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TRANSFORMERS AND AC CIRCUITS

Lesson One

Principles of Alternating Current
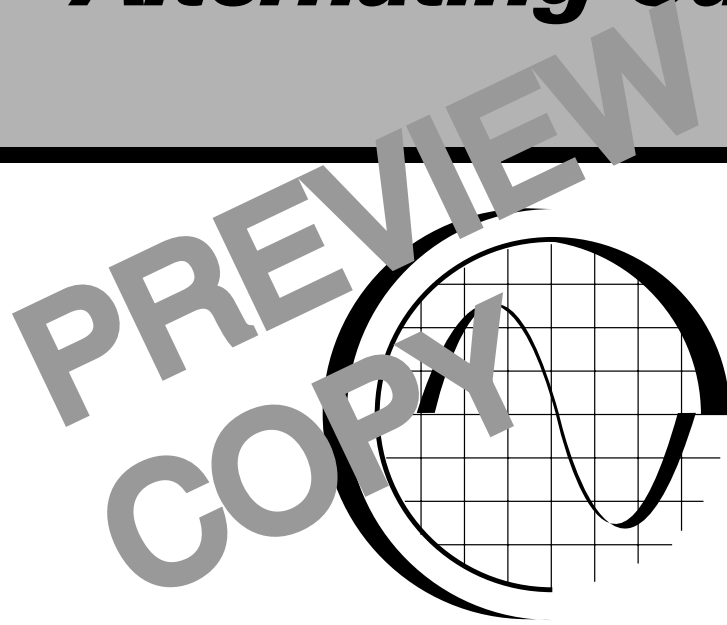
TPC Training Systems

20301

Lesson

1 *Principles of Alternating Current*

TOPICS

AC and DC Electricity
Waveforms
AC Waveform
Frequency
Peak-to-Peak Values

Average Values
Effective Values
Energy Storage
Faraday's Law
Basic Circuit Concepts

OBJECTIVES

After studying this lesson, you should be able to…

- State of definition of a waveform.
- Demonstrate how to calculate the frequency of an alternator's output.
- Explain how to calculate an effective value.

- Name the kinds of values that must be used when applying the dc rules and laws to ac circuits.

KEY TECHNICAL TERMS

Waveform 1.09 a graph showing changes in electrical values over a period of time

Sine wave 1.14 the most common ac waveform, based on the sine function in trigonometry

Amplitude 1.17 the maximum height of a waveform above the horizontal axis

Frequency 1.19 the number of cycles an electrical system goes through in a unit of time

Hertz 1.20 the standard unit of frequency, equal to one cycle per second

Peak-to-peak value 1.40 the distance of a waveform from the maximum point to the minimum point, equal to twice the amplitude if the waveform is symmetrical about zero

AC circuits are more complex than dc circuits because alternating current is always changing while direct current remains steady. In order to maintain the equipment in your plant, you must first understand the fundamentals of alternating current.

This lesson explains the principles and characteristics of ac circuits. This information will help you understand why and how certain electrical equipment works. It will also make the job of troubleshooting electrical faults easier.

This lesson explains waveforms, sine waves, amplitude, and peak-to-peak values. It also explains how to calculate frequency and average and effective values. The last section of this lesson explains the basic laws and rules governing electric circuits.

AC and DC Electricity

1.01   The electricity from an electrochemical cell, from a battery, or from a dc power supply is the simplest kind of electricity.

- The potential difference between the terminals is constant and steady. The positive terminal is always positive, and the negative terminal is always negative.

- The current from such a source is steady and in one direction. The electrons move in only one direction and at a constant rate.

- The calculations of power, energy, current, and other values do not depend on which instant of time you are referring to, because all the values are the same at one instant as at any other instant.

1.02   The electricity commonly used in industrial plants, homes, hospitals, and almost every other place is more complex. This electricity almost always comes from the generating plants of public utilities.

- The potential difference between the terminals is always changing. The terminal that is positive at one moment is negative a moment later.

