Chapter 6

Alternating Current Power Systems

Some of the basics of *alternating current (AC) power systems* were discussed in Chapter 2. You should already have an understanding of the effects of resistance, inductance, and capacitance in AC circuits. Therefore, this chapter will deal primarily with the systems that are used to *produce* AC electrical power.

The vast majority of the electrical power produced in the United States is *alternating current.* Massive mechanical generators at power plants throughout our country provide the necessary electrical power to supply our homes and industries. Most generators produce *three-phase* alternating current; however, *single-phase* generators are also used for certain applications of a smaller nature. The operation of mechanical generators relies upon a fundamental principle of electricity called *electromagnetic induction.*

IMPORTANT TERMS

Chapter 6 deals with AC power systems. After studying this chapter, you should have an understanding of the following terms:

Electromagnetic Induction
Faraday's Law
Left-Hand Rule of Generation
Single-Phase AC Voltage
Generator
Stator
Rotor
Field Pole
Prime Mover

Slip Ring/Brush Assembly
AC Sine Wave
Single-Phase AC Generator
Rotating-Armature Method
Rotating-Field Method
Three-Phase AC Generator
Three-Phase Wye Connection
Three-Phase Delta Connection
High-Speed Generator
Low-Speed Generator
Frequency
Harmonics
Voltage Regulation
Efficiency

ELECTROMAGNETIC INDUCTION

The basic principle that allows electrical power to be produced by alternators was discovered in the early 1800s by Michael Faraday, an English scientist. *Faraday's Law* is the basis of electrical power production. The principle of *electromagnetic induction* was one of the most important discoveries in the development of modern technology. Without electrical power, our lives would certainly be different. Electromagnetic induction, as the name implies, involves electricity and magnetism. When electrical conductors, such as alternator windings, are moved within a magnetic field, an electrical current develops in the conductors. The electrical current produced in this way is caned an *induced current.* A simplified illustration showing how induced electrical current develops is shown in Figure 6-1

A *conductor* is placed within the magnetic field of a horseshoe magnet so that the left side of the magnet has a north polarity (N), and the right side has a south polarity (*S*). *Magnetic lines of force* travel from the north polarity of the magnet to the south polarity. The ends of the conductor are connected to a current meter to measure the induced current. The meter is the zero-centered type, so its needle can move either to the left or to the right. When the conductor is moved, current will flow through the conductor. *Electromagnetic induction* takes place whenever there is relative motion between the conductor and the magnetic field. Either the conductor can be moved through the magnetic field, or the conductor can be held stationary and the magnetic field can be moved past it. Thus, current will be induced as long as there is *relative motion* between the conductor and magnetic field.

If the conductor shown in Figure 6-1 is moved upward, the needle of the meter will move to the right. However, if the conductor is moved *downward,* the needle of the meter will deflect to the left. This shows that the direction of movement of the conductor within the magnetic field determines the direction of current flow. In one case, the current flows through the conductor from the front of the illustration to the back. In the other situation, the current travels from the back to the front. The direction of current flow is indicated by the direction of the meter deflection. The principle demonstrated here is the basis for electrical power generation.

In order for an *induced current* to be developed, the conductor must have a complete path or closed circuit. The meter in Figure 6-1 was connected to the conductor to make a complete current path. If there is no closed circuit, electromagnetic induction cannot take place. It is important to remember that an induced current causes an induced electromotive force (voltage) across the ends of the conductor.

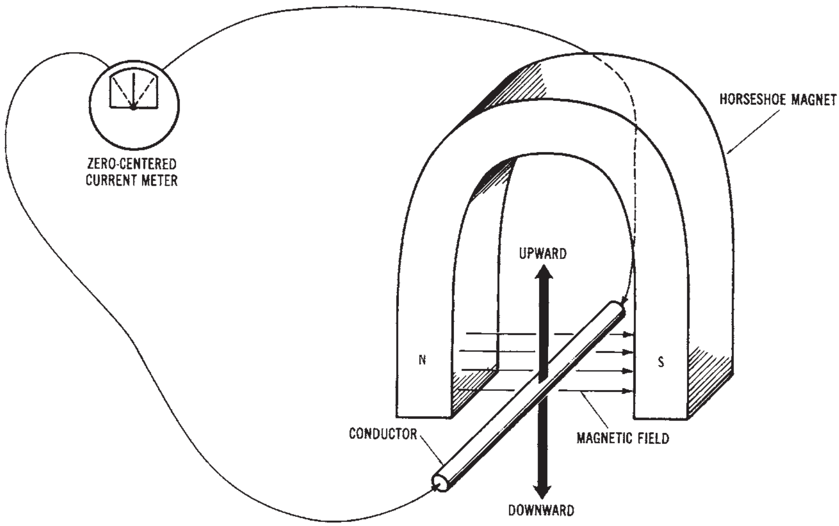


Figure 6-1. Electromagnetic induction

BASIC GENERATOR OPERATION

As stated previously, the operation of the electrical generators used today depends upon the principle of *electromagnetic induction.* When conductors move through a magnetic field, or when a magnetic field is moved past conductors, an induced current develops. The current that is induced into the conductors produces an induced electromotive force or voltage.

Left-hand Rule

We can determine the direction of current flow through a moving conductor within a magnetic field by using the *left-hand rule.* Refer to Figure 6-2 and use your left hand in the following manner:

1. Arrange your *thumb, forefinger,* and *middle finger* so that they are at approximately right angles to one another.
2. Point your *thumb* in the direction of conductor movement.

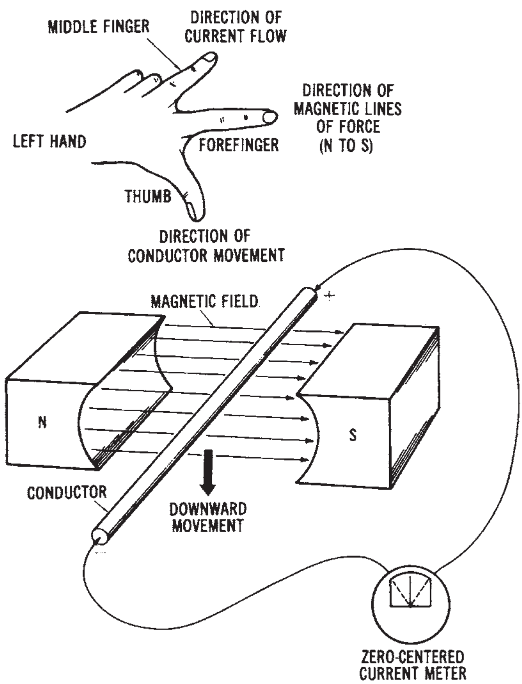


Figure 6-2. Left-hand rule of induced current

3. Point your *forefinger* in the direction of the magnetic lines of force (from north to south).
4. Your *middle finger* will now point in the direction of induced current flow (negative to positive).

Voltage Development in a Generator

It is known that when a conductor moves across a certain number of magnetic lines of force in one second, an *induced electromotive force (emf)* of one volt is developed across the conductor. Thus, the induced voltage value can be changed by modifying either the strength of the magnetic field, or the speed of conductor movement through the magnetic field. If the magnetic field is made stronger, more voltage will be induced. If the conductor is moved at a faster speed, more voltage will be induced. Likewise, if more conductors are concentrated within the magnetic field, a greater voltage will develop. These rules of electromagnetic induction are very important for the operation of mechanical generators that produce electrical power.

Sample Problem: Voltage Induced into A Conductor

In electrical generators, the coils move with respect to a magnetic field or flux. Electromagnetic induction occurs in accordance with *Faraday's Law,* which was formulated in 1831. This law states: 1) If a magnetic flux that links a conductor loop has relative motion, a voltage is induced, and 2) the value of the induced voltage is proportional to the rate of change of flux.

The voltage induced in a conductor of a generator is defined by Faraday's Law as follows:

$$V_i = B \times L \times v$$

where:

V_i = induced voltage in volts,
B = magnetic flux in teslas,
L = length of conductor within the magnetic flux in meters, and
v = relative speed of the conductor in meters per second.

Given: the conductors of the stator of a generator have a length of 0.5 M. The conductors move through a magnetic field of 0.8 teslas at a rate of 68 m/s.

Find: the amount of induced voltage in each conductor.
Solution:

$$
\begin{aligned}
V_i &= B \times L \times v \\
&= 0.8 \times 0.5 \times 60 \\
V_i &= 24 \text{ Volts}
\end{aligned}
$$

SINGLE-PHASE AC POWER SYSTEMS

Electrical power can be produced by *single-phase generators,* commonly called *alternators.* The principle of operation of a single-phase alternator is shown in Figure 6-3. In order for a generator to convert mechanical energy into electrical energy, three conditions must exist:

1. There must be a *magnetic field* developed.
2. There must be a group of *conductors* adjacent to the magnetic field.
3. There must be *relative motion* between the magnetic field and the conductors.

These conditions are necessary in order for electromagnetic induction to take place.

Generator Construction

Generators used to produce electrical power require some form of *mechanical energy.* This mechanical energy is used to move electrical conductors through the magnetic field of the generator. Figure 6-3 shows the basic parts of a mechanical generator. A generator has a stationary part and a rotating part. The stationary part is called the *stator,* and the rotating part is called the *rotor.* The generator has magnetic field poles of north and south polarities. Also, the generator must have a method of producing a rotary motion, or a *prime mover,* connected to the generator shaft. There must also be a method of electrically connecting the rotating conductors to an external circuit. This is done by a *slip ring/brush assembly.* The stationary brushes are made of carbon and graphite. The slip rings used on AC generators are made of copper. They are permanently mounted on the shaft of the generator. The two slip rings connect to the ends of a *conductor loop.* When a *load* is connected, a closed external circuit is made. With all of these generator parts functioning together, electromagnetic induction can take place and electrical power can be produced.

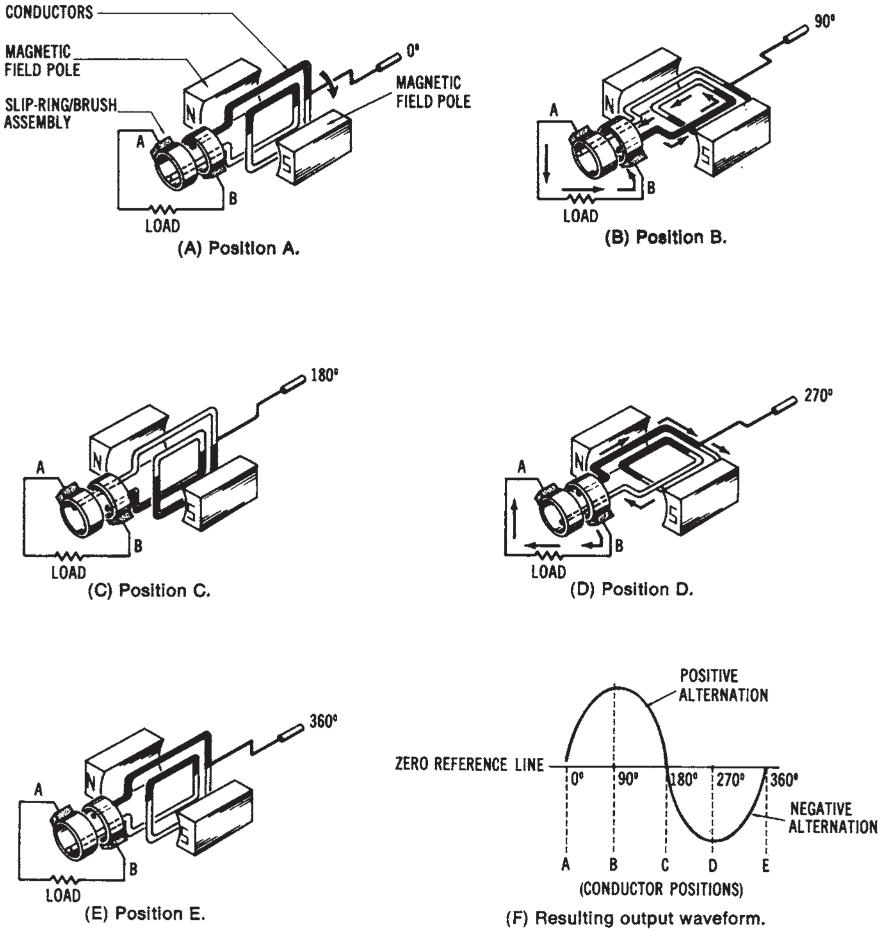


Figure 6-3. Basic principle of a single-phase alternator: (A) Position A, (B) Position B, (C) Position C, (D) Position D, (E) Position E, (F) Resulting output waveform

Generating AC Voltage

Figure 6-3 shows a magnetic field developed by a set of *permanent magnets. Conductors* that can be rotated are placed within the magnetic field, and they are connected to a *load* device by means of a *slip ring/brush assembly.* Figure 6-3 simulates a single-phase alternator.

In position A (Figure 6-3A), the conductors are positioned so that the minimum amount of *magnetic lines of force* is "cut" by the conductors as they rotate. No current is induced into the conductors at position A, and the resulting current flow through the load will be zero. If the conductors are rotated 90° in a clockwise direction to position B (Figure 6-3B), they will pass from the *minimum* lines of force to the most concentrated area of the magnetic field. At position B, the induced current will be maximum, as shown by the waveform diagram of Figure 6-3F. Note that the induced current rises gradually from the zero reference line to a *maximum* value at position B. As the conductors are rotated another 90° to position C (Figure 6-3C), the induced current becomes zero again. No current flows through the load at this position. Note, in the diagram in Figure 6-3F, how the induced current drops gradually from maximum to zero. This part of the induced AC (from 0° to 180°) is called the *positive alternation.* Each value of the induced current, as the conductors rotate from the 00 position to the 1800 position, is in a positive direction. This action could be observed visually if a meter were connected in place of the load.

When the conductors are rotated another 90° to position D (Figure 6-30), they once again pass through the most concentrated portion of the magnetic field. *Maximum* current is induced into the conductors at this position. However, the direction of the induced current is in the opposite direction from that of position B. At the 270 position, the induced current is maximum in a negative direction. As the conductors are rotated to position E (same as at position A), the induced current is minimum once again. Note, in the diagram of Figure 6-3E, how the induced current decreases from its maximum negative value back to zero again (at the 360° position). The part of the induced current from 180° to 360° is called the *negative alternation.* The complete output, which shows the induced current through the load, is called an AC waveform. As the conductors continue to rotate through the magnetic field, the *cycle* is repeated.

AC Sine Wave

The induced current produced by the method discussed above is in the form of a *sinusoidal* waveform or *sine wave.* This waveform is referred to as a sine wave because of its mathematical origin, based on the trigonometric sine function. The current induced into the conductors, shown in Figure 6-3, varies as the sine of the *angle of rotation* between the conductors and the magnetic field. This induced current produces a voltage. The instantaneous voltage induced into a single conductor can be expressed as:

$$V_i = V_{max} \times \sin \theta$$

where:

V_i = the instantaneous induced voltage,

V_{max} = the maximum induced voltage, and

θ = the angle of conductor rotation from the zero reference.

For example, at the 30° position (Figure 6-4), if the maximum voltage is 100 volts, then

$$V_i = 100\ \text{V} \times \sin\theta$$

The sine of 30° = 0.5. Therefore:

$$\begin{aligned} V_i &= 100\ \text{V} \times 0.5 \\ &= 50\ \text{volts} \end{aligned}$$

SINGLE-PHASE AC GENERATORS

Although much *single-phase* electrical power is used, particularly in the home, very little electrical power is produced by single-phase *alternators*. The single-phase electrical power used in the home is usually devel-

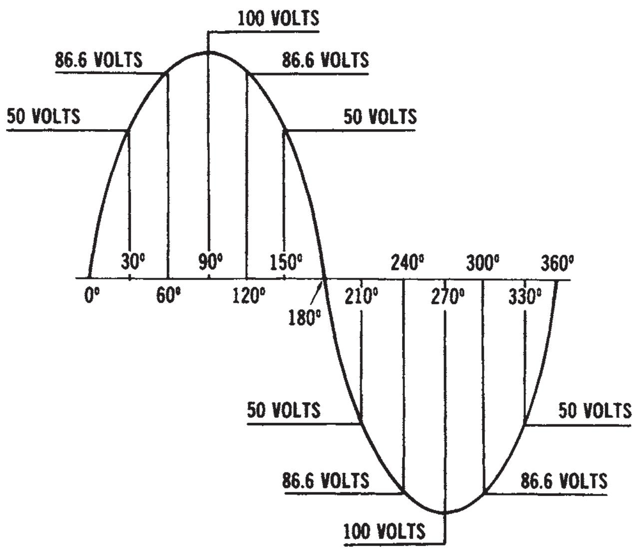


Fig 6-4. Mathematic origin of an AC sine wave.

