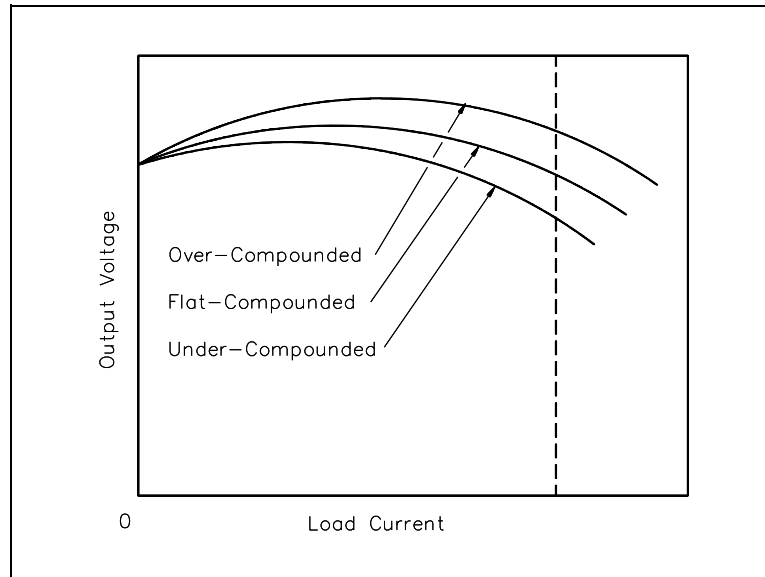
Figure 13 Voltage-vs-Current for a Compounded DC Generator

For some applications, the series winding is wound so that it overcompensates for a change in the shunt field. The output gradually rises with increasing load current over the normal operating range of the machine. This type of generator is called an *over-compounded* generator. The series winding can also be wound so that it undercompensates for the change in shunt field strength. The output voltage decreases gradually with an increase in load current. This type of generator is called an *under-compounded* generator.

<u>Summary</u>

DC generator construction is summarized below.

DC Generator Construction Summary

- A shunt-wound DC generator is constructed so that the field winding is in parallel with the armature winding.

- The voltage of a shunt-wound DC generator decreases with an increase in load current.

- A series-wound DC generator is constructed so that the field winding is in series with the armature winding.

- The voltage of a series-wound DC generator increases sharply with an increase in load.

- In a cumulatively-compounded DC generator, the series and shunt fields aid one another.

- In a differentially-compounded DC generator, the series and shunt fields oppose one another.

- The voltage of a flat-compounded DC generator changes less than 5 percent from no-load to full-load.

- The voltage of an over-compounded DC generator gradually rises with an increasing load.

PART 4: DC MOTORS - TABLE OF CONTENTS

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DC MOTOR THEORY

DC motors are widely used to drive various equipment. The speed and torque produced in a DC motor depends on a variety of factors.

EO 1.1   **Using the right-hand rule for motors, DETERMINE the direction of the magnetic field, direction of current flow, or force on a conductor.**

EO 1.2   **STATE the function of torque in a direct current motor and how it is developed.**

EO 1.3   **DESCRIBE how Counterelectromotive Force (CEMF) is developed in a DC motor.**

EO 1.4   **DESCRIBE the relationship between field current and magnetic field size in a DC motor.**

EO 1.5   **STATE the function of the CEMF that is developed in a DC motor.**

EO 1.6   **DESCRIBE how the speed of a DC motor is adjusted.**

EO 1.7   **DESCRIBE the relationship between armature current and torque produced in a DC motor.**

Inducing a Force on a Conductor

There are two conditions which are necessary to produce a force on a conductor.

- The conductor must be carrying current.

- The conductor must be within a magnetic field.

When these two conditions exist, a force will be applied to the conductor, which will attempt to move the conductor in a direction perpendicular to the magnetic field. This is the basic theory by which all DC motors operate.

Theory of Operation

Every current-carrying conductor has a magnetic field around it. The direction of this magnetic field may be found by using the left-hand rule for current-carrying conductors. When the thumb points in the direction of current flow, the fingers will point in the direction of the magnetic field produced, as shown in Figure 1.