- The current also keeps changing. It alternates back and forth from one direction to the other. Electrons move in both directions.

- The calculations of power, energy, current, and other values depend on which instant of time you are referring to. All the values in the equations keep changing from instant to instant, changing the result.

1.03   Figure 1-1 is a diagram showing the difference between direct current (dc) and alternating current (ac). Each line represents a conductor. The dots on the lines represent the positions of a single electron after equal intervals of time. The positions are numbered.

1.04   On the line labeled dc, the electron starts from the position labeled 0.

- At the end of the first interval of time, it has moved to the position labeled 1.

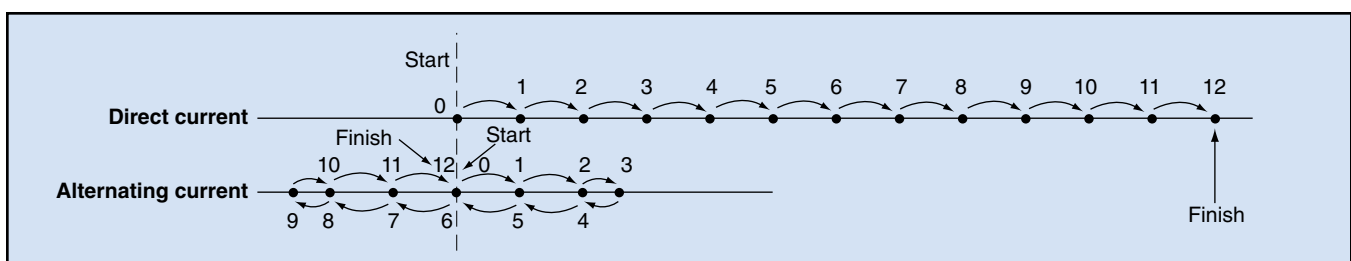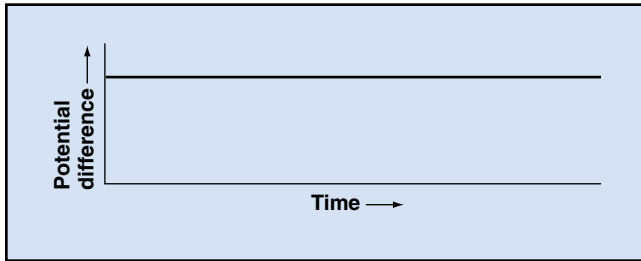**Fig. 1-1. Movement of one electron in a conductor**

Fig. 1-2. DC Waveform

- At the end of the second interval of time, it has moved an equal distance to the position labeled 2.

1.05   This process continues. The electron moves equal distances in equal time intervals. At the end of the twelfth interval, it has moved twelve equal distances along the wire and is in the position labeled 12.

1.06   On the line labeled ac, the electron also starts from the position labeled 0. The time intervals are the same as those for the dc line. But the electron does not move equal distances, because its speed changes. It reaches a certain point, labeled 3, and then reverses its motion. At the end of the sixth interval, it has returned to its starting point.

1.07   Then the electron moves to the left of its starting position. At the end of the ninth interval, it

Fig. 1-3. Bell circuit

again reverses its direction and heads back toward the starting position. At the end of the twelfth interval, the electron has returned to the starting position.

1.08   In an ac circuit, each electron moves in a special way. Its motion is exactly like the motion of a mass moving up and down on the end of a spring. It moves at its highest speed past the central position, and slows down as it reaches each extreme. It reverses its direction at regular intervals. The overall motion of the electron over a long period of time—many oscillations—is zero, just as for the mass on the spring.

Waveforms

1.09   A *waveform* is a graph showing how electrical values change over a period of time.

- The value being measured is always represented by the height of the graph, measured on the *vertical axis*.

- Time is always represented along the *horizontal axis*.

1.10   A typical waveform for dc potential difference is shown in Fig. 1-2. The graph is a straight, horizontal line, indicating that the potential difference does not change as time goes on.