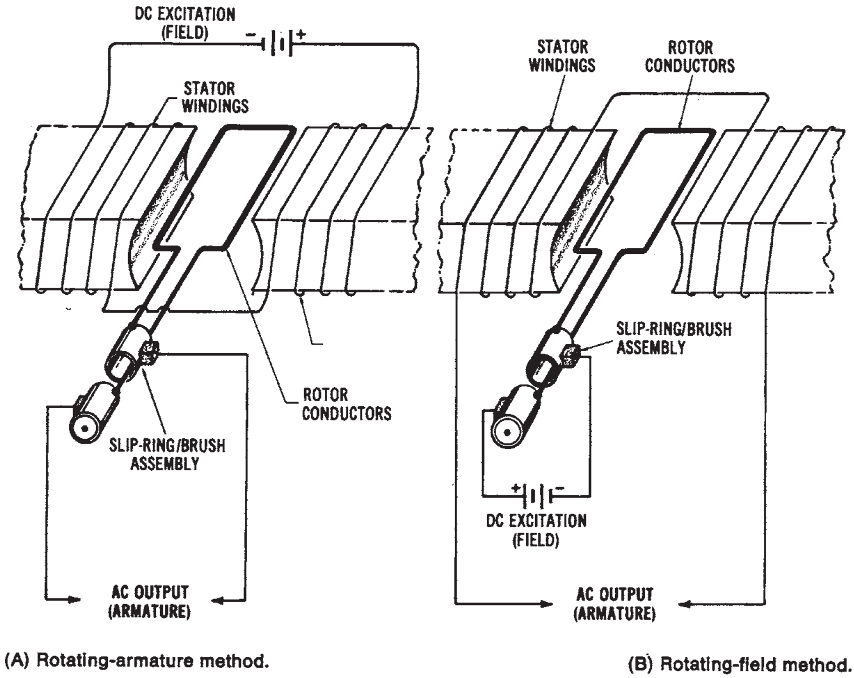


Figure 6-5. The two basic methods of generating single-phase alternating current: (A) Rotating-armature method, (B) Rotating-field method

oped by three-phase alternators, and then converted to single-phase electricity by the power distribution system. There are two basic methods that can be used to produce single-phase AC. One method is called the *rotating-armature method,* and the other is the *rotating field method.* These methods are illustrated in Figure 6-5.

Rotating-armature Method

In the *rotating-armature method,* shown in Figure 6-4A, an AC voltage is induced into the conductors of the rotating part of the machine. The electromagnetic field is developed by a set of stationary pole pieces. Relative motion between the conductors and the magnetic field is provided by a prime mover, or mechanical energy source, connected to the shaft (which is a part of the rotor assembly). Prime movers may be steam turbines, gas turbines, or hydraulic turbines, gasoline engines, diesel engines, or possibly gas engines, or electric motors. Remember that all generators convert mechanical energy into electrical energy, as shown in Figure 6-6. Only small power ratings can be used with the rotating-armature type of alternator. The major disadvantage of this method is that the AC voltage is extracted from a slip ring/brush assembly (see Figure 6-5A). A high voltage could produce tremendous sparking or arc-over between the brushes and the slip rings. The maintenance involved in replacing brushes and repairing the slip-ring commutator assembly would be very time-consuming and expensive. Therefore, this method is used only for alternators with low power ratings.

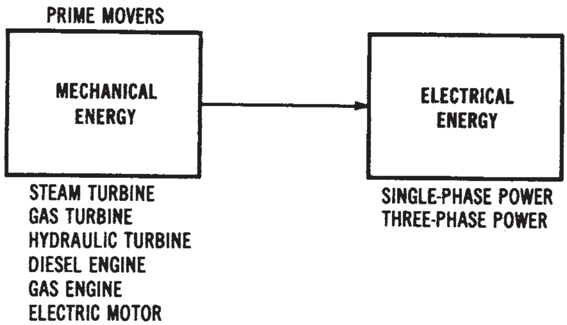


Figure 6-6. Energy conversion by generators

Rotating-field Method

The *rotating-field method,* shown in Figure 6-5B, is used for alternators capable of producing larger amounts of power. The direct current (DC) excitation voltage, which develops the magnetic field, is applied to the rotating portion of the machine. The AC voltage is induced into the stationary conductors of the machine. Since the DC-excitation voltage is a much lower value than the AC voltage that is produced, maintenance problems associated with the slip ring/brush assembly are minimized. In addition, the conductors of the stationary portion of the machine may be larger, so as to handle more current, since they do not rotate.

THREE-PHASE AC GENERATORS

The vast majority of electrical power produced in the United States is *three-phase* power. Because of their large power ratings, three-phase generators utilize the rotating field method. A typical three-phase generator in a power plant might have 250 volts DC excitation applied to the rotating field through the slip ring/brush assembly, while 13.8 kilovolts AC is induced into the stationary conductors.

Commercial power systems use many *three-phase alternators* connected in parallel to supply their regional load requirements. Normally, industrial loads represent the largest portion of the load on our power systems. The residential (home) load is somewhat less. Because of the vast load that has to be met by the power systems, three-phase generators have high power ratings. Nameplate data for a typical commercial three-phase alternator are shown in Figure 6-7. The nameplate of a generator specifies the manufacturer's rated values for the machine. It is usually a metal plate that is placed in a visible position on the generator frame. The following information would typically be listed on the nameplate:

TURBINE GENERATOR

STEAM TURBINE *No. 128917*

Rating 66000 kW	*3600 RPM*	*21 Stages*	
Steam: Pressure	*1250 PSIG*	*Temp 950 F*	*Exhaust Pressure 1.5″ HG. ABS.*

GENERATOR

No. 8287069 Hydrogen Cooled		Rating	Capability	Capability
Type ATB 2 Poles 60 Cycles	Gas Pressure	30 PSIG	15 PSIG	0.5 PSIG
3 PH. Y Connected For 3800 Volts	KVA	88235	81176	70588
Excitation 250 Volts	Kilowatts	75000	69000	60000
Temp Rise Guaranteed Not To Exceed	Armature Amp	3691	3396	2953
45 C On Armature By Detector	Field Amp	721	683	626
74 C On Field By Resistance	Power Factor	0.85	0.85	0.85

Figure 6-7. Nameplate data for a commercial three-phase alternator: (A) Power rating (in kilowatts), (B) Voltage rating (in volts), (C) Current rating (in amperes), (D) Temperature rise (in degrees Centigrade)

Generation of Three-phase Voltage

The basic construction of a *three-phase AC generator* is shown in Figure 6-8, with its resulting output waveform given in Figure 6-10. Note that three-phase generators must have at least six stationary *poles,* or two poles for each phase. The three-phase generator shown in the drawing is a *rotating-field* type generator. The magnetic field is developed electromagnetically by a DC voltage. The DC voltage is applied from an external power

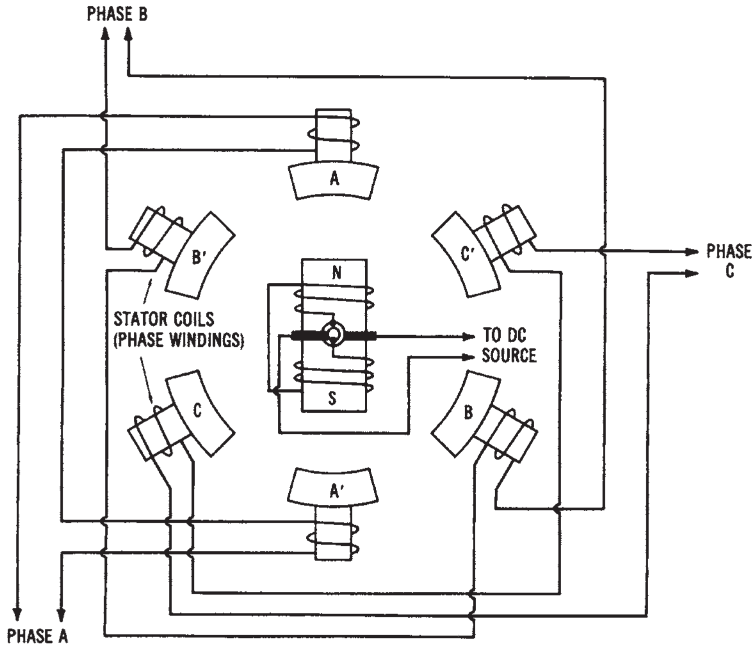


Figure 6-8. Simplified drawing showing the basic construction of a three-phase AC generator

source through a slip ring/brush assembly to the windings of the rotor. The magnetic polarities of the rotor, as shown, are north at the top and south at the bottom of the illustration. The magnetic lines of force develop around the outside of the electromagnetic rotor assembly.

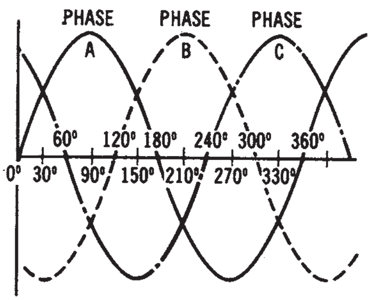


Figure 6-9. Output waveforms of a three-phase AC generator

Through *electromagnetic induction,* a current can be induced into each of the stationary (stator) coils of the generator. Since the beginning of phase A is physically located 120° from the beginning of phase B, the induced currents will be 120° apart. Likewise, the beginnings of phase B and phase C are located 120° *apart.* Thus, the voltages developed as a result of electromagnetic induction are 1200 apart, as shown in Figure 6-9.

Voltages are developed in each stator winding as the electromagnetic field rotates within the enclosure that houses the stator coils.

Three-Phase Connection Methods

In Figure 68, poles A′, B′, and C′ represent the beginnings of each of the phase windings of the alternator. Poles A, B, and C represent the ends of each of the phase windings. There are two methods that may be used to connect these windings together. These methods are called *wye* and *delta connections.*

Three-phase Wye-connected Generators

The windings of a three-phase generator can be connected in a *wye configuration* by connecting either the beginnings or the ends of the windings together. The unconnected ends of the windings become the three-phase power lines from the generator. A three-phase wye-connected generator is illustrated in Figure 6-10. Notice that the beginnings of the windings (poles A′, B′, and C′) are connected together. The other ends of the windings (poles A, B, and C) are the three-phase power lines that are connected to the load to which the generator will supply power.

Three-phase Delta-connected Generators

The windings of a three-phase generator may also be connected in a *delta arrangement,* as shown in Figure 6-11. In the *delta configuration,* the

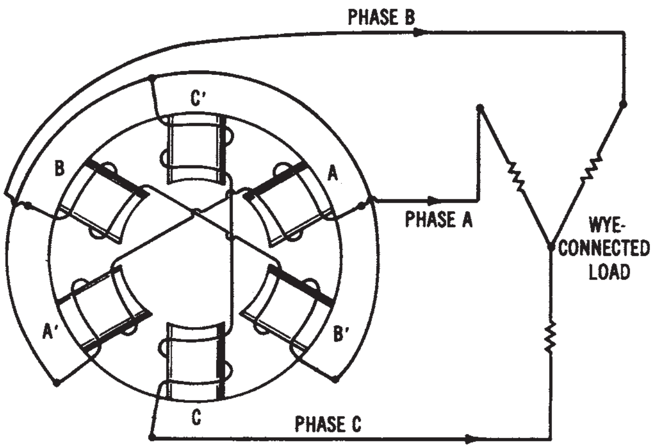


Figure 6-10. Simplified drawing of the stator of a three-phase generator that is connected in a *wye* configuration

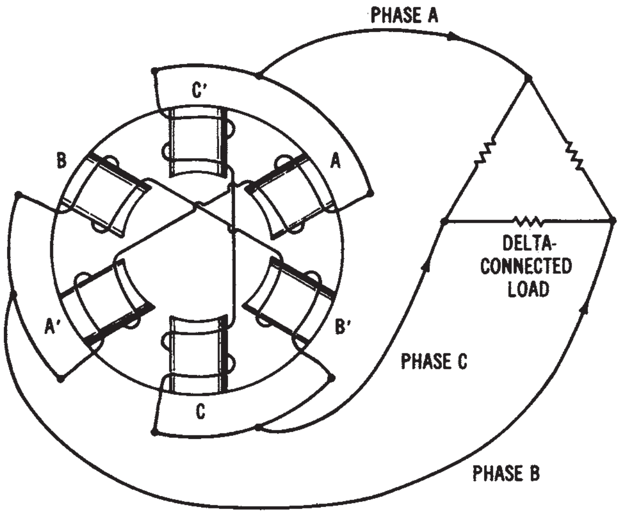


Figure 6-11. Simplified drawing of the stator of a three-phase generator that is connected in a delta configuration

beginning of one phase winding is connected to the end of the adjacent phase winding. Thus, the beginnings and ends of all adjacent phase windings are connected together. The voltage, current, and power characteristics of three-phase wye and delta connections were discussed earlier in Chapter 2.

Advantages of Three-phase Power

Three-phase power is used primarily for industrial and commercial applications. Many types of industrial equipment use three-phase AC power because the power produced by a three-phase voltage source, as compared to single-phase power, is less pulsating. You can see this effect by observing that a peak voltage occurs every 120° in the three-phase waveform in Figure 6-9. A single-phase voltage has a peak voltage only once every 360° (Figure 6-3). This comparison is somewhat similar to comparing the power developed by an eight-cylinder engine to the power developed by a four-cylinder engine. The eight-cylinder engine provides smoother, *less-pulsating* power. The effect of smoother power development on electric motors (with three-phase voltage applied) is that it produces a more *uniform torque* in the motor. This factor is very important for the large motors that are used in industry.

Three separate single-phase voltages can be derived from a three-phase transmission line, and three-phase power is more *economical* than single-phase power to distribute from plants to consumers that are located a considerable distance away. *Fewer conductors* are required to distribute the three-phase voltage. Also, the equipment that uses three-phase power is physically *smaller in size* than similar single-phase equipment.

HIGH-SPEED AND LOW-SPEED GENERATORS

Generators can also be classified as either *high-speed* or *low-speed* types (Figure 6-12). The type of generator used depends upon the prime mover used to rotate the generator. *High-speed generators* are usually driven by steam turbines. The high-speed generator is smaller in diameter and longer than a low-speed generator. The high-speed generator ordinarily has two stator poles per phase; thus, it will rotate at *3600* rpm to produce a 60-hertz frequency.

Low-speed generators are larger in diameter and not as long as high-speed machines. Typical low-speed generators are used at hydroelectric power plants. They have large-diameter revolving fields that use many poles. The number of stator poles used could, for example, be twelve for a 600-rpm machine, or eight for a 900-rpm generator. Notice that a much larger number of poles is required for low-speed generators.