If a current-carrying conductor is placed in a magnetic field, the combined fields will be similar to those shown in Figure 2. The direction of current flow through the conductor is indicated with an "x" or a "·". The "x" indicates the current flow is away from the reader, or into the page. The "·" indicates the current flow is towards the reader, or out of the page.
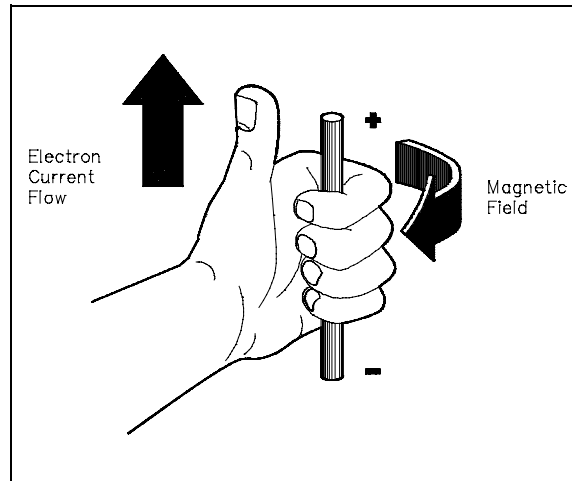
Figure 1 Left-Hand Rule for Current-Carrying Conductors
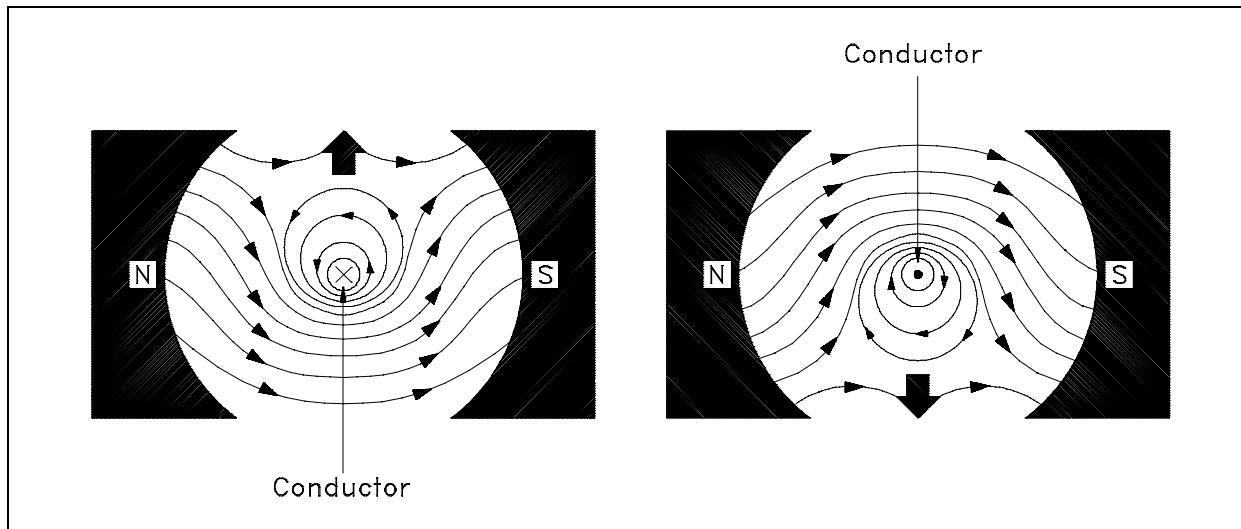
Figure 2 Current-Carrying Conductor in a Magnetic Field

Above the conductor on the left, the field caused by the conductor is in the opposite direction of the main field, and therefore, opposes the main field. Below the conductor on the left, the field caused by the conductor is in the same direction as the main field, and therefore, aids the main field. The net result is that above the conductor the main field is weakened, or flux density is decreased; below the conductor the field is strengthened, or flux density is increased. A force is developed on the conductor that moves the conductor in the direction of the weakened field (upward).