1.11   Figure 1-3 shows the circuit for a bell operated by a battery.
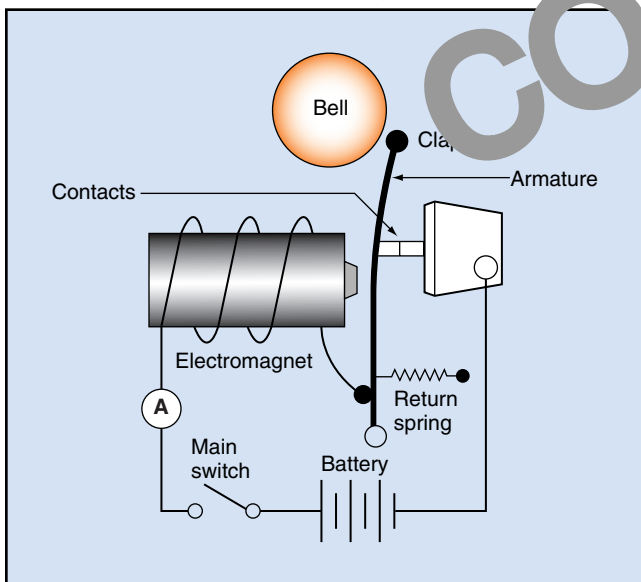
- When current flows in the coil of the electromagnet, the magnet attracts the armature and the clapper strikes the bell.

- When the armature moves, it opens the contact that controls the flow of electricity through the coil, and the current is interrupted.

- The electromagnet then releases the armature, and the spring pulls the armature back.

- As it returns, the armature closes the contacts again, and the cycle repeats itself.

1.12   A graph of the current in the electromagnet coil looks like the waveform in Fig. 1-4.

- The current increases quickly to a constant value when the bell is first turned on.

- The current remains constant until the armature moves far enough to open the contacts.

- Then the current drops to zero until the contacts close again.

This cycle repeats itself as long as the main switch stays closed.

AC Waveform

1.13   The waveform for alternating current has a special shape. This shape is determined by the construction of the generator that produces alternating current. The shape is the same as the shape of a graph showing the height of a mass oscillating up and down on the end of a spring.

1.14   The ac waveform is called a *sine wave*. The name "sine" comes from the branch of mathematics called *trigonometry*. The waveform matches a graph of the sine of an angle as the angle increases. The output of an ac generator is proportional to the sine of the angle of the spinning rotor in the generator. The waveform for one complete revolution of the generator is shown in Fig. 1-5.

1.15   In ac electricity, the potential difference changes in a very regular way.

- It increases from zero to a maximum value.

- Then it decreases to zero again.

- It continues decreasing until it reaches a maximum negative value.

- Then it increases and returns to zero.

1.16   This complete set of values is called a *cycle*. It repeats continuously as long as the circuit remains unchanged.

1.17   The maximum height of the waveform is called its *amplitude*. It is the value at the peak of the waveform. In a sine wave, the amplitude is the height of the peak above the horizontal axis. The minimum points—the "negative peaks"—are an

Fig. 1-4.   Waveform for pulsating dc
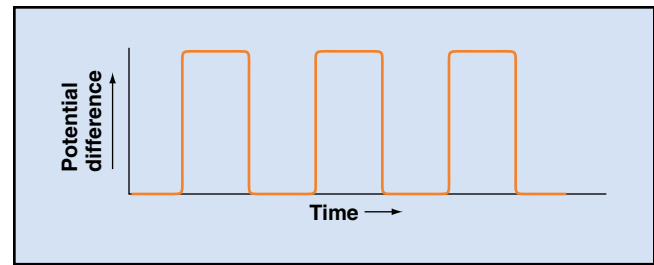
equal distance below the horizontal axis, as shown in Fig. 1-5.

1.18   Almost all the ac waveforms you will work with will be sine waves. They may differ in their height above and below the horizontal axis, and they may differ in the amount of time between peaks. Variations in both these values are shown in Fig. 1-6, on the following page. But all the sine waves will have the same basic shape.