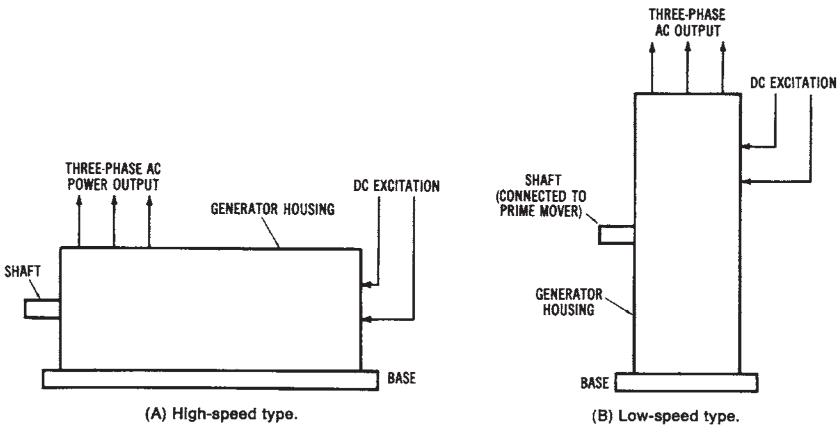


Figure 6-12. High- and low-speed AC generators

GENERATOR FREQUENCY

The *frequency* of the sinusoidal waveforms (sine waves) produced by an AC generator is usually *60 hertz.* One *cycle* of alternating current is generated when a conductor makes one complete revolution past a set of north and south field poles. A speed of 60 revolutions per second (3600 revolutions per minute) must be maintained to produce 60 hertz. The frequency of an AC generator (alternator) may be expressed as:

$$f = \frac{\text{speed of rotation (rpm)} \times \text{number of poles per phase}}{120}$$

where f is the frequency in hertz.

Sample Problem:

Given: a six-pole three-phase alternator rotates at a speed of 3600 rpm.

Find: the frequency of the alternator.

Solution:

$$f = \frac{N/3 \times \text{rpm}}{120}$$

$$\frac{6/3 \times 3600}{120}$$

$$= 60\ \text{Hz}$$

Note that if the number of *poles* is increased, the *speed of rotation* may be reduced while still maintaining a 60-Hz frequency.

HARMONICS

The voltage and current of power lines are often distorted because of the effect of *harmonics.* This distortion can be caused by magnetic effects in transformers, or by power control equipment. Harmonics are frequencies that are whole number multiples of the power line frequency.

Sample Problem:

Given: a power line frequency of 60 hertz is applied to an electric motor.

Find:

1. fundamental frequency
2. 3rd harmonic
3. 5th harmonic
4. 7th harmonic

Solution:

1. fundamental = 60 Hz
2. 3rd harmonic = 60 × 3 = 180 Hz
3. 5th harmonic = 60 × 5 = 300 Hz
4. 7th harmonic = 60 × 7 = 420 Hz

GENERATOR VOLTAGE REGULATION

As an increased electrical *load* is added to an alternator, it tends to slow down. The decreased speed causes the generated voltage to decrease. The amount of voltage change depends on the generator design and the type of load connected to its terminals. The amount of change in generated voltage from a no-load condition to a rated full-load operating condition is referred to as *voltage regulation.* Voltage regulation may be expressed as:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where:

VR = the voltage regulation in percent,
V_{NL} = the no-load terminal voltage, and
V_{FL} = the rated full-load terminal voltage.

Sample Problem:

Given: a single-phase alternator has a no-load output voltage of 122.5 volts and a rated full-load voltage of 120.0 volts.

Find: the voltage regulation of the alternator.

Solution:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

$$= \frac{122.5 - 120 \times 100}{120} \times 100$$

$$VR = 0.02 = 2\%$$

GENERATOR EFFICIENCY

Generator *efficiency* is the ratio of the *power output* in watts to the *power input* in horsepower. The efficiency of a generator may be expressed as:

$$\text{Efficiency } (\%) = \frac{P_{out}}{P_{in}} \times 100$$

where:

P_{in} = the power input in horsepower, and
P_{out} = the power output in watts.

Sample Problem:

Given: a three-phase alternator has a power output of 22 MW and a power input of 35,000 horsepower.

Find: efficiency of the alternator.

Solution:

$$= (\%) \text{ Eff} = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{22{,}000{,}000 \text{ W}}{35{,}000 \text{ hp} \times 746} \times 100$$

$$\%\text{Eff} = 84\%$$

To convert horsepower to watts, remember that 1 horsepower = 746 watts. The efficiency of a generator usually ranges from 70 percent to 85 percent.

Chapter 7

Direct Current Power Systems

Alternating Current (AC) is used in greater quantities than *direct current* (DC); however, many important operations are dependent upon DC power. Industries use DC power for many specialized processes. Electroplating and DC variable-speed motor drives are only two examples that show the need for DC power to sustain industrial operations. We use DC *power* to start our automobiles, and many types of portable equipment in the home use DC power. Most of the electrical power produced in the United States is *three-phase AC,* and this three-phase AC power may be easily converted to DC for industrial or commercial use. Direct current is also available in the form of primary and secondary *chemical cells.* These cells are used extensively. In addition, *DC generators* are also used to supply power for specialized applications.

IMPORTANT TERMS

Chapter 7 deals with DC power systems. After studying this chapter, you should have an understanding of the following terms:

Primary Cell
Secondary Cell
Electrolyte Electrode
Battery
Internal Resistance
Carbon-Zinc Cell
Mercury Cell
Alkaline Cell
Nuclear Cell
Lead-Acid Cell

Specific Gravity
Ampere-Hour Rating
Nickel-Iron (Edison) Cell
Nickel-Cadmium Cell
Silver Cell
DC Generator
Split-Ring Commutator
DC Permanent-Magnet Generator
DC Separately Excited Generator
DC Self-Excited Series-Wound Generator
DC Self-Excited Shunt-Wound Generator
DC Self-Excited Compound-Wound Generator
Armature Reaction
Interpoles
Rectification
Single-Phase, Half-Wave Rectifier
Single-Phase, Full-Wave Rectifier
Single-Phase, Bridge Rectifier
Three-Phase, Half-Wave Rectifier
Three-Phase, Full-Wave Rectifier
Silicon-Controlled Rectifier (SCR)
Rotary Converter
Filter Circuit
Capacitor Filter
RC Filter
Pi (π) Filter
Regulation
Zener Diode Regulator
Series Transistor Regulator
Shunt Transistor Regulator

DC PRODUCTION USING CHEMICAL CELLS

The conversion of chemical energy into electrical power can be accomplished by the use of *electrochemical cells.* A *cell* is composed of two dissimilar metals, which are immersed in a conductive liquid or paste called an electrolyte. Chemical cells are classified as either *primary cells* or *secondary cells. Primary cells* are ordinarily not usable after a certain period of time. After this period of time its chemicals can no longer produce electrical energy. *Secondary cells* can be renewed after they are used, by reactivating the chemical process that is used to produce electrical energy. This reactivation is known as charging. Both primary cells and secondary cells have many applications. When two or more cells are connected in series, they form a battery.

CHARACTERISTICS OF PRIMARY CELLS

The operational principle of a *primary cell* involves the placing of two unlike conductive materials called *electrodes* into a conductive solution called an electrolyte. When the chemicals that compose the cell are brought together, their molecular structures are altered. During this alteration, their atoms may either gain additional electrons or lose some of their electrons. These atoms then have either a positive or a negative electrical charge, and are referred to as ions. The *ionization* process thus develops a chemical solution capable of conducting an electrical current. A *carbon-zinc primary cell* is shown in Figure 7-1.

When an external *load* device, such as a lamp, is connected to a cell, a current will flow from one electrode to the other through the electrolyte material. Current leaves the cell through its *negative electrode,* flows through the load device, then reenters the cell through its *positive electrode,* as shown in Figure 7-2. Thus, a complete circuit is established between the cell (source) and the lamp (load).

The voltage developed by a *primary cell* is dependent upon the electrode materials and the type of electrolyte used. The familiar *carbon-zinc cell* of Figure 7-1 produces approximately 1.5 volts. The negative electrode of the cell is the zinc container, and the positive electrode is a carbon rod. A sal ammoniac paste, which acts as the electrolyte, is placed between the electrodes. This type of cell is usually called a *dry cell.*

Internal Resistance of Cells

An important characteristic of a chemical cell is its *internal resistance.* Since a cell conducts electrical current, its resistance depends on its cross-sectional area, the length of its current path, the type of materials used, and the operational temperature. The amount of *current* that a cell will deliver to a load is expressed as:

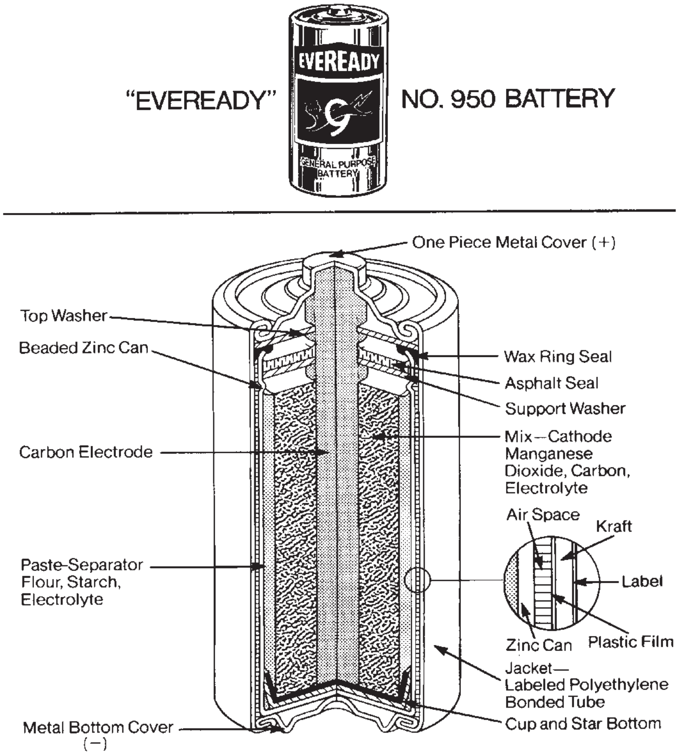


Figure 7-1. Batteries—Common sources of direct current (DC): Cutaway of a general purpose carbon-zinc cell *(Courtesy Eveready Corp.)*

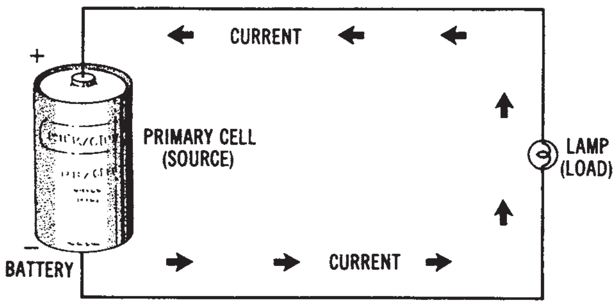


Figure 7-2. Current path for a primary cell

$$I = \frac{V}{R_i + R_L}$$

where:

I = the current in amperes,
V = the voltage or electromotive force (emf) of the cell in volts,
R_i = the internal resistance of the cell in ohms, and
R_L = the resistance of the load in ohms.

Sample Problem:

Given: a 1.5 volt battery has an internal resistance of 0.8 ohms.

Find: load current when 10.0 ohms of load resistance is connected to the battery.

Solution:

$$I = \frac{1.5\ V}{0.8 + 10.00\Omega}$$

$$= 0.139\ A$$

This formula, and another circuit that illustrates it, are shown in Figure 7-3. The formula shows that when a cell delivers current to a load, some of the voltage developed must be used to overcome the internal resistance of the cell. As load current increases, the voltage drop ($I \times R$) within the cell increases. This increased voltage drop causes the output voltage (V_o) of the cell to decrease. Thus,

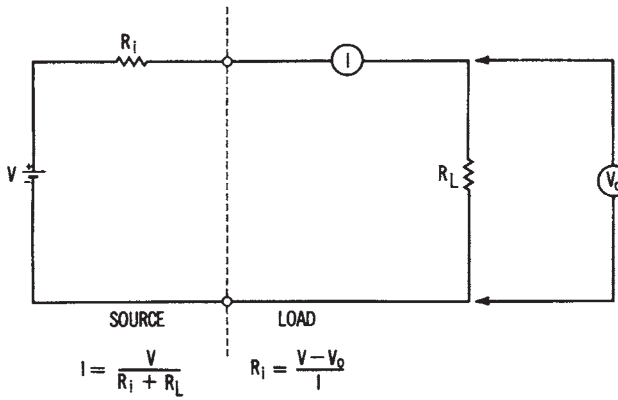


Figure 7-3. Illustrating the internal resistance of a cell

$$V_o = V - IR_i$$

where:

V_o = the output voltage of the cell in volts,
V = the no-load cell voltage in volts,
I = the load current in amperes, and
R_i = the internal resistance of the cell in ohms.

Sample Problem:

Given: the no-load voltage of a battery is 9.05 volts. Its rated load current is 200 mA, and its internal resistance is 0.1 ohms.

Find: the rated output voltage of the battery.

Solution:

$$\begin{aligned} V_o &= V - IR_i \\ &= 9.05\text{ V} - (.2\text{ A} \times 0.1\Omega) \\ Vo &= 9.03\text{ Volts} \end{aligned}$$

Modifying this formula to solve directly for R_i, we obtain

$$R_i = \frac{V - V_o}{I}$$

Sample Problem:

Given: the rated output of a battery is 30.0 volts, and its no-load voltage is 30.15 volts. Its full-load current is 350 mA.

Find: the internal resistance of the battery.

Solution:

$$R_i = \frac{V - V_o}{I}$$

$$= \frac{30.15 - 30.0\text{ V}}{0.35\text{ A}}$$

$$R_i = 0.43\text{ ohms}$$

The same method is used to determine the *internal resistance* of all voltage sources, including primary cells, secondary cells, and generators.

Applications of Primary Cells

There are many types of *primary cells* available today, with unlimited applications. The *carbon-zinc* (or Lechanche) cell, discussed previously, is the most often used type of dry cell. This cell has a low initial cost and is available in a variety of sizes. It is used primarily for portable equipment or instruments. For uses that require a higher voltage or current than one cell can deliver, manufacturers combine several cells in series, parallel, or series-parallel arrangements to form batteries suitable for specialized applications. *Carbon-zinc batteries* can be obtained in voltage ratings from 1.5 volts, at over I-ampere capability, up to about 3000 volts.

Mercury Cells—Another type of primary cell is the *mercury* or *zinc-mercuric oxide cell,* shown in Figure 7-4. This cell was developed as an improvement of the carbon-zinc cell. The mercury cell has a more constant voltage output, a longer active service time, and a smaller physical size. However, the mercury cell is more expensive and produces a voltage of 1.35 volts, which is lower than that of the carbon-zinc cell.

Alkaline Cells—An *alkaline or zinc-magnesium dioxide cell,* shown in Figure 7-5, is another type of primary cell. These cells have very low internal resistance and a voltage per cell of 1.5 volts. Because of their low internal resistance, alkaline cells will supply higher currents to the electrical loads connected to them. Alkaline cells are capable of a much longer service life than the equivalent carbon-zinc cells.