Above the conductor on the right, the field caused by the conductor is in the same direction as the main field, and therefore, aids the main field. Below the conductor on the right, the field caused by the conductor is in the opposite direction of the main field, and therefore, opposes the main field. The net result is that above the conductor the field is strengthened, or flux density is increased, and below the conductor, the field is weakened, or flux density is decreased. A force is developed on the conductor that moves the conductor in the direction of the weakened field (downward).
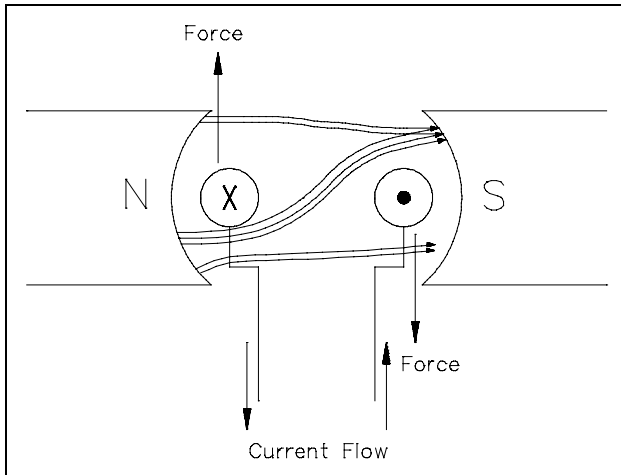

Figure 3   Motor Action

In a DC motor, the conductor will be formed in a loop such that two parts of the conductor are in the magnetic field at the same time, as shown in Figure 3.

This combines the effects of both conductors to distort the main magnetic field and produce a force on each part of the conductor. When the conductor is placed on a rotor, the force exerted on the conductors will cause the rotor to rotate clockwise, as shown on Figure 3.

You can think of these magnetic lines of force as rubber bands that are always trying to shorten themselves. The lines of force above the conductor exert a downward force due to the magnetic lines of force trying to straighten themselves.

The above explanation of how a force is developed is convenient; however, it is somewhat artificial. It is based on a fundamental principle of physics which may be stated as follows:

"A current-carrying conductor in a magnetic field tends to move at right angles to that field."

Another important way to show the relationship between the current-carrying conductor, magnetic field, and motion, is the right-hand rule for motors, as shown in Figure 4.
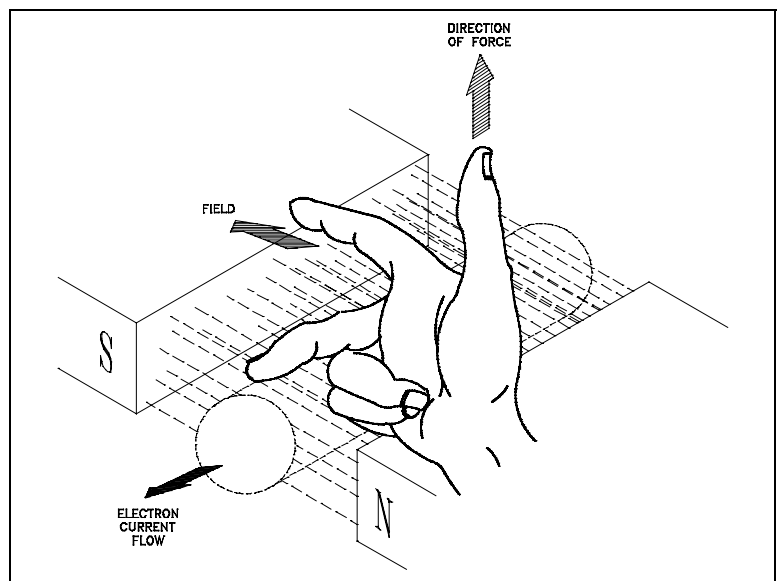

Figure 4 Right-Hand Rule for Motors

The right-hand rule for motors shows the direction in which a current-carrying conductor moves in a magnetic field. When the forefinger is pointed in the direction of the magnetic field lines, and the center finger is pointed in the direction of current flow, the thumb will point in the direction of force (motion).

Torque

Torque is defined as that force which tends to produce and maintain rotation. The function of torque in a DC motor is to provide the mechanical output or drive the piece of equipment that the DC motor is attached to.