Frequency

1.19   How many cycles an electrical system goes through in a unit of time is called the *frequency* of the system. Most ac equipment is designed to operate on an input that has a specific frequency. If the input frequency differs from the frequency the equipment is designed for, the equipment will not work properly.

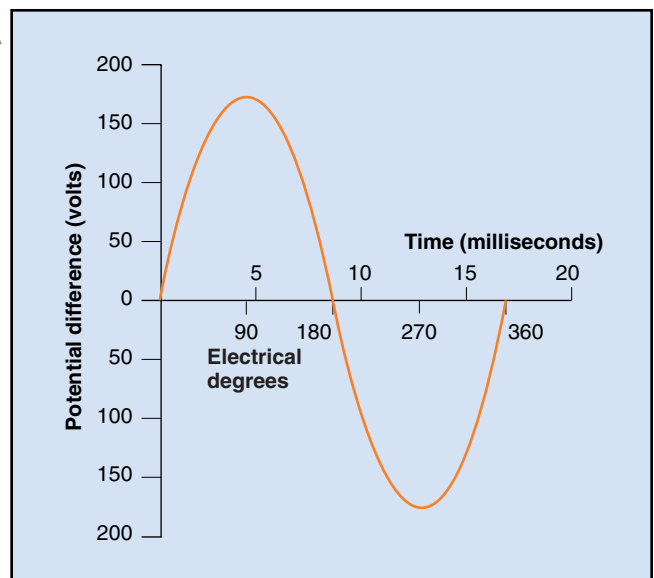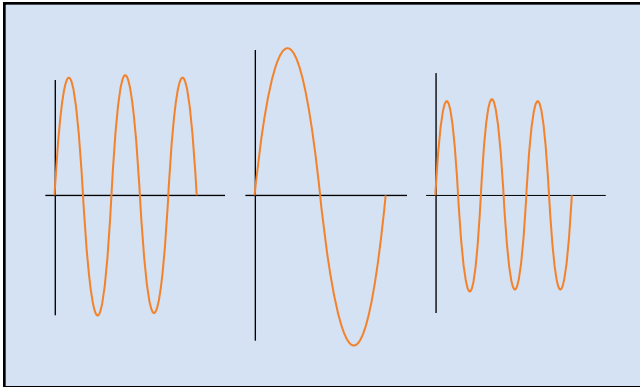**Fig. 1-5.   AC cycle for 120 V, 60 Hz**

Fig. 1-6. AC waveforms

1.20 Frequency is measured in *hertz*, abbreviated Hz. One hertz is defined as one cycle per second. The unit is named in honor of Heinrich Hertz, a German physicist who, in 1887 and 1888, performed important experiments dealing with the formation of electromagnetic waves.

1.21 In the United States and Canada, the standard ac frequency is 60 Hz. Many other countries have also adopted a standard ac frequency of 60 Hz, and nearly all the rest have adopted 50 Hz as the standard.

1.22 Figure 1-7 is the standard waveform for electric power at 60 Hz. It is a sine wave that repeats 60 times each second. Figure 1-7 shows 15 complete cycles, lasting a total of one-fourth of a second. A single complete cycle in this series lasts $1/60$ of a second.

1.23 The amount of time required for one complete cycle is related to the frequency. This amount of time is called the *period* of the waveform. On the graph, it is the amount of time represented by the horizontal distance from one peak to the next. Mathematically, the period is the reciprocal of the frequency.

$$P = \frac{1}{f}$$

where P = period, measured in seconds

f = frequency, measured in Hz

1.24 High frequencies are measured in *kilohertz* (thousand of hertz, abbreviated kHz) and in *megahertz* (millions of hertz, abbreviated MHz). Frequencies measured in these units are common in radio, television, and other electronic equipment. Electrical equipment in the plant normally runs on frequencies measured simply in hertz, as for example, 50 Hz or 60 Hz.