Nuclear Cells—A recent source of DC power that has been developed

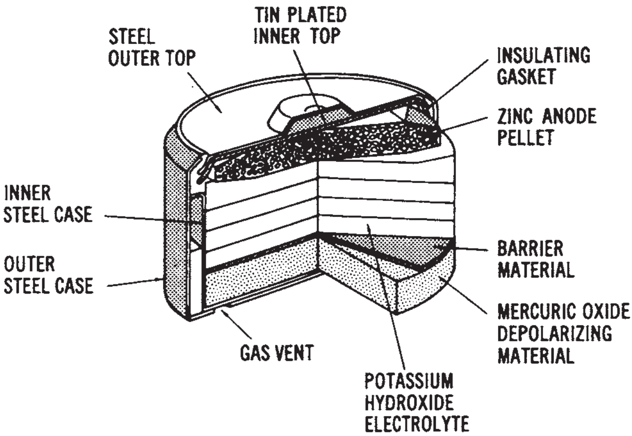


Figure 7-4. Cutaway drawing of a mercury primary cell

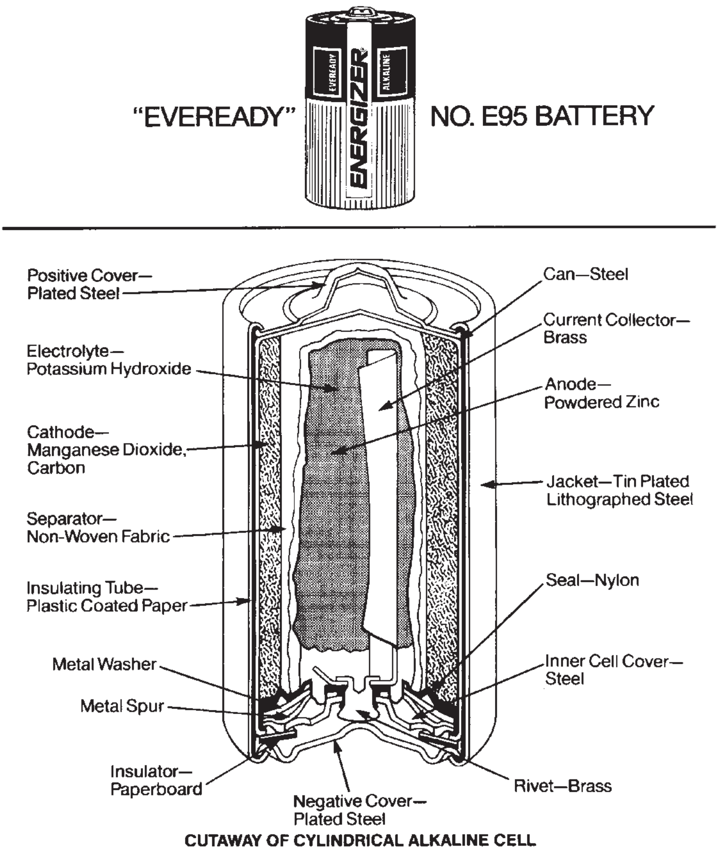


Figure 7-5. Alkaline cells: Cutaway of a cylindrical alkaline cell (Courtesy *Eveready* Corp.)

is the *nuclear cell.* Such cells convert the energy given off by atomic nuclei into electrical energy. At present, a high-voltage type (thousands of volts with a picoampere current capacity) and a low-voltage type (approximately 1 volt with a microampere current capability) are available.

The illustration in Figure 7-6 shows the design of one type of *nuclear cell.* The radioactive source is connected to one electrode of the cell. The source used here is tritium gas absorbed in zirconium metal, which emits beta particles. The carbon-collector electrode collects these beta particles as they are emitted from the *tritium* source, thus producing an electrical charge. The electrodes are separated by either a vacuum or some other type of dielectric, which electrically isolates the two electrodes. The nuclear cell shown in Figure 7-6 has air removed through the center tube to form the vacuum inside it that isolates the positive and negative electrodes. The DC output produced by this cell is extracted through terminals connected to the tritium source (negative) and to the carbon connector (positive). The output of this cell is dependent upon the nuclear energy generated by the tritium source; therefore, the voltage output decreases as the cell ages.

CHARACTERISTICS OF SECONDARY CELLS

Regardless of the type of *primary cell* used, its usable time is limited. When its chemicals are expended, it becomes useless. This disadvantage is overcome by *secondary cells.* The chemicals of a secondary cell may be reactivated by a charging process. Secondary cells are also called *storage cells.* The most common types of secondary cells are the *lead-acid cell, nickel-iron (Edison) cell,* and *nickel-cadmium cell*

The Lead-acid Cell

The widely used *lead-acid cell* is one type of *secondary cell.* The electrodes of the lead-acid cell are made of lead and lead peroxide. The *positive plate* is lead peroxide (PbO_2), and the *negative plate* is *lead (Pb).* The *electrolyte* is dilute sulfuric acid (H_2SO_4). When the lead-acid cell supplies cur-

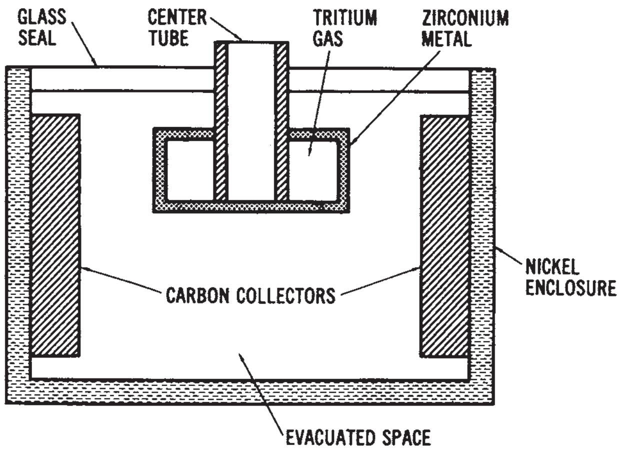


Figure 7-6. Cutaway drawing of a nuclear cell

rent to a load connected to it, the chemical process can be expressed as:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbS\ O_4 + 2H_2O.$$

The sulfuric acid ionizes to produce four positive hydrogen *ions* (H^+) and two negative sulfate (SO_{4-}) ions. A negative charge is developed on the lead plate when an SO_{4-} ion combines with the lead plate to form lead sulfate ($PbSO_4$). The positive hydrogen *ions* (H^+) combine with electrons of the lead-peroxide plate and become neutral hydrogen atoms. They next combine with the oxygen (O) of this plate to become water (H_2O). The lead-peroxide plate thus becomes *positively charged.* A fully charged lead-acid cell has an electrical potential developed between electrodes of approximately 2.0 volts.

After a cell discharges by supplying current to a load for a certain period of time, it is no longer able to develop an output voltage. The cell may then be charged by causing direct current to flow through the cell in the opposite direction.

The chemical process is thus reversed as follows:

$$2Pb\ SO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4.$$

Thus, the original state of the chemicals is reestablished by the charging action.

Specific Gravity of Secondary Cells

The amount of charge may be measured by a specific-gravity test using a hydrometer to sample the electrolyte. The *specific gravity* of a liquid provides an index of how much heavier than water the liquid is. Pure sulfuric acid has a specific gravity of 1.840, while the dilute sulfuric acid of a *fully charged* lead-acid cell varies from 1.275 to 1.300. During *discharge* of a cell, water is formed, reducing the specific gravity of the electrolyte. A specific gravity of between 1.120 and 1.150 indicates a *fully discharged* cell. Recharging is accomplished using battery chargers.

Ampere-hour Rating of Secondary Cells

The capacity of a battery composed of lead-acid cells is given by an *ampere-hour rating.* A 60-ampere hour battery could theoretically deliver 60 amperes for 1 hour, 30 amperes for 2 hours, or 15 amperes for 4 hours. However, this is an approximate rating dependent upon the rate of discharge and the operating temperature of the battery. The normal operating temperature is considered to be 800 Fahrenheit.

Nickel-iron Cells

The *nickel-iron* (or *"Edison") cell,* shown in Figure 7-7 is a secondary cell constructed with an unbreakable case of welded nickel-plated sheet steel. The positive plate is made of nickel tubes about V. inch in diameter and 4-1/4 inches long. Nickel oxide (NiO_2) is contained in the tubes, which are mounted into steel grids and forced into position under high pressure. The *positive plates* are assembled into groups. The *negative plates* of the Edison cell are made of flat nickel-plated steel pockets, which are composed of iron oxide. They are built into steel grids in groups, in the same way as the positive plates. The *electrolyte* is a solution of potassium hydroxide (KOH) with lithium hydroxide added.

Chemical action of the *nickel-oxide cell* is very complex as compared to that of the lead-acid cell; however, they are similar in many respects. The potassium hydroxide electrolyte (KOH) breaks up into negative and positive *ions.* The *negative ions* move toward the iron plate, oxidize the iron, and give up excess electrons to the plate. This plate becomes negatively charged. The positive ions move to the nickel-oxide plate and take electrons from the plate. The deficiency of electrons causes the nickel-oxide plate to become positively charged. The voltage produced by the chemical action of a nickel-iron cell is about 1.4 volts.

The *internal resistance* of the nickel-iron (Edison) cell is higher than that of the lead-acid cell. This resistance increases quickly as the cell discharges. Unlike the lead-acid cell, the nickel-iron cell cannot be tested using a hydrometer to show its discharge level. A voltmeter is used to indi-

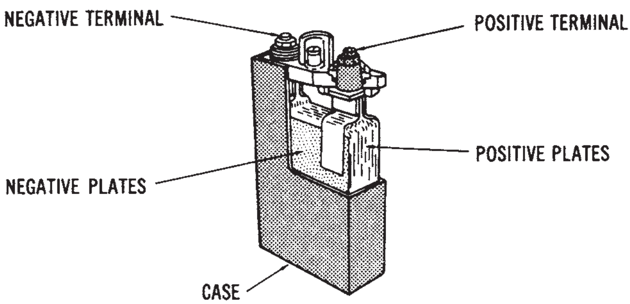


Figure 7-7. Cutaway drawing of a nickel-iron (Edison) secondary cell

cate the state of charge of the nickel-iron cell. This cell is also charged by applying a DC voltage to the *positive* and *negative* terminals and causing current within the cells to flow in reverse. The chemicals are thus reactivated so that the cells may be used again.

Other Types of Secondary Cells

Another type of secondary cell that has gained recent popularity is the *nickel-cadmium cell,* sometimes called a *"Ni-cad" battery.* These cells are available in large or small sizes with capacities up to 2000 ampere-hours. Figure 7-8 shows the small *rechargeable* type of nickel-cadmium cell, which is used extensively in portable equipment. The *positive plate* of this cell is nickel hydroxide, the *negative plate* is cadmium hydroxide, and the *electrolyte* is potassium hydroxide. These cells are extremely reliable, operate over a wide range of temperatures, and have a long life expectancy. A fully charged nickel-cadmium cell has a voltage of approximately 1.35 volts per cell.

There are a few other types of *secondary cells* in use today. Most of these types are for specialized applications. Other cells include the *silver-oxide-zinc cell* and the *silver-cadmium cell.* These cells have the highest output per physical size and the longest life, but they are more expensive than other cells.

Applications of Secondary Cells

Secondary cells, in the form of storage batteries, are used in industry and commercial buildings to provide emergency power in the event of a power failure. Such standby systems are necessary to sustain lighting and some critical operations when power is not available. Industrial trucks and loaders use storage batteries for their everyday operation. Many types of instruments and portable equipment rely upon batteries for power. Several of these instruments get their power from rechargeable secondary cells rather than primary cells. Railway cars use batteries for lighting when they are not in motion. Of course, automotive systems of all kinds use secondary batteries to supply DC power for starting and lighting.

DC GENERATING SYSTEMS

Mechanical generators are used in many situations to produce direct current. These generators convert mechanical energy into DC electrical energy.

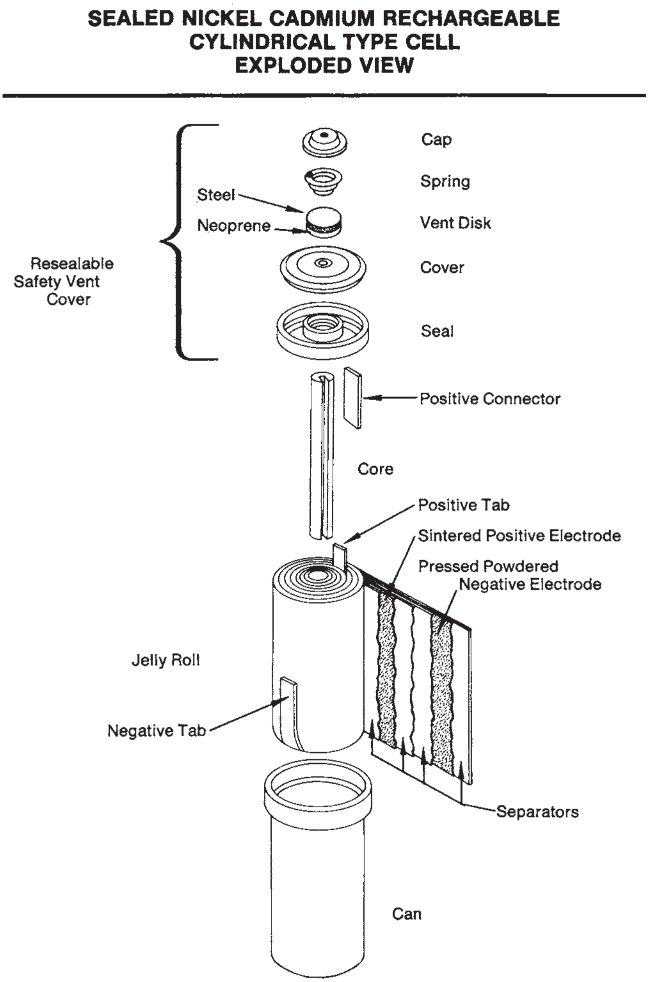


Figure 7-8. Sealed nickel-cadmium rechargeable cylindrical type cell-exploded view (Courtesy Eveready Corp.)

Construction of DC Generators

The parts of a simple *DC generator* are shown in Figure 7-9. The principle of operation of a DC generator is similar to that of the AC generator, which was discussed previously. A rotating *armature* coil passes through a *magnetic field* that develops between the north and south polarities of permanent magnets or electromagnets. As the coil rotates, *electromagnetic induction* causes a current to be induced into the coil. The current produced is an *alternating current.* However, it is possible to convert the alternating current that is induced into the armature into a form of *direct current.* This conversion of AC into DC is accomplished through the use of a *split-ring commutator.* The conductors of the armature of a DC generator are connected to split-ring commutator segments. The split-ring commutator shown in Figure 7-12 has two segments, which are insulated from one another and from the shaft of the machine on which it rotates. An end of each armature conductor is connected to each commutator segment. The purpose of the *split-ring commutator* is to reverse the armature-coil connection to the external load circuit at the same time that the current induced in the armature coil reverses. This causes DC of the correct polarity to be applied to the load at all times.

Voltage Output of DC Generators

The voltage developed by the single-coil generator shown in Figure 7-9 would appear as illustrated in Figure 7-10. This pulsating DC is not suitable for most applications. However, using many turns of wire around the armature and several *split-ring commutator* segments causes the voltage developed to be a smooth, direct current like that produced by a battery. This type of output is shown in Figure 7-10b. The voltage developed by a DC generator depends upon the strength of the *magnetic field,* the number of *coils* in the armature, and the *speed* of rotation of the armature. By increasing any of these factors, the voltage output can be increased.

Sample Problem: Voltage Output of a DC Generator

Voltage output of a DC generator can be expressed as:

$$V_o = \frac{Z \times n \times \Phi}{60}$$

where:

V_o = voltage developed across the generator brushes in volts,
Z = total number of armature conductors,
n = speed of rotation in r/min, and
Φ = magnetic flux per pole in webers.

Given: a four-pole DC generator rotates at 1200 r/min. The armature has 36 slots, and each coil has four turns of wire. The magnetic flux per pole is 0.05 webers.

Find: the voltage output of the generator.