When a voltage is applied to a motor, current will flow through the field winding, establishing a magnetic field. Current will also flow through the armature winding, from the negative brush to the positive brush as shown in Figure 5.

Since the armature is a current-carrying conductor in a magnetic field, the conductor has a force exerted on it, tending to move it at right angles to that field. Using the left-hand rule for current-carrying conductors, you will see that the magnetic field on one side is strengthened at the bottom, while it is weakened on the other side. Using the right-hand rule for

Figure 5 Armature Current in a Basic DC Motor

motors, we can see that there is a force exerted on the armature which tends to turn the armature in the counter-clockwise direction. The sum of the forces, in pounds, multiplied by the radius of the armature, in feet, is equal to the torque developed by the motor in pound-feet (1b - ft).

It is evident from Figure 5 that if the armature current were reversed, but the field were the same, torque would be developed in the opposite direction. Likewise, if the field polarity were reversed and the armature remained the same, torque would also be developed in the opposite direction.

The force that is developed on a conductor of a motor armature is due to the combined action of the magnetic fields. The force developed is directly proportional to the strength of the main field flux and the strength of the field around the armature conductor. As we know, the field strength around each armature conductor depends on the amount of current flowing through the armature conductor. Therefore, the torque which is developed by the motor can be determined using Equation (6-1).
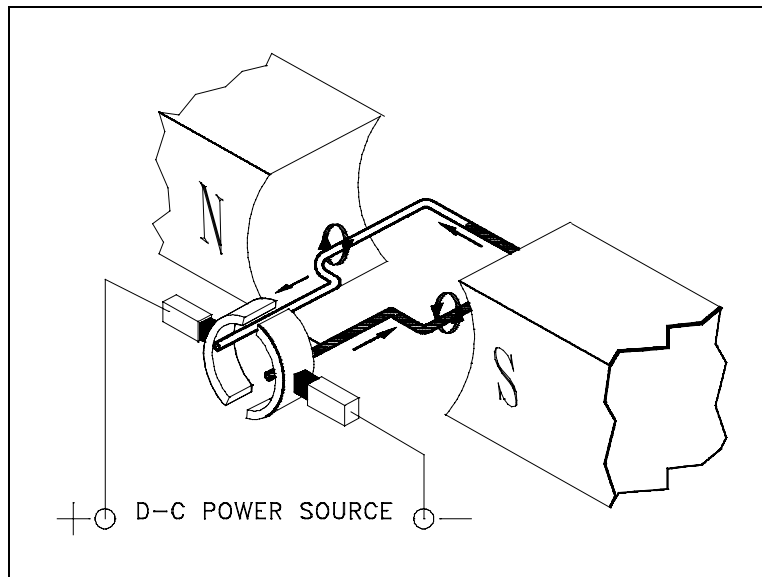
$$T = K\Phi I_a \tag{6-1}$$

where

- T = torque, lb-ft
- K = a constant depending on physical size of motor
- Φ = field flux, number of lines of force per pole
- I_a = armature current

Generator Action in a Motor

A generator action is developed in every motor. When a conductor cuts lines of force, an EMF is induced in that conductor.

Current to start the armature turning will flow in the direction determined by the applied DC power source. After rotation starts, the conductor cuts lines of force. By applying the left-hand rule for generators, the EMF that is induced in the armature will produce a current in the opposite direction. The induced EMF, as a result of motor operation, is called counterelectromotive force, or CEMF, as illustrated in Figure 6.
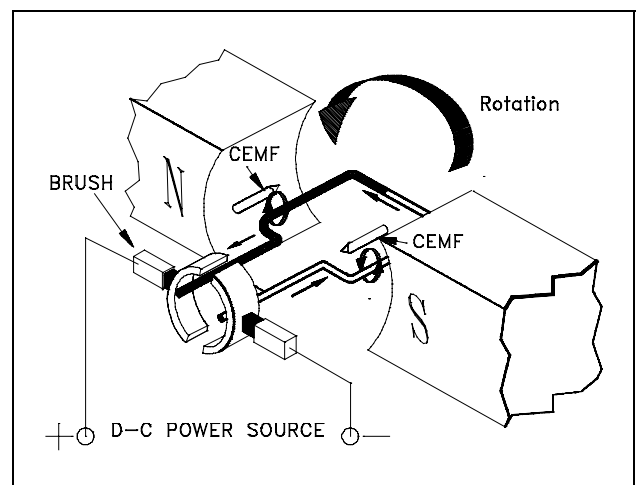
Figure 6   Counterelectromotive Force (CEMF)