1.25 To generate ac electricity, a conductor must pass through a magnetic field. The magnetic field exists between two magnetic poles, one north and one south. Some alternators have complex magnetic fields produced by more than one pair of poles. For example, a four-pole alternator has two north poles and two south poles located 90° apart around the machine.

1.26 An alternator cannot have an odd number of magnetic poles. The poles are always in pairs—a north pole plus a south pole—and they always alternate around the machine. As the rotor spins, each conductor goes past a north pole, then a south pole, and then comes to another north pole. As it does so, the output of the conductor goes through one complete cycle of 360 electrical degrees.

Fig. 1-7. 60 Hz ac waveform
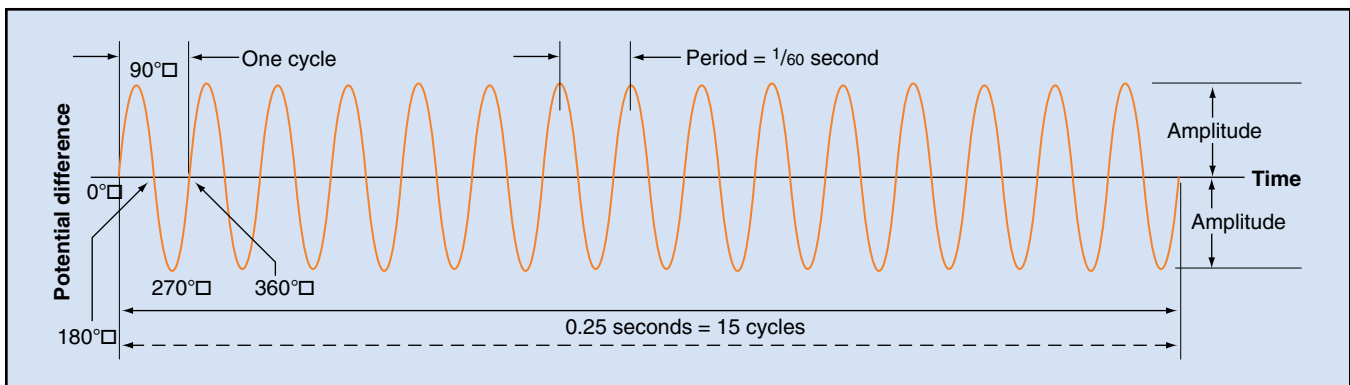
1.27   The number of cycles in one complete revolution of the rotor equals half the number of poles. The following equation expresses this relationship mathematically:

$$C = \frac{N}{2}$$

where C = number of electrical cycles/revolution

N = number of poles in the alternator.

1.28   You can use this information to figure out the frequency of an alternator's output. If S is the rotor speed in revolutions per unit of time, then the frequency of the output in Hz is calculated as shown below.

$$f = \frac{\text{cycles}}{\text{time}} = \frac{\text{cycles}}{\text{revolution}} \times \frac{\text{revolution}}{\text{time}}$$

$$= C \times S$$

$$= \frac{N}{2} \times S$$

1.29   For example, suppose a two-pole alternator rotates at 3600 revolutions per minute (rpm). You can calculate the frequency of the output as follows:

$$f = \frac{N}{2} \times S$$

$$= \frac{2 \text{ poles / rev.}}{2 \text{ poles / cycle}} \times 3600 \frac{\text{revolutions}}{\text{minute}}$$

$$= 3600 \frac{\text{cycles}}{\text{minute}}$$

$$= 3600 \frac{\text{cycles}}{60 \text{ seconds}}$$

$$= \frac{3600 \text{ cycles}}{60 \text{ second}}$$

$$= 60 \frac{\text{cycles}}{\text{second}}$$

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

1.30   Notice that if the speed of the alternator is in revolutions per minute, the frequency is in cycles per minute. If you want to calculate the frequency in Hz (cycles per second), you must divide the result by 60.