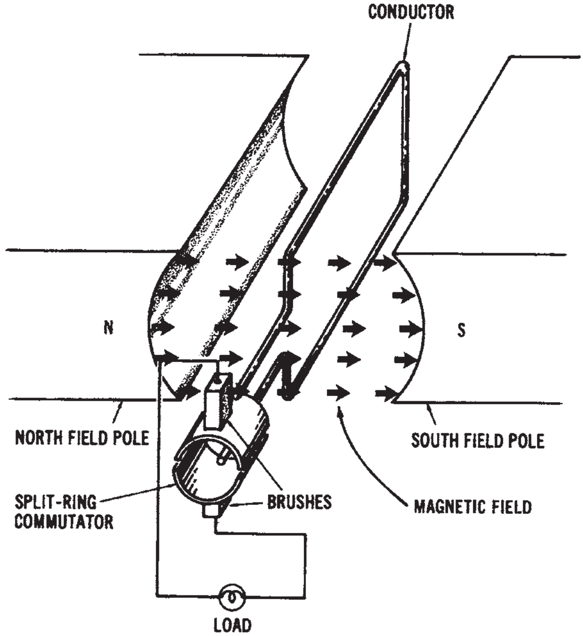


Figure 7-9. Simplified drawing of the basic parts of a DC generator

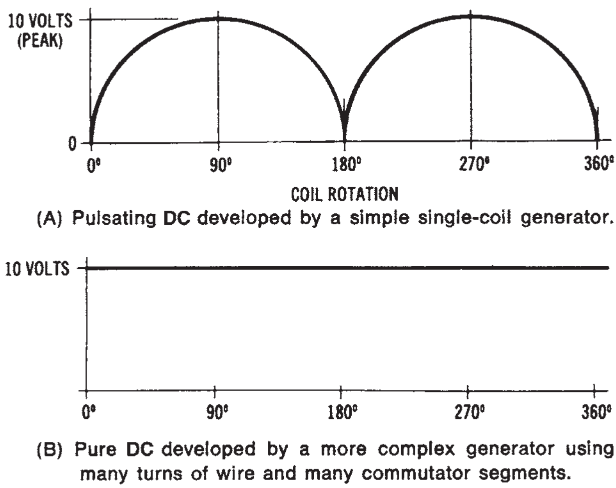


Figure 7-10. Output waveforms of a DC generator: (A) Pulsating DC developed by a simple single-coil generator, (6) Pure DC developed by a more complex generator using many turns of wire and many commutator segments

Solution: since each turn has 2 conductors, and 36 slots are used in the armature core, Z = 36 coils × 2 coils per turn × 4 turns of wire per coil = 288 conductors.

$$V_o = \frac{288 \times 1200 \times 0.05}{60}$$

$$V_o = 288 \text{ volts}$$

Types of DC Generators

DC generators are classified according to the way in which a magnetic field is developed in the stator of the machine. One method is to use a permanent-magnet field. It is also possible to use electromagnets to develop a magnetic field by applying a separate source of DC to the electromagnetic coils. However, the most common method of developing a magnetic field is for part of the generator output to be used to supply DC power to the field of the machine. Thus, there are three basic classifications of DC generators: (1) *permanent-magnet field,* (2) *separately excited field,* and (3) *self-excited field.* The self-excited types are further subdivided according to the method used to connect the armature windings to the field circuit. This can be accomplished by the following connection methods: (1) *series,* (2) *parallel (shunt),* or *(3) compound.*

Permanent-magnet DC Generator—A simplified diagram of a *permanent-magnet DC generator* is shown in Figure 7-11. The *conductors* shown in this diagram are connected to the *split-ring commutator and brush assembly* of the machine. The *magnetic field* is established by using permanent magnets made of Alnico (an alloy of aluminum, nickel, cobalt, and iron), or some other naturally magnetic material. It is possible to group several permanent magnets together to create a stronger magnetic field.

The *armature* of the permanent-magnet DC generator consists of many turns of insulated conductors. Therefore, when the armature rotates within the permanent-magnetic field, an induced voltage develops that can be applied to a load circuit. Applications for this type of DC generator are usually confined to those that require low amounts of power. A *magneto* is an example of a permanent-magnet DC generator.

*Separately Excited DC Generato*r—Where large amounts of DC electrical energy are needed, generators with electromagnetic fields are used. Stronger fields can be produced by electromagnets. It is possible to control the strength of the electromagnetic field by varying the current through

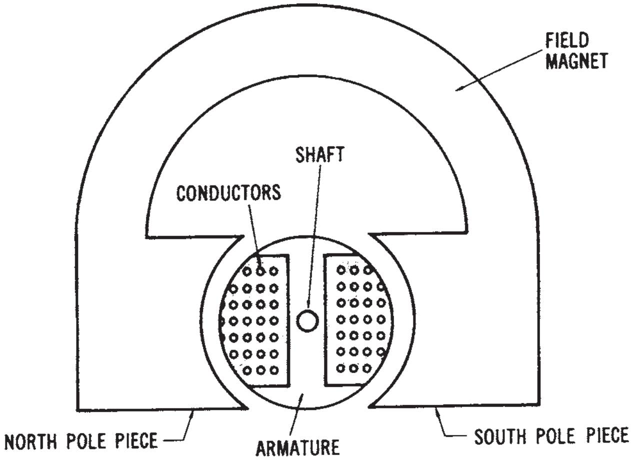


Figure 7-11. Simplified drawing of a permanent-magnet DC generator: (A) Pictorial diagram, (B) Schematic diagram

the field coils. The output voltage of generators that use *electromagnetic fields* can be controlled with ease.

The direct current used to establish the electromagnetic field is referred to as the *excitation* current. When DC excitation current is obtained from a source separate from the generator, the generator is called a *separately excited DC generator.* This type of generator is shown in Figure 7-12. Storage batteries are often used to supply the DC excitation current to this type of generator. The field current is independent of the armature current. Therefore, the separately excited generator maintains a very stable output voltage. Changes in load of the external circuit affect the armature current, but do not vary the strength of the field. The voltage output of a separately excited DC generator can be varied by adjusting the current through the field. A high-wattage *rheostat* (variable resistance) connected in series with the field coils will accomplish field control of a separately excited DC generator.

Separately excited DC generators are used only in certain applications where precise voltage control is essential. Automatic control processes in industry often require such precision. However, the cost of a separately excited DC generator is often prohibitive, and, therefore, other means of obtaining DC electrical power are usually used.

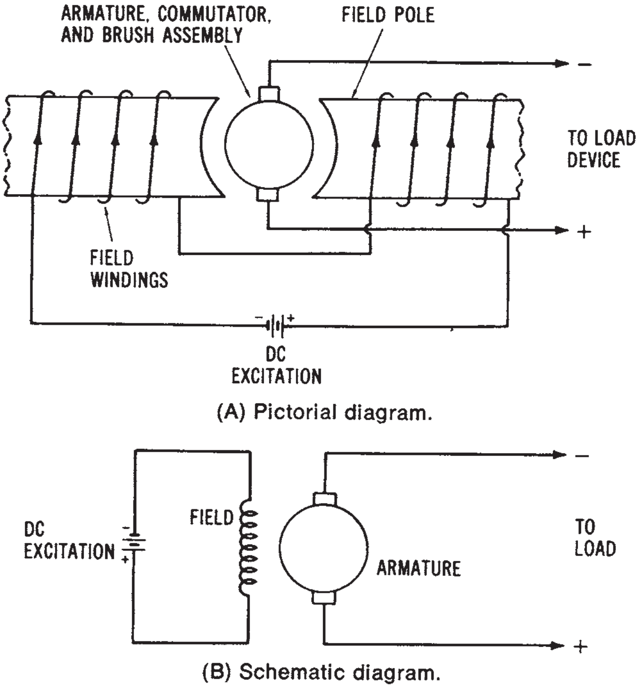
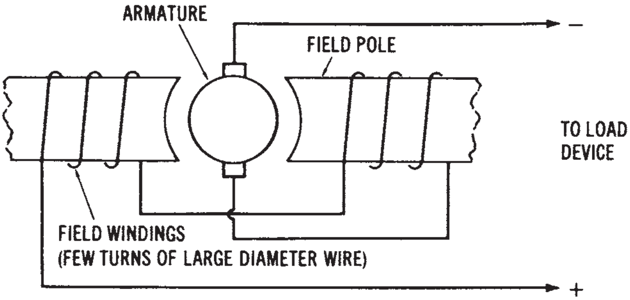


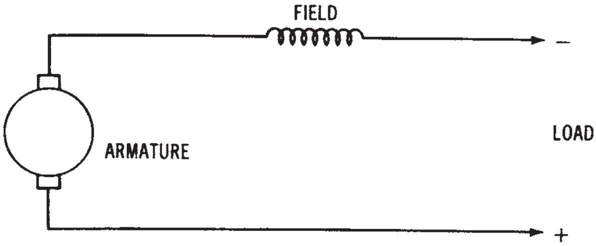
Figure 7-12. Simplified illustration of a separately excited DC generator: (A) Pictorial diagram, (B) Schematic diagram

Self-excited Series-wound DC Generators—Since DC generators produce direct current, it is possible to extract part of the output of a generator to obtain *excitation* current for the field coils. Generators that use part of their own output to supply the excitation current for the electromagnetic field are called *self-excited DC generators.* The method used to connect the armature windings to the field windings determines the characteristics of the generator. It is possible to connect armature and field windings in *series, parallel (shunt),* or *series-parallel (compound).*

The *self-excited series-wound DC generator* has its armature windings connected in *series* with the field coils and the load circuit, as shown in Figure 7-13. In this generator, the total current flowing through the load also flows through the field coils. The field coils are, therefore, wound using only a *few turns* of *low-resistance* large-diameter wire. A sufficient electromagnetic field can then be produced by the large current flowing through the coils.



(A) Pictorial diagram.



(B) Schematic diagram.

Figure 7-13. Simplified illustration of a self-excited, series-wound DC generator: (A) Pictorial diagram, (8) Schematic diagram

If the load circuit is disconnected, no current flows through the generator. However, the field coils retain a small amount of magnetism known as *residual magnetism*. Because of residual magnetism, a current will begin to flow through the generator and the load circuit when a load circuit is connected. The current will continue to increase, thus causing an increase in the magnetic strength of the field. The output voltage rises proportionally with increases in current flow through the load and generator circuits. The output curve of a *series-wound DC generator* is shown in Figure 7-14. The peak of the curve is reached when magnetic saturation of the field occurs. *Magnetic saturation* prohibits any increase in output voltage. After saturation is reached, any increase in load current causes a rapid decline in the output voltage due to circuit losses.

The output voltage of a *self-excited series-wound DC generator* varies appreciably with changes in load current. However, beyond the peak of its output curve, the load current remains fairly stable, even with large variations in voltage. There are specific applications, such as arc welding,

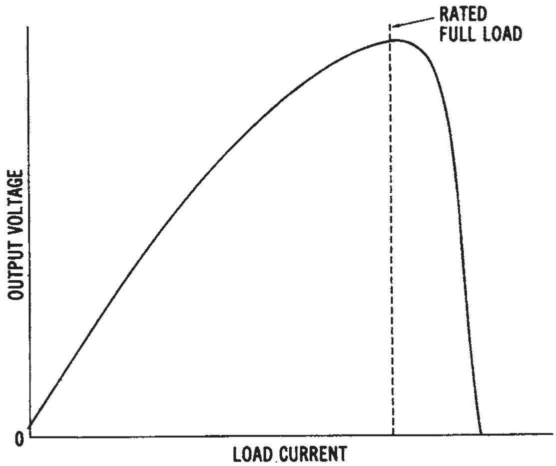


Figure 7-14. The output curve of a series-wound DC generator

that require stable load current as the voltage changes. However, the self-excited series-wound generator has very few applications.

Self-excited Shunt-wound DC Generator—connecting the field coils, the armature circuit, and the load circuit in parallel produces a shunt-wound DC generator configuration. Figure 7-15 shows this type of generator. The *output current* developed by the *generator* (I_A) has one path through the *load circuit* (I_L) and another through the *field coils* (I_F). The generator is usually designed so that the field current is not more than 5 percent of the total *armature current* (I_A).

In order to establish a *strong electromagnetic field* and to limit the amount of field current, the field coils are wound with many turns of small diameter wire. These *high-resistance* coils develop a strong field that is due to the number of turns, and, therefore, they rely very little on the amount of field current to develop a strong magnetic field.

With no load circuit connected to the shunt-wound DC generator, an induced voltage is produced as the armature rotates through the electromagnetic field. Again, the presence of *residual magnetism* in the field coils is critical to the operation of the machine. A current flows in the armature and field circuit as long as there is residual magnetism. As the generated current increases, the output voltage also increases, up to a peak level.

When a *load circuit* is connected to the shunt generator, the *armature current* (I_A) increases, because of the additional parallel path. This, then,

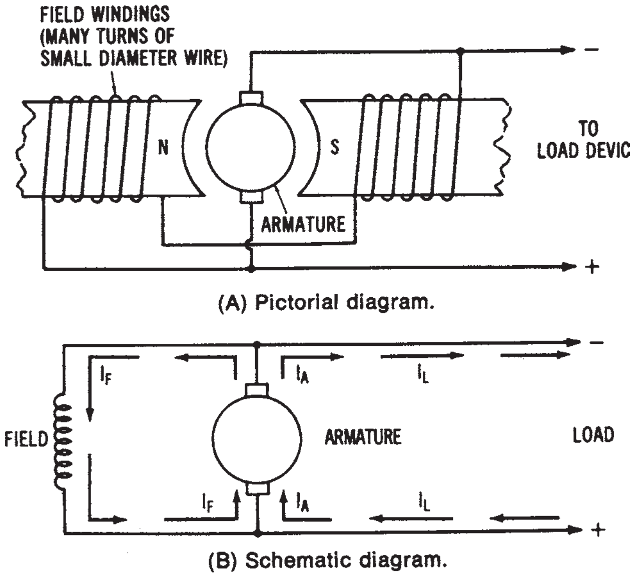


Figure 7-15. Simplified illustration of a self-excited, shunt-wound DC generator: (A) Pictorial diagram, (B) Schematic diagram

will increase the I × R drop in the armature, resulting in a smaller output voltage. Further increases in load current cause corresponding decreases in output voltage, as shown in the output curve of Figure 7-16. With small load currents, the output voltage remains nearly constant as load current

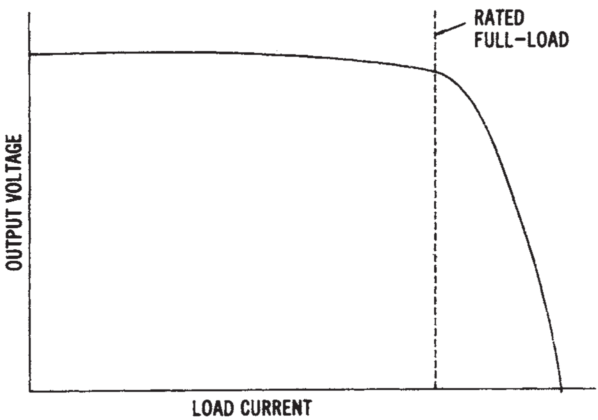


Figure 7-16. Output curve of a shunt-wound DC generator

varies. A large load causes the armature current to decrease. This decrease is desirable because it provides the generator with a built-in protective feature, in case of a short circuit.

The *self-excited shunt-wound DC generator* is used when a constant output voltage is needed. It may be used to supply excitation current to a large AC generator or to charge storage batteries. However, in applications where initial expense is not critical, the compound-wound generator described next may be more desirable.

Self-excited Compound-wound DC Generator—The *compound-wound DC generator* has two sets of field windings. One set is made of *low-resistance windings* and is connected in series with the armature circuit. The other set is made of *high-resistance* wire and is connected in parallel with the armature circuit. A *compound-wound DC generator* is illustrated in Figure 7-17.

As discussed previously, the *output voltage* of a series-wound DC generator increases with an increase in load current, while the output voltage of a shunt-wound DC generator decreases with an increase in load current. It is possible to produce a DC compound-wound generator, utilizing both series and shunt windings, that has an almost constant voltage output under changing loads. A constant voltage output can be obtained with varying loads, if the series-field windings have the proper characteristics to set up a sufficient magnetic field to counterbalance the voltage reduction caused by the I × R drop in the armature circuit.