Since the CEMF is generated by the action of the armature cutting lines of force, the value of CEMF will depend on field strength and armature speed, as shown in Equation (6-2).

$$E_{CEMF} = K\Phi N \tag{6-2}$$

where

- E_{CEMF} = counter EMF
- K = constant
- Φ = field flux strength
- N = speed of the armature

The CEMF opposes the applied voltage and functions to lower armature current. The effective voltage acting in the armature of a motor is the applied voltage, minus the counter EMF. Armature current can be found by using Ohm's law, as shown in Equation (6-3).

$$I_a = \frac{E_t - E_{CEMF}}{R_a} \qquad (6\text{-}3)$$

where

I_a	= armature current
E_t	= terminal voltage
E_{CEMF}	= counter EMF
R_a	= armature resistance

DC Motor Speed

The field of a DC motor is varied using external devices, usually field resistors. For a constant applied voltage to the field (E), as the resistance of the field (R_f) is lowered, the amount of current flow through the field (I_f) increases as shown by Ohm's law in Equation (6-4).

$$\uparrow I_f = \frac{\overset{\leftrightarrow}{E}}{\underset{\downarrow}{R_f}} \qquad (6\text{-}4)$$

An increase in field current will cause field flux (Φ_f) to increase. Conversely, if the resistance of the field is increased, field flux will decrease. If the field flux of a DC motor is decreased, the motor speed will increase. The reduction of field strength reduces the CEMF of the motor, since fewer lines of flux are being cut by the armature conductors, as shown in Equation (6-5).

$$\downarrow E_{CEMF} = \overset{\rightarrow \quad \downarrow \quad \rightarrow}{K \, \Phi_F \, N} \qquad (6\text{-}5)$$

A reduction of counter EMF allows an increase in armature current as shown in Equation (6-6).

$$\uparrow I_a = \frac{\overset{\rightarrow}{E_t} - \overset{\downarrow}{E_{CEMF}}}{\underset{\rightarrow}{R_a}} \qquad (6\text{-}6)$$

This increase in armature current causes a larger torque to be developed; the increase in armature current more than offsets the decrease in field flux as shown in Equation (6-7).

$$\uparrow T = \overset{\rightarrow \quad \downarrow \quad \uparrow}{K \, \Phi_F \, I_a} \qquad (6\text{-}7)$$

This increased torque causes the motor to increase in speed.

$$\uparrow T \propto N \uparrow$$

This increase in speed will then proportionately increase the CEMF. The speed and CEMF will continue to increase until the armature current and torque are reduced to values just large enough to supply the load at a new constant speed.

Summary

DC motor theory is summarized below.

DC Motor Theory Summary

- There are two conditions necessary to produce a force on a conductor:

    - The conductor must be carrying current.
    - The conductor must be within a magnetic field.

- The right-hand rule for motors states that when the forefinger is pointed in the direction of the magnetic field lines, and the center finger is pointed in the direction of current flow, the thumb will point in the direction of motion.

- The function of torque in a DC motor is to provide the mechanical output to drive the piece of equipment that the DC motor is attached to.

- Torque is developed in a DC motor by the armature (current-carrying conductor) being present in the motor field (magnetic field).

- CEMF is developed in a DC motor by the armature (conductor) rotating (relative motion) in the field of the motor (magnetic field).

- The function of the voltage that is developed in a DC motor (CEMF) opposes the applied voltage and results in the lowering of armature current.

- The speed of a DC motor may be changed by using resistors to vary the field current and, therefore, the field strength.

TYPES OF DC MOTORS

There are various types of DC motors found in industry today. Each type contains various characteristics that makes it desirable for certain applications.

EO 1.8   **DESCRIBE the differences in construction between a shunt-wound and a series-wound DC motor with respect to the relationship between the field and the armature windings.**

EO 1.9   **DESCRIBE the construction of a compounded DC motor.**

EO 1.10   **DESCRIBE the torque-vs-speed characteristics for a shunt-wound and a series-wound DC motor.**

DC Motor Connections

Figure 7 shows schematically the different methods of connecting the field and armature circuits in a DC motor. The circular symbol represents the armature circuit, and the squares at the side of the circle represent the brush commutator system. The direction of the arrows indicates the direction of the magnetic fields.
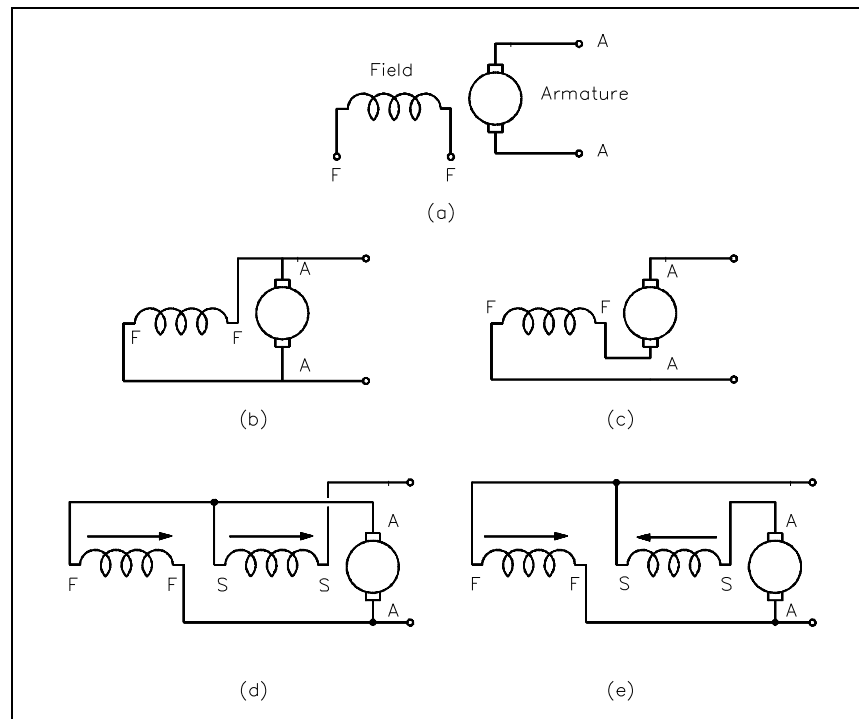

Figure 7 DC Motor Connections

- Figure 7a shows an externally-excited DC motor. This type of DC motor is constructed such that the field is not connected to the armature. This type of DC motor is not normally used.

- Figure 7b shows a shunt DC motor. The motor is called a "shunt" motor because the field is in parallel, or "shunts" the armature.

- Figure 7c shows a series DC motor. The motor field windings for a series motor are in series with the armature.

- Figures 7d and 7e show a compounded DC motor. A compounded DC motor is constructed so that it contains both a shunt and a series field. Figure 7d is called a "cumulatively-compounded" DC motor because the shunt and series fields are aiding one another. Figure 7e is called a "differentially-compounded" DC motor because the shunt and series field oppose one another.

Shunt-Wound Motor Operation

The speed-torque relationship for a typical shunt-wound motor is shown in Figure 8.

A shunt-wound DC motor has a decreasing torque when speed increases. The decreasing torque-vs-speed is caused by the armature resistance voltage drop and armature reaction. At a value of speed near 2.5 times the rated speed, armature reaction becomes excessive, causing a rapid decrease in field flux, and a rapid decline in torque until a stall condition is reached.