A constant output voltage is produced by a *flat-compounded DC generator.* The no-load voltage is equal to the rated full-load voltage in this type of machine, as shown by the output curves in Figure 7-18. If the series windings produce a stronger field, the generator will possess a series characteristic. The voltage output will increase with an increase in load. A compound-wound generator whose full-load voltage is greater than its no-load voltage is called an *overcompounded DC generator.* Likewise, if the shunt windings produce a stronger field, the output will be more characteristic of a shunt generator. Such a generator, whose full-load voltage is less than its no-load voltage, is called an *undercompounded DC generator.*

Compound-wound DC generators can be constructed so that the series and shunt fields either aid or oppose one another. If the magnetic polarities of adjacent fields are the same, the magnetic fields aid each other and are said to be *cumulatively wound.* Opposing polarities of adjacent coils produce a *differentially wound* machine. For almost all applications of compound-wound machines, the cumulative-wound method is used. A generator wound in this way maintains a fairly constant voltage output with

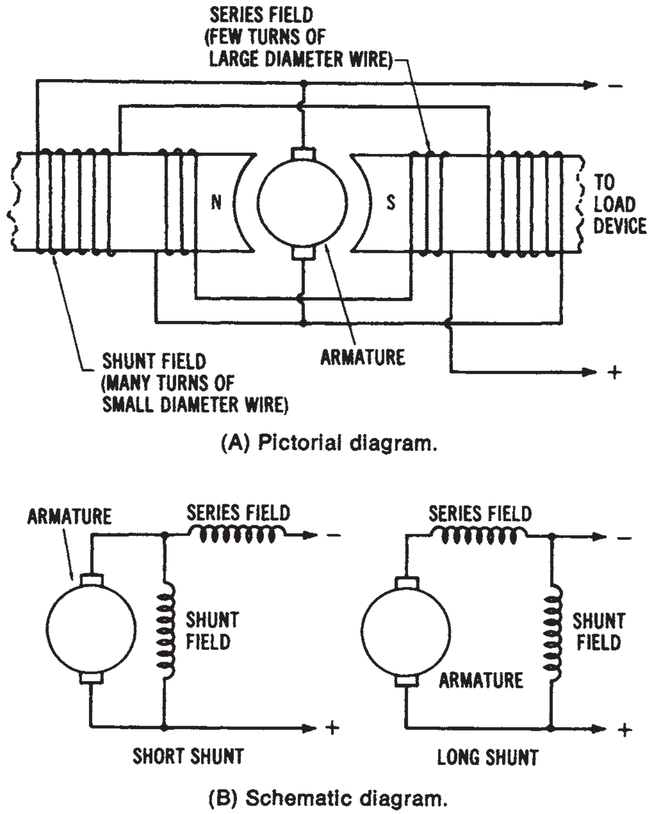


Figure 7-17. Simplified illustration of a compound-wound DC generator,: (A) Pictorial diagram, (B) Schematic diagram

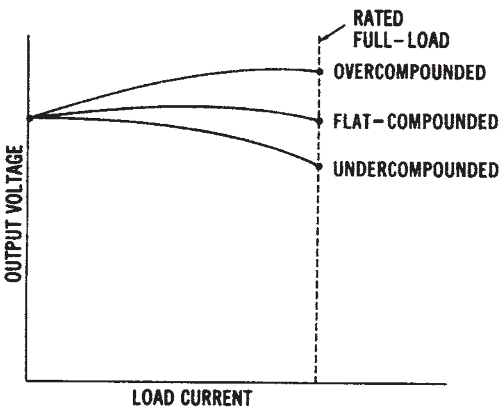


Figure 7-18. Output curves for a compound-wound DC generator

variations in load current. The compound-wound DC generator is used more extensively than other DC generators, because of its constant voltage output and its design flexibility, which allows it to obtain various output characteristics.

Common DC Generator Characteristics

DC generators are used primarily for operation with mobile equipment. In industrial plants and commercial buildings, they are used for standby power, for battery charging, and for specialized DC operations such as electroplating. In many situations, rectification systems that convert AC to DC have replaced DC generators, since they are cheaper to operate and maintain.

DC generators supply power to a load circuit by converting the mechanical energy of some prime mover, such as a gasoline or diesel engine, into electrical energy. The *prime mover* must rotate at a definite speed in order to produce the desired voltage.

When DC generators operate, a characteristic known as *armature reaction* takes place. The current through the armature windings produces a magnetic flux that reacts with the main field flux, as shown in Figure 7-19. The result is that a force is created that tends to rotate the armature in the opposite direction. As load current increases, the increase in armature current causes a greater amount of armature reaction to take place. This condition can cause a considerable amount of sparking between the brushes and the commutator. However, armature reaction may be reduced by placing windings called *interpoles* between the main field windings of the stator. These windings are connected in series with the armature windings. Thus, an increase in armature current creates a stronger magnetic field around the interpoles, which counteracts the main field distortion created by the armature conductors.

Rating of DC Generator—The *output* of a DC generator is usually rated in kilowatts, which is the electrical power capacity of a machine. Other ratings, which are specified by the manufacturer on the *nameplate* of the machine, are current capacity, output voltage, speed, and temperature. DC generators are made in a wide range of physical sizes, and with various electrical characteristics.

DC Generator Applications—DC generator use has declined rapidly since the development of the low-cost silicon rectifier. However, there are still certain applications where DC generators are used. These applications include railroad power systems, synchronous motor-generator units,

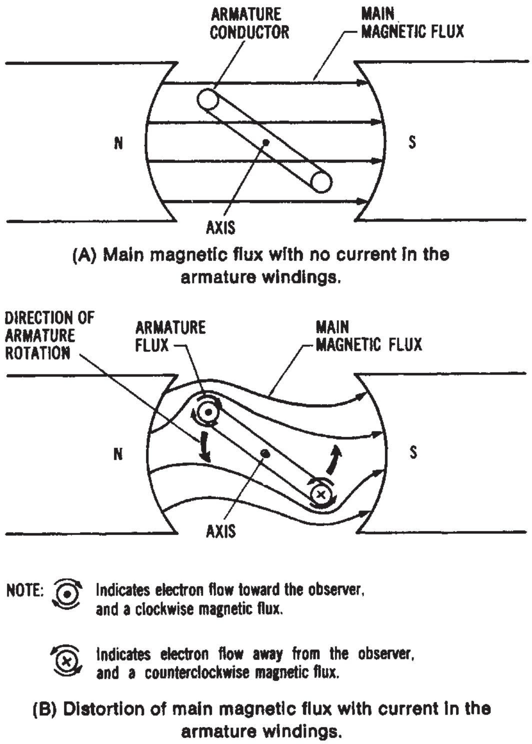


Figure 7-19. Illustration of armature reaction: (A) Main magnetic flux with no current flow in the armature windings, (B) Distortion of main magnetic flux with current flow in the armature windings

power systems for large earth-moving equipment, and DC motor-drive units for precise equipment control.

DC CONVERSION SYSTEMS

Most of the electrical power produced is 60-Hz *three-phase alternating current.* However, the use of direct current is necessary for many applications. For instance, DC motors have more desirable speed control and torque characteristics than AC motors. We have already discussed two methods of supplying direct current-batteries and DC generators. The fact that batteries and DC generators have been used as DC power sources for many years has been discussed. In many cases today, where large amounts of DC power are required, it is more economical to use a system for converting AC to DC. DC load devices may be powered by systems, called either *rectifiers* or *converters,* that change AC into a suitable form of DC.

Single-phase Rectification Systems

The simplest system for converting AC to DC is *single-phase rectification.* A single-phase rectifier changes AC to *pulsating* DC. The most common and economical method is the use of low-cost, silicon, semiconductor rectifiers.

Single-phase Half-wave Rectification

A *single-phase half-wave rectifier* circuit, such as shown in Figure 7-20, converts an AC source voltage into a pulsating direct current. Let us assume that during the positive alternation of the AC cycle, the anode of the diode is positive (Figure 7-20). The diode will then conduct, since it is *forward biased* and the pn junction is low-resistant. The positive half cycle of the alternating current will then appear across the load device (represented by a resistor). When the negative portion of the AC alternation is input to the circuit, the anode of the diode becomes negative. The diode is now *reverse biased,* and no significant current will flow through the load device (Figure 7-20B). Therefore, there will be no voltage across the load. The input and resulting *output* waveforms of the half-wave rectifier circuit are shown in Figure 7-20C. The *pulsating* direct current of the output has an average DC level. The average value of the pulsating DC produced by single-phase half-wave rectification is expressed as:

$$V_d = 0.318 \times V_{max}$$

where:

V_{dc} = the average value of rectified voltage, and
V_{max} = the peak (maximum) value of applied AC voltage.

<u>Sample Problem</u>:

Given: a single-phase, half-wave rectifier has 15 volts (rms) applied to its input.

Find: DC output voltage of the rectifier.

Solution:

$$V_{dc} = 0.318 \times V_{max}$$
$$= 0.318 \times (15\text{ V} \times 1.41)$$
$$V_{dc} = 6.72\text{ volts}$$

Certain diode ratings should be considered for half-wave rectifier circuits. The maximum *forward current* (I_{max}) is the largest current that can flow through the diode while it is forward biased, without damaging the

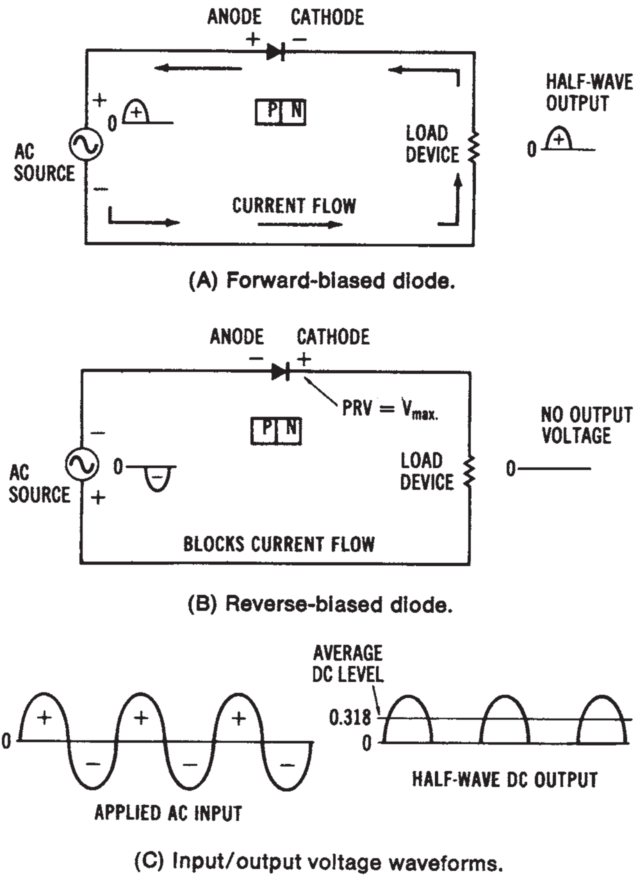


Figure 7-20. Single-phase half-wave rectification: (A) Forward-biased diode, (8) Reverse-biased diode, (C) Input/output voltage waveforms

device. The *peak inverse voltage (piv)* is the maximum voltage across the diode while it is reverse biased. For the half-wave rectifier, the maximum voltage developed across the diode is V_{max} of the applied AC. As shown in the preceding formula, the piv of a diode used in a half-wave circuit must be much larger than the DC voltage developed.

Single-phase Full-wave Rectification

In order to obtain a more pure form of DC energy, it is possible to improve upon half-wave rectification systems. Figure 7-21 shows a *single-phase full-wave rectifier* that uses two diodes and produces a DC output voltage during each alternation of the AC input. The rectified *output* of the full-wave rectifier has twice the DC voltage level of the half-wave rectifier.

The *full-wave rectifier* utilizes a *center-tapped transformer* to transfer AC source voltage to the diode rectifier circuit. During the *positive half cycle* of AC source voltage, the instantaneous charges on the transformer secondary are as shown in Figure 7-21. The peak voltage (V_{max}) is developed across each half of the transformer secondary. At this time, diode D1 is *forward biased,* and diode D2 is reverse biased. Therefore, conduction occurs from the center-tap, through the load device, through D1, and back to the outer terminal of the transformer secondary. The positive half cycle is developed across the load, as shown.

During the *negative half cycle* of the AC source voltage, diode D1 is *reverse biased,* and diode D2 is forward biased by the instantaneous charges shown in Figure 7-21. The current path is from the center-tap, through the load device, through O_2, and back to the outer terminal of the transformer secondary. The negative half cycle is also produced across the load, developing a full-wave output, as illustrated in Figure 7-21.

Each diode in a full-wave rectifier circuit must have a *piv rating* of twice the value of the peak voltage developed at the output, since twice the peak voltage ($2V_{max}$) is present across the diode when it is reverse biased. The *average voltage* for a full-wave rectifier circuit is:

$$\begin{aligned} V_{dc} &= 2\,(0.318 \times V_{max}) \\ &= 0.636 \times V_{max} \end{aligned}$$

<u>Sample Problem</u>:

Given: a single-phase, half-wave rectifier has 120 volts (rms) applied to its input.

Find: DC output voltage of the rectifier.

Solution:

$$\begin{aligned} Vdc &= 0.636 \times V_{max} \\ &= 0.636 \times (120\text{ V} \times 1.41) \\ Vdc &= 107.61\text{ volts} \end{aligned}$$

This type of rectifier circuit produces twice the DC voltage output of a half-wave rectifier circuit. However, it requires a bulky center-tapped transformer, as well as diodes that have a piv rating of twice the peak value of applied AC voltage.

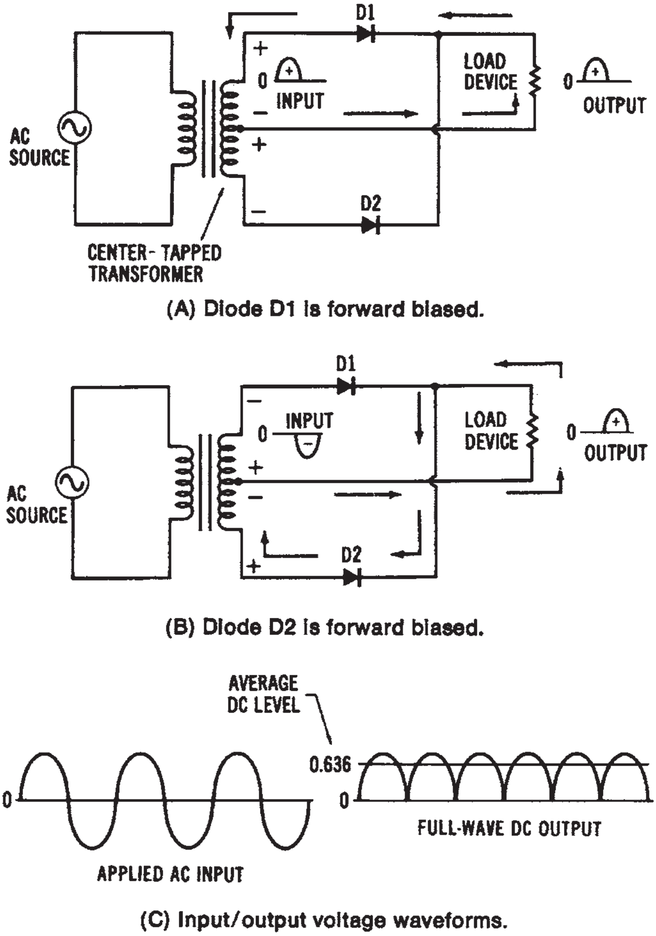


Figure 7-21. Single-phase full-wave rectification: (A) Diode D1 is forward biased, (B) Diode D2 is forward biased, (C) Input/output voltage waveforms

Single-phase Bridge Rectification

One disadvantage of the *full-wave rectifier* discussed previously is the requirement for a large center-tapped transformer. To overcome this disadvantage, four diodes may be used to form *a full-wave bridge rectifier,* as shown in Figure 7-22. Additionally, the diode piv rating is only required to be the peak output voltage value (V_{max}).

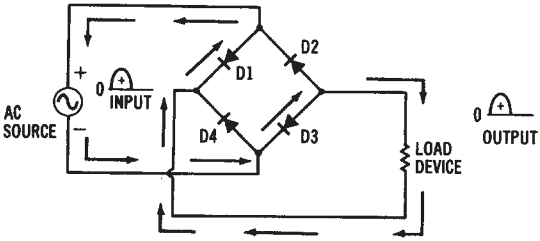
During the operation of a *bridge rectifier,* two diodes are forward biased during each alternation of the AC input. When the positive half cycle occurs, as shown in Figure 7-22A, diodes D1 and D3 are *forward biased,* while diodes D2 and D4 are *reverse biased.* This biasing condition is due to the instantaneous charges occurring during the positive alternation. The conduction path is from the instantaneous negative side of the AC source, through diode D3, through the load device, through diode D1, and back to the instantaneous positive side of the AC source.

During the *negative alternation* of the AC input, diodes D2 and D4 are *forward biased,* while diodes 01 and 03 are *reverse biased.* Conduction occurs, as shown in Figure 7-22B, from the instantaneous negative side of the source, through diode D2, through the load device, through diode 04, and back to the instantaneous positive side of the AC source. Since a voltage is developed across the load device during both half-cycles of the AC input, a full-wave output is produced, as shown in Figure 7-22, that is similar to that of the full-wave rectifier discussed previously. For high values of DC output voltage, the use of a bridge rectifier is desirable, since the diode piv rating is one-half that of other single-phase rectification methods. A typical design of a bridge rectifier unit is shown in Figure 7-22.

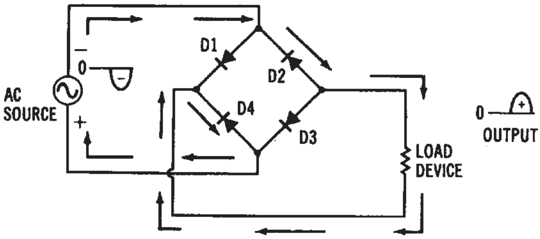
Three-phase Half-wave Rectification

Most industries are supplied with three-phase AC. It is therefore beneficial, because of the inherent advantages of three-phase power, to use *three-phase rectifiers* to supply DC voltage for industrial use. Single-phase rectifiers are ordinarily used where low amounts of DC power are required. To supply larger amounts of DC power for industrial requirements, a three-phase rectifier circuit, such as the one shown in Figure 7-23, could be employed. Three-phase rectifier circuits produce a purer DC voltage output than single-phase rectifier circuits, thus wasting less AC power.

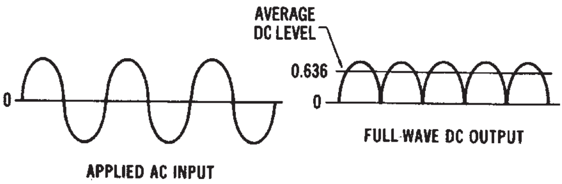
Figure 7-23 shows a *three-phase half-wave rectifier* circuit that does not use a transformer. Phases A, B, and C of the wye-connected three-phase source supply voltage to the anodes of diodes D1, D2, and D3. The load device is connected between the cathodes of the diodes and the neutral point of the *wye-connected* source. Maximum conduction occurs through diode D1, since it is forward biased, when phase A is at its peak positive value. No conduction occurs through diode D1 during the negative alternation of phase A. The other diodes operate in a similar manner, conducting during the positive AC input alternation and not conducting during the associated negative AC alternation. In a sense, this circuit combines three single-phase, half-wave rectifiers to produce a half-wave DC out-



(A) Diodes D1 and D3 are forward biased.



(B) Diodes D2 and D4 are forward biased.



(C) Input/output voltage waveforms.

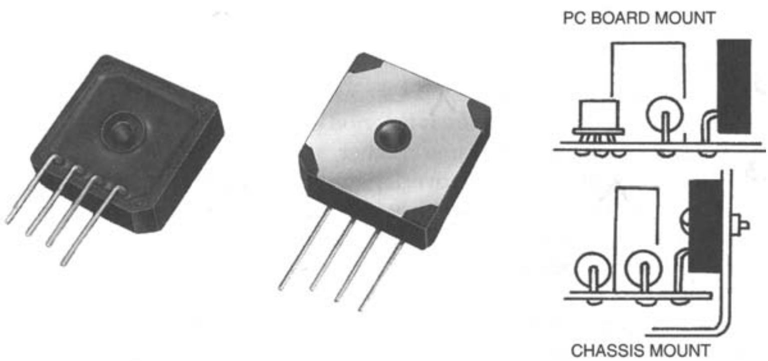
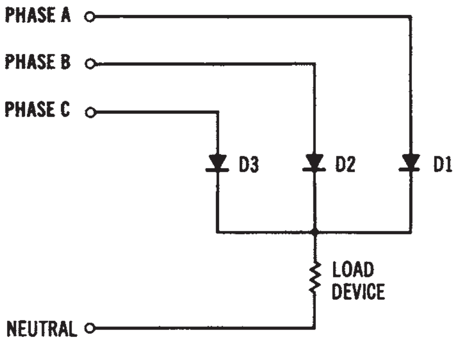


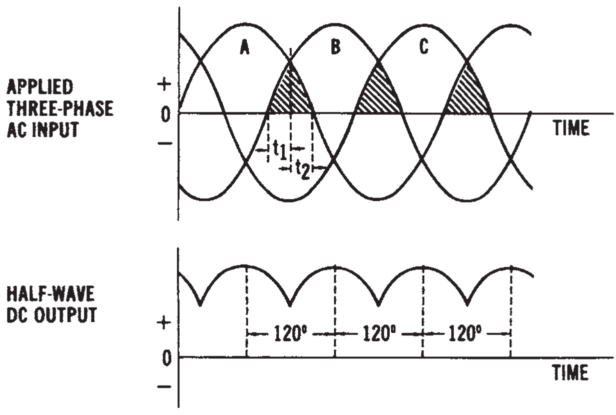
Figure 7-22. Single-phase full-wave bridge rectification: (A) Diodes D1 an D3 and forward biased, (B) Diodes D2 and D4 ore forward biased, (C) Input/output voltage waveforms, (D) Printed circuit board rectifier unit (Courtesy *Electronic* Devices, Inc.)

put, as shown in Figure 7-23B. Of course, the voltages appearing across the diodes are 120° out of phase. There is a period of time during each AC cycle when the positive alternations overlap one another, as shown in the shaded areas of the diagram (Figure 7-23B). During the overlap time period t_1, the phase A voltage is more positive than the phase B voltage, while during the t_2, interval, the phase B voltage is more positive. Diode D1 will conduct until the time period t_1 ends, then diode D_2 will conduct, beginning at the end of t_1 until the next area of overlapping is reached.

Note that *voltage* across the load device rises to a peak value twice during each phase alternation of the AC input voltage. These peaks are



(A) Schematic diagram.



(B) Input/output voltage waveforms.

Figure 7-23. Three-phase half-wave rectification: (A) Schematic diagram, (B) Input/output voltage waveforms

120° *apart.* Since the DC output voltage never falls to zero, less AC ripple is present, which results in a purer form of DC than single-phase rectifiers produce. The *average DC output voltage* (V_{dc}) is expressed as:

$$V_{dc} = 0.831 \times V_{max}$$

which compares very favorably with single-phase full-wave rectifier circuits.

Sample Problem:

Given: a three-phase, half-wave rectifier circuit has 240 volts (rms) applied to its input.

Find: the DC output voltage of the rectifier.

Solution:

$$\begin{aligned} V_{dc} &= 0.831 \times V_{max} \\ &= 0.831 \times (240\ \text{V} \times 1.41) \\ V_{dc} &= 281.2 \text{ volts} \end{aligned}$$

A disadvantage of this type of three-phase rectifier is that the AC lines are *not isolated.* Isolation is a direct connection to the AC lines; the lack of isolation could be a safety hazard. To overcome this disadvantage, a transformer may be used, as shown in Figure 7-24, to form a similar three-phase, half-wave rectifier. The secondary voltage may be either increased or decreased by the proper selection of the transformer, thus providing a variable DC voltage capability. The circuit illustrated in Figure 7-24 has a delta-to-wye-connected transformer. The operation of this circuit is identical to that of the three-phase, half-wave rectifier previously discussed; however, line *isolation* has been accomplished.

Three-phase Full-wave Rectification

The *full-wave* counterpart of the three-phase, half-wave rectifier circuit is shown in Figure 7-24A. This type of rectifier circuit is popular for many industrial applications. Six rectifiers are required for operation of the circuit. The anodes of D4, D5, and D6 are connected together at point A, while the cathodes of D1, D2, and D3 are connected together at point B. The load device is connected across these two points. The three-phase AC lines are connected to the anode-cathode junctions of D1 and D4, D2 and D5, and D3 and D6. This circuit does not require the neutral line of the three-phase source; therefore, a delta-connected source could be used.

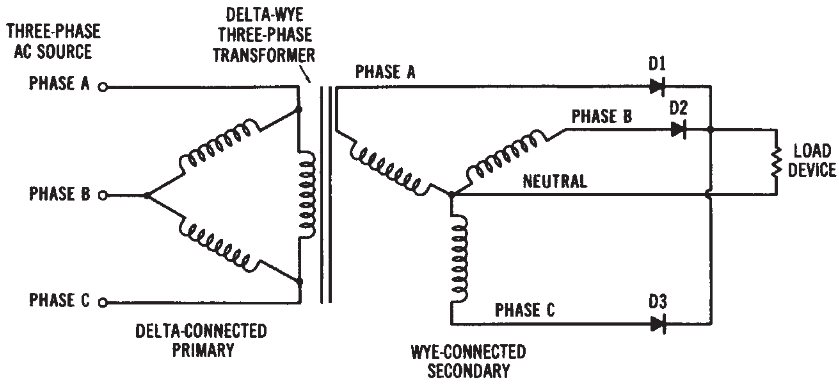


Figure 7-24. Three-phase half-wave rectification using a transformer

The resulting DC *output voltage* of the *three-phase, full-wave rectifier* circuit is shown in Figure 7-25B. The operation of the circuit is similar to that of a single-phase bridge rectifier in many respects. At any single instant of time during the three-phase AC input cycle, the anode voltage of one of the diodes is more positive than that of all the others, while the cathode voltage of another diode is more negative than that of all the others. These two diodes will then form the conduction path for that time period. This conducting action is similar to a bridge rectifier, since two diodes conduct during a time interval. Each rectifier in this circuit conducts during one-third of an AC cycle (120°). Peak positive DC output voltage occurs during every 60° of the three-phase AC input.

Rotary Converters

Another method that has been used to convert AC to DC is the use of a *rotary converter.* Rotating AC-to-DC converters are seldom used today. However, a motor-driven generator unit, such as shown in Figure 7-26 can be used to convert DC to AC. This system is called an *invertor.* When operated as a converter to produce DC, the machine is run off an AC line. The AC is transferred to the machine windings through slip rings and converted to DC by a split-ring commutator located on the same shaft. The amount of DC voltage output is determined by the magnitude of the AC voltage applied to the machine. Converters may be designed as two units, with motor and generator shafts coupled together, or as one unit housing both the motor and generator.

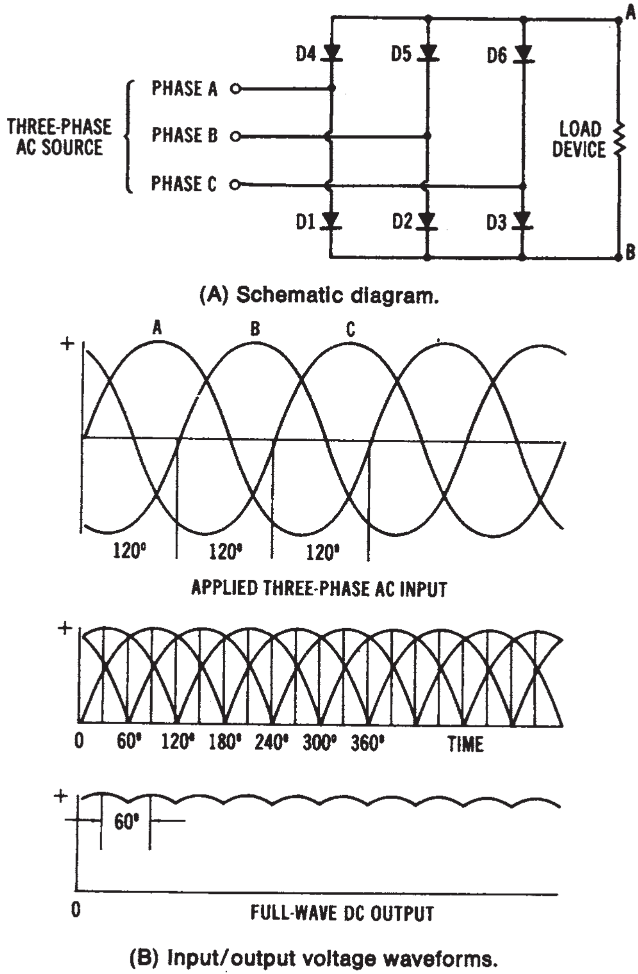


Figure 7-25. Three-phase full-wave rectification: (A) Schematic diagram, (B) Input/output voltage waveforms

DC FILTERING METHODS

The *pulsating direct current* produced by both single-phase and three-phase rectifier circuits is not *pure* DC. A certain amount of AC ripple is evident in each type of rectifier. For many applications, a smooth DC output voltage, with the AC ripple removed, is required. Circuits used to remove AC variations of rectified DC are called *filter circuits.*

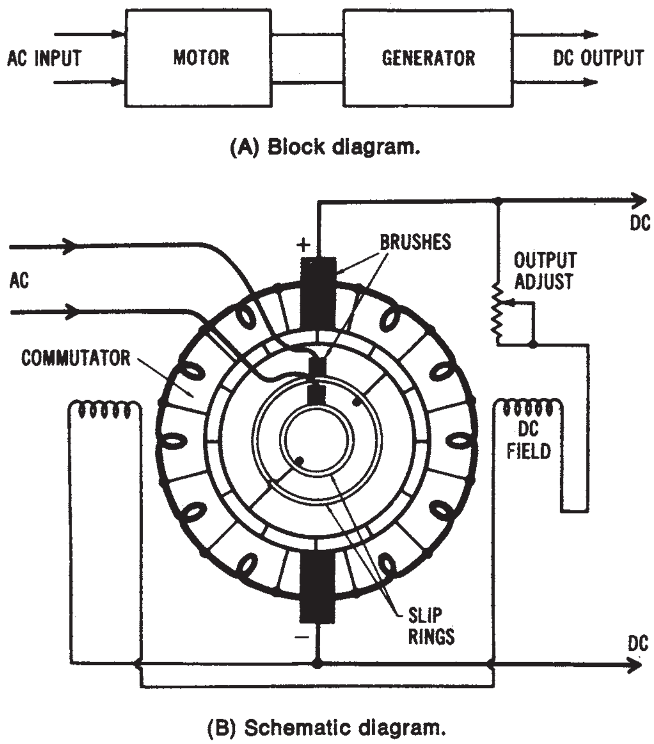


Figure 7-26. Rotary AC-to-DC converter

The output of a rectifier has a DC value and an AC ripple value, as shown in Figure 7-27. To gain a relative index of the amount of AC variation, the *ripple factor* of a rectifier output waveform may be determined. Ripple factor is expressed as:

$$r = \frac{V_{r(rms)}}{V_{dc}}$$

where:

r = the ripple factor,
$V_{r(rms)}$ = the rms value of the AC component, and
V_{dc} = the average value of the rectified DC voltage.

Another index used to express the amount of AC ripple is the percent of ripple of a rectified DC voltage. *Ripple percentage* is expressed as:

$$\% \text{ ripple} = \frac{V_{r(rms)}}{V_{dc}} = 100$$

<u>Sample Problem</u>:

Given: a power supply has an AC input of 24 volts (rms) and a p-p ripple of 1.5 volts at its output, as measured with an oscilloscope.

Find: DC voltage output of the power supply.

Solution:

$$V_{DC} = V_{max} - \frac{V_{r(p-p)}}{2}$$

$$= (24\text{ V} \times 1.41) - \frac{1.5\text{ V}}{2}$$

$$V_{DC} = 33.09 \text{ volts}$$

A full-wave rectified voltage has a lower percentage of ripple than a half-wave rectified voltage. When a DC supply must have a low amount of ripple, a full-wave rectifier circuit should be used.

Capacitor Filter

A simple *capacitor filter* may be used to smooth the AC ripple of a rectifier output. Figure 7-28 shows the result of adding a capacitor across the output of a single-phase, full-wave bridge rectifier. The output waveform after the capacitor has been added is shown in Figure 7-28C.

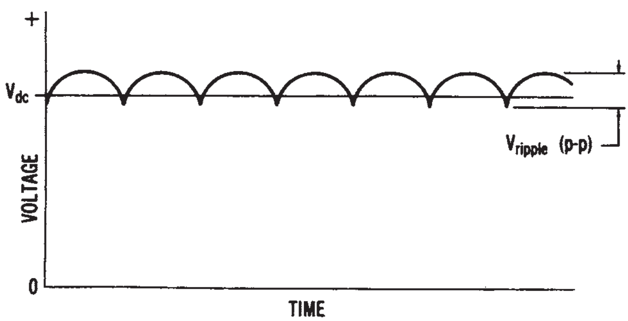


Figure 7-27. Rectifier output voltage

The *ideal* filtered DC voltage would be one with *no AC ripple* and a value equal to the peak voltage (V_{max}) from the rectifier output. Note that in Figure 7-28, the value of V_{dc} is approaching that of V_{max}, and compare this to the full-wave rectified voltage of Figure 7-28. There are two time intervals shown in Figure 7-28. Time period t_1 represents diode conduction that charges the filter capacitor (C) to the peak rectified voltage (V_{max}). Time period t_2 is the time required for the capacitor to discharge through the load (R_L).