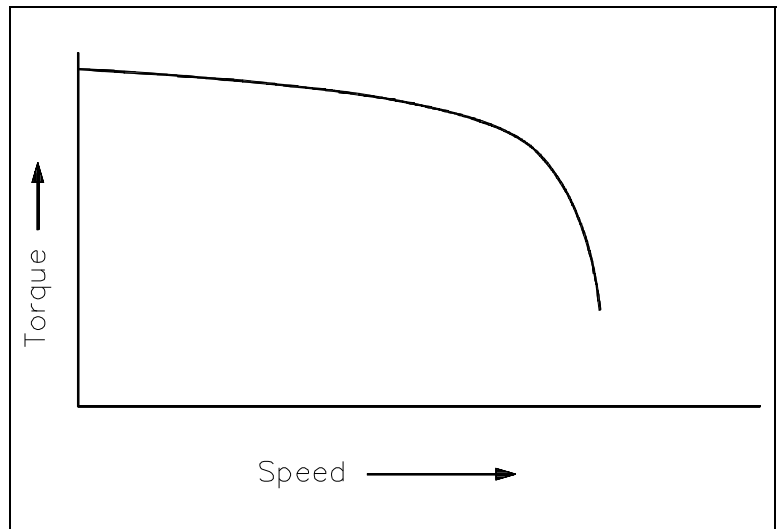Figure 8 Torque-vs-Speed for a Shunt-Wound DC Motor

Shunt-Wound Motor Applications

The characteristics of a shunt-wound motor give it very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as load is increased. Shunt-wound motors are used in industrial and automotive applications where precise control of speed and torque are required.

Series-Wound Motor

Since the armature and field in a series-wound motor are connected in series, the armature and field currents become identical, and the torque can be expressed as shown in Equation (6-8).

$$T = KI_a^2 \qquad (6\text{-}8)$$

The torque-vs-speed characteristics of a series-wound motor with a constant voltage source are shown in Figure 9. As the speed decreases, the torque for a series-

Figure 9 Torque-vs-Speed for a Series-Wound Motor

wound motor increases sharply. As load is removed from a series motor, the speed will increase sharply. For these reasons, series-wound motors must have a load connected to prevent damage from high speed conditions.
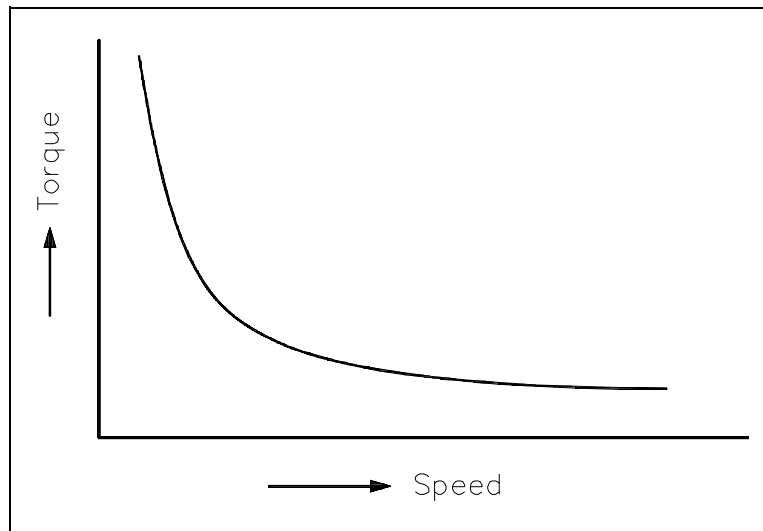
Series-Wound Motor Applications

The advantage of a series-wound motor is that it develops a large torque and can be operated at low speed. It is a motor that is well-suited for starting heavy loads; it is often used for industrial cranes and winches where very heavy loads must be moved slowly and lighter loads moved more rapidly.

Compounded Motor

The compounded motor is desirable for a variety of applications because it combines the characteristics of a series-wound motor and a shunt-wound motor. The compounded motor has a greater torque than a shunt motor due to the series field; however, it has a fairly constant speed due to the shunt field winding. Loads such as presses, shears, and reciprocating machines are often driven by compounded motors.

Summary

The types of DC motors are summarized below.

Types of DC Motors Summary

- In a shunt-wound motor, the field is in parallel, or "shunts" the armature.