If a different value of filter capacitor were put into the circuit, a change in the rate of discharge would result. If capacitor C discharged a very small amount, the value of V_{dc} would be closer to the value of V_{max}. With *light loads (high resistance)*, the capacitor filter will supply a high DC voltage with little ripple. However, with a *heavy (low resistance) load* connected, the DC voltage would drop, because of a greater ripple. The increased ripple is caused by the lower resistance discharge path for the filter capacitor. The effect of an increased load on the filter capacitor is shown in Figure 7-28.

By utilizing the value indicated on the waveforms of Figure 7-28, it is possible to express V_{dc} and $V_{r(rms)}$ as:

$$V_{dc} = V_{max} - \frac{V_{r(p-p)}}{2}$$

and

$$V_{r(rms)} = \frac{V_{r(p-p)}}{2 \times \sqrt{3}}$$

Sample Problem:

Given: the measured AC ripple voltage at the output of a filtered power supply is 0.8V (rms), and the DC output voltage is 15.0 volts.

Find: the percent ripple of the power supply.

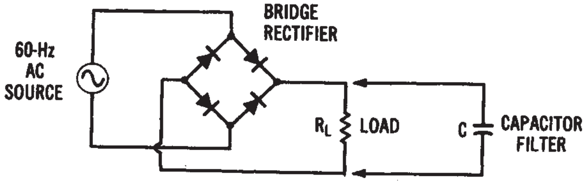
Solution:

$$\%r = \frac{0.8V \times 100}{15.0\ V}$$

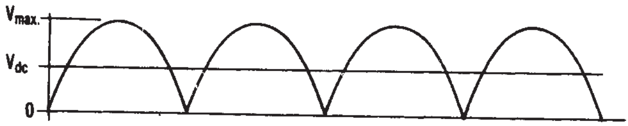
$$= 5.33\%$$

Sample Problem:

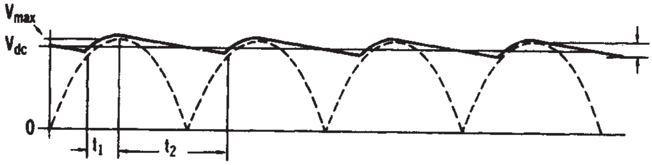
Given: a power supply has a p-p ripple of 1.2 volts at its output.
Find: the rms ripple voltage of the power supply.



(A) Bridge rectifier circuit with filter capacitor.



(B) Full-wave output waveform with no filter capacitor.



(C) Full-wave output waveform with filter capacitor across load.

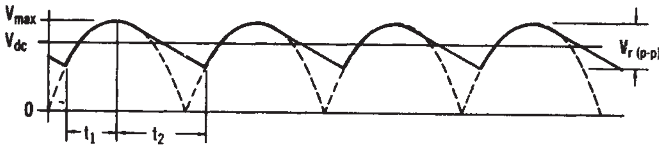


Figure 7-28. Filter capacitor operation: (A) Bridge rectifier circuit with filter capacitor, (8) Full-wave output waveform with no filter capacitor, (C) Full-wove output waveform with filter capacitor across load, (D) Full-wave output waveform with filter capacitor across heavier (lower resistance) load

Solution:

$$V_{r(rms)} = \frac{V_{r(p-p)}}{2 \times \sqrt{3}}$$

$$= \frac{1.2\ \text{V}}{3.46}$$

$$V_{r(rms)} = 0.34\ \text{V}$$

We can also express the amount of *ripple* of a 60-Hz full-wave filter-capacitor circuit with a light load as:

$$V_{r(rms)} = \frac{2.4 I_{dc}}{C}$$

Sample Problem:

Given: a power supply has a DC load current of 800 mA, and a capacitor filter of 300 uF is used.

Find: the value of ripple voltage.

Solution:

$$V_{r(rms)} = \frac{2.4 I_{dc}}{C}$$

$$= \frac{2.4 \times 800 \text{ mA}}{300 \text{ uF}}$$

$$V_{r(rms)} = \frac{2.4}{R_L C}$$

$$r = \frac{2.4}{R_L C}$$

where:

I_{dc} = the load current in milliamperes,
C = the filter capacitor value in microfarads, and
R_L = the load resistance in kilohms.

Sample Problem:

Given: a power supply has a DC load resistance of 500 ohms connected to its output, and a capacitor filter 100 uF is used.

Find: the value of ripple voltage.

Solution:

$$r = \frac{2.4}{R_L C}$$

$$= \frac{2.4}{0.5 \text{ K} \times 10.0 \text{ uF}}$$

$$r = 0.00048 = 0.048\%$$

The *average DC voltage* output can be expressed as:

$$V_{dc} = V_{max} - \frac{4.16 I_{dc}}{C}$$

Sample Problem:

Given: the peak AC voltage applied to a power supply is 28.2 volts. A 500 uF filter capacitor is used.

Find: the DC output voltage when 300 mA of load current flows.

Solution:

$$V_{dc} = V_{max} - \frac{4.16 \times I_{dc}}{C}$$

$$= 28.2 - \frac{4.16 \times 300 \text{ mA}}{500 \text{ uF}}$$

$$V_{dc} = 25.7 \text{ volts}$$

Again, the value of V_{dc} is for a full-wave filter-capacitor circuit with a light load.

With a *heavier load (lower resistance)* connected to the filter circuit, more *current (I_{dc})* is drawn. As I_{dc} increases, V_{dc} decreases. However, if the value of filter capacitor C is made larger, the value of V_{dc} becomes closer to that of V_{max}. The value of C for a full-wave rectifier can be determined by using the equation:

$$C = \frac{2.4 \times I_{dc}}{V_{r(rms)}}$$

Sample Problem:

Given: a power supply is rated at 950 mA of load current and maximum ripple of 0.5 volts (rms).

Find: the minimum value of capacitor filter needed for a filter using a full-wave rectifier.

Solution:

$$C = \frac{2.4 \times I_{dc}}{V_{r(rms)}}$$

$$= \frac{2.4 \times 950 \text{ mA}}{0.5 \text{ V}}$$

$$C = 4550 \text{ uF}$$

It should be pointed out that as the value of C increases, the value of the peak current through the diodes will also increase. There is, therefore, a practical limit for determining the value of C that is reflected in the foregoing equation.

The *capacitor filter* produces a high DC voltage with low AC ripple for light loads. However, its major disadvantages are higher ripple and lower Vdc at heavier loads, poor voltage regulation, and high peak current through the diodes.

RC Filter

It is possible to improve upon the previous filter circuit by using an *RC filter.* Figure 7-29 shows an RC filter stage. This filter has lower ripple than a capacitor filter, but has a lower average DC voltage, because the voltage is dropped across R1.

The purpose of R1 and C2 is to add another filter network, in addition to C1, to further reduce the ripple. This circuit also operates best with light loads connected. It is possible to have many stages of RC filters to further reduce AC ripple.

Pi- or π-type Filter

The use of the resistor (R1) in the RC filter is not desirable in many cases, since it reduces the average DC output of the circuit. To compensate for the DC voltage reduction, a *pi-type (or π-type) filter* may be used. Figure 7-30 shows this type of filter. The advantage of the choke coil (L1) over the resistor (R1) of the RC filter is that it offers only a small DC series re-

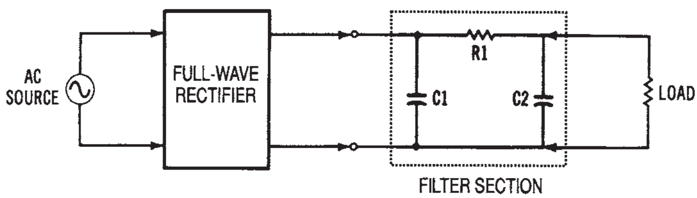


Figure 7-29. An RC filter circuit

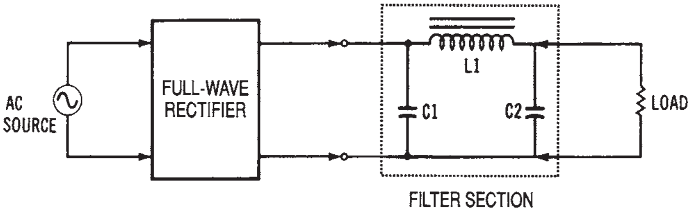


Figure 7-30. A pi-type filter circuit

sistance, but its AC impedance is much larger. It therefore passes DC and blocks the AC component of the rectified voltage.

DC REGULATION METHODS

The concept of *voltage regulation* can best be understood by referring to the formula:

$$VR = \frac{V_{NL} - V_{FL} \times 100}{V_{FL}}$$

where:

VR = the voltage regulation in percent,
V_{NL} = the no-load (open-circuit) voltage, and
V_{FL} the rated, full-load voltage.

Sample Problem:
Given: a power supply has a no-load voltage of 24.85 volts and a rated full-load voltage of 24.0 volts.

Find: the voltage regulation of the power supply.

Solution:

$$\%VR = \frac{V_{NL} - V_{FL} \times 100}{V_{FL}}$$

$$= \frac{24.85 - 24.0 \times 100}{24.0}$$

$$= \quad \%\ VR = 3.5\%$$

In an ideally regulated circuit, V_{NL} would equal V_{FL}.

In all types of power supplies that convert AC to DC, the DC output levels are affected by variations in the load. The lower the percentage of *regulation* (approaching 0 percent), the better regulated the circuit is. For instance, power supplies are capable of having a voltage regulation of less than 0.01 percent, which means that the value of the load has little effect on the DC output voltage produced. A well-regulated DC *power supply* is necessary for many industrial applications.

Voltage Regulators

A simple *voltage regulation* circuit that uses a zener diode is shown in Figure 7-31. This circuit consists of a series resistor (Rs) and a zener diode (D1) connected to the output of a rectifier circuit. However, we should review zener diode operation before discussing the circuit operation.

Zener diodes are similar to conventional diodes when they are *forward biased.* When they are *reverse biased,* no conduction takes place until a specific value of *reverse breakdown voltage (or "zener" voltage)* is reached. The zener is designed so that it will operate in the reverse breakdown region of its characteristic curve (see Figure 7-31B). The reverse breakdown voltage is predetermined by the manufacturer. When used as a voltage regulator, the zener diode is reverse biased so that it will operate in the breakdown region. In this region, changes in current through the diode have little effect on the voltage across it. The constant-voltage characteristic of a zener diode makes it desirable for use as a regulating device.

The circuit of Figure 7-31A is a *zener diode shunt regulator.* The zener establishes a constant voltage across the load resistance within a range of rectified DC voltages and output load currents. Over this range, the voltage drop across the zener remains constant. The current through the zener (I_Z) will vary to compensate for changes in load resistance, since $I_Z = I_T - I_L$. Thus, the output voltage will remain constant.

Transistor Voltage Regulators

An improvement over the zener voltage regulator is a *transistorized regulator,* as shown in the circuit in Figure 7-32. This regulator has transistor Q1 placed in series with the load device (R_L). Transistor Q1, then, acts to produce variable resistance to compensate for changes in the input voltage. The collector-emitter resistance of Q1 varies automatically with changes in the circuit conditions. The zener diode establishes the DC bias placed on the base of transistor Q1. When this circuit is operating proper-

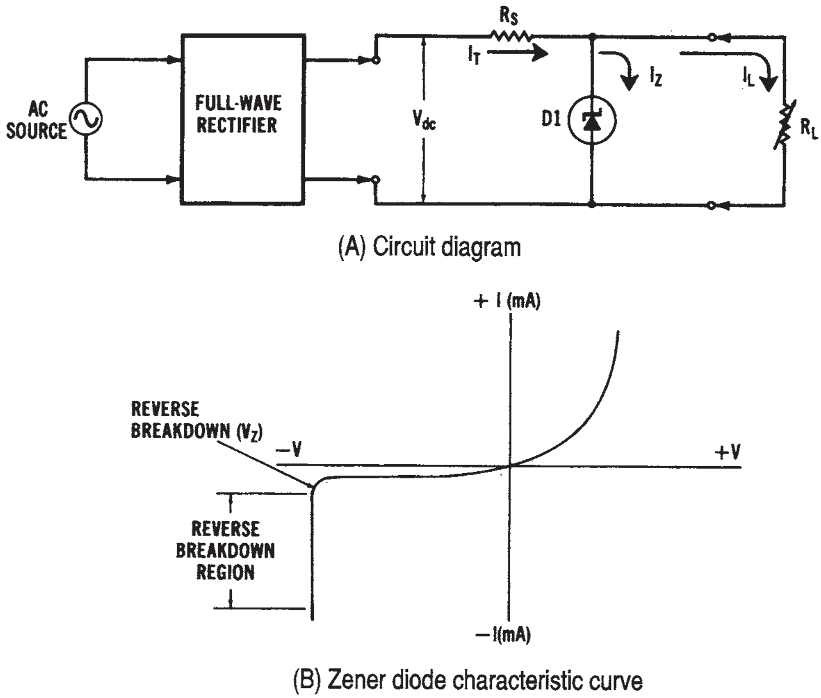


Figure 7-31. Zener diode voltage regulator: (A) Circuit diagram, (B) Zener diode characteristic curve

ly, if the voltage across the load increases, the rise in emitter voltage makes the base less positive. The current through Q1 will then be reduced, which results in an increase in the collector-emitter resistance of Q1. The increase in resistance will cause a larger voltage drop across transistor Q1, which will now compensate for the change in voltage across the load. Opposite conditions would occur if the load voltage were to decrease. Many variations of this circuit are used in regulated power supplies today.

Shunt regulators are also used in DC power supplies. The circuit of Figure 7-33 is a shunt voltage regulator. Again, the zener diode (D1) is used to establish a constant DC bias level. Therefore, voltage variations across the DC output will be sensed only by resistor R2. If the DC output voltage rises, an increased positive voltage will be present at the base of transistor Q2. The increased forward bias on transistor Q2 will cause it to conduct more. This makes the base of transistor Q1 more positive, and Q1 will then conduct more heavily. Increased current flow through both transistors causes an increase in the voltage drop across resistor R1. This increased voltage drop across R1 will counterbalance the rise in output voltage. Thus, the DC output voltage will remain stabilized. Decreases in DC output voltage would cause the circuit action to reverse. In addition, *integrated circuit voltage regulators* are now used extensively in power supplies that convert AC to DC.

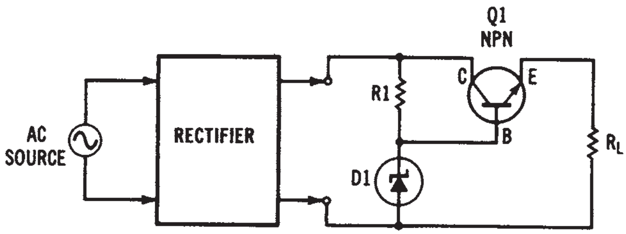


Figure 7-32. Transistor series voltage regulator circuit

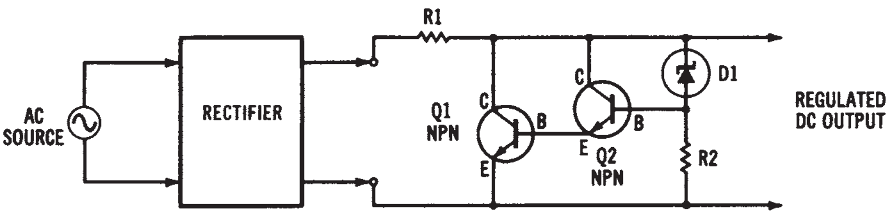


Figure 7-33. Transistor shunt voltage regulator circuit