- In a series-wound motor, the field is in series with the armature.

- A compounded DC motor is constructed so that it contains both a shunt and a series field.

- A shunt-wound DC motor has a decreasing torque as speed increases.

- The characteristics of a shunt-wound motor give it very good speed regulation, and it is classified as a constant speed motor, even though the speed does slightly decrease as load is increased.

- A series-wound motor has a rapidly increasing torque when speed decreases. As load is removed from a series-wound motor, the speed will increase sharply.
- The advantages of a series-wound motor are that it develops a large torque and can be operated at low speed. It is a motor that is well-suited for starting heavy loads.

DC MOTOR OPERATION

DC motors require special starting resistors for operation due to their unique design. A knowledge of the operation of these starting resistors is necessary to understand DC motor operation.

EO 1.11   **EXPLAIN why starting resistors are necessary for large DC motors.**

EO 1.12   **LIST the four nameplate ratings for a DC motor.**

Starting of DC Motors

At the moment a DC motor is started the armature is stationary and there is no counter EMF being generated. The only component to limit starting current is the armature resistance, which, in most DC motors is a very low value (approximately one ohm or less), as shown in Equation (6-9).

$$I_a = \frac{E_t - E_{CEMF}}{R_a}$$

(6-9)

In order to reduce this very high starting current, an external resistance must be placed in series with the armature during the starting period. To show why this is essential, let us consider a 10-hp motor with an armature resistance of 0.4 ohms. If the motor were supplied by a 260 VDC source, the resulting current would be as shown in Equation (6-9).

$$I_a = \frac{E_t - E_{CEMF}}{R_a}$$

$$I_a = \frac{260 \, VDC - 0}{0.4 \, \Omega}$$

$$I_a = 650 \; amps$$

This large current is approximately twelve times greater than actual full-load current for this motor. This high current would, in all probability, cause severe damage to the brushes, commutator, or windings. Starting resistors are usually incorporated into the motor design to limit starting current to 125 to 200 percent of full load current.

The amount of starting resistance necessary to limit starting current to a more desirable value is calculated using Equation (6-10.

$$R_s = \frac{E_t}{I_s} - R_a \qquad (6\text{-}10)$$

where

R_s = starting resistance
E_t = terminal voltage
I_s = desired armature starting current
R_a = armature resistance

Example: If the full load current of the motor mentioned previously is 50 amps, and it is desired to limit starting current to 125% of this value, find the required resistance that must be added in series with the armature.

$$R_s = \frac{E_t}{I_s} - R_a$$

$$R_s = \frac{260\,\text{VDC}}{125\%(50\ \text{amps})} - 0.4\Omega$$

$$R_s = 3.76\,\Omega$$

The starting resistors are used in a DC motor by placing them in the starting circuit of the motor controller that is used to start the DC motor. Starting resistors are normally of variable resistances, with the value of resistance in the circuit at any time being either manually or automatically controlled. The maximum amount of resistance will always be inserted when the motor is first started. As the speed of the motor increases, counter EMF will begin to increase, decreasing armature current. The starting resistors may then be cut out, in successive steps, until the motor reaches full running speed.

DC Motor Ratings

The nameplate ratings of a DC motor refer to the conditions of voltage, current, speed, and power at which the motor is normally operated. The principal rating is known as the *continuous* rating, which is the rating described on the nameplate of a motor. The continuous power rating is a thermal rating. At this power, the motor can be operated for long periods of time without a large rise in temperature and beyond the limits of the conductor insulating material, bearings and other components, which are greatly affected by temperature.

The speed rating of a DC motor is often given on the nameplate. This speed is the upper limit at which a motor can be operated without mechanical damage occurring.

Summary

DC motor operation is summarized below.

DC Motor Operation Summary

•   Starting resistors are necessary for large DC motors to prevent damage due to high currents while starting the motor.

•   Starting resistors are placed in the starting circuits for the controllers that start the motor. When the motor reaches full speed, the starting resistors are cut out of the circuit.

•   The four nameplate ratings for a DC motor include:

- voltage
- current
- speed
- power