1.31   You can modify the equation so that the result will be in Hz instead of cycles per minute. You simply divide the right side of the equation by 60. The resulting equation is as follows:

$$f = \frac{N}{120} \times S$$

where f = frequency in Hz

N = number of poles in the alternator

S = speed in rpm.

1.32   This equation can also be used for calculating the synchronous speed of an ac motor. You simply solve the equation for S, resulting in the following equation:

$$S = \frac{120 \times f}{N}$$

1.33   For example, suppose a four-pole motor is running on ac power at a frequency of 60 Hz. The synchronous speed is calculated in the following way:

$$S = \frac{120 \times f}{N}$$

$$= \frac{120 \times 60}{4}$$

$$= 1800 \text{ rpm.}$$

1.34   The same motor running on a frequency of 50 Hz would have a synchronous speed of only 1500 rpm, as shown by the following calculation. In this calculation, the value for f is changed from 60 Hz to 50 Hz.

$$S = \frac{120 \times f}{N}$$

$$\frac{120 \times 50}{4}$$

$$= 1500 \text{ rpm}$$

Table 1-1. Motor and generator speeds

Number of poles	Speed (rpm)	
	f = 50 Hz	*f* = 60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
40	150	180

1.35   Table 1-1 lists several combinations of speed, frequency, and number of poles for motors and generators. Notice that a motor runs slower on 50 Hz than on 60 Hz.

Fig. 1-8. Peak-to-peak value
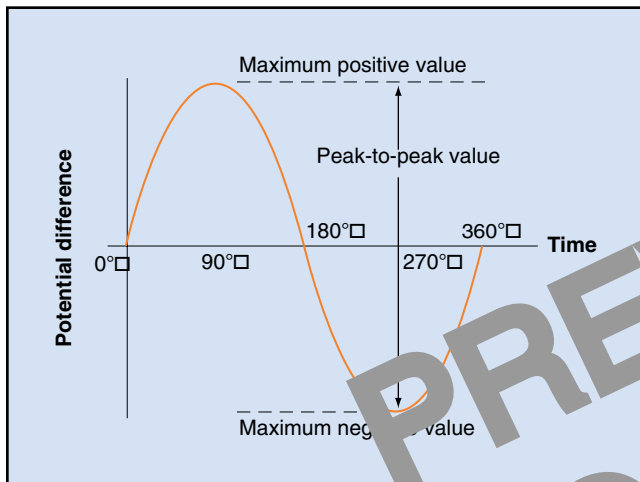
1.36   An ac waveform is a continuous sine wave. Every section of the sine wave has the same amplitude, the same period, and the same frequency.

Peak-to-Peak Values

1.37   The maximum value on a sine curve is the highest point that appears on the graph. If the curve is a graph of potential difference compared to time, the highest point represents the maximum positive potential difference that occurs, as shown in Fig. 1-8.

1.38   Likewise, there is a minimum value. It is represented by the lowest point of the graph. This point represents the maximum negative value that occurs.

1.39   In all but rare cases, the maximum point on the graph is as far above the horizontal axis as the minimum point is below it. That is, the waveform is symmetrical about zero. The distance from zero to maximum point equals the amplitude of the waveform.

1.40   The distance from the maximum point to the minimum point is called the *peak-to-peak* value. It is normally twice the amplitude of the waveform.

The Programmed Exercises on the following page will tell you how well you understand the material you have just read. Before starting the exercises, remove the Reveal Key from the back of your book. Read the instructions printed on the Reveal Key. Follow these instructions as you work through the Programmed Exercises.

1-1.   A(n) _____ is a graph showing how an electrical value changes over a period of time.

1-1.   WAVEFORM

Ref: 1.09

1-2.   The ac waveform is called a(n) _____ wave.

1-2.   SINE

Ref: 1.14

1-3.   Frequency is the number of _____ an electrical system goes through in a unit of _____.

1-3.   CYCLES; TIME

Ref: 1.19

1-4.   In what unit is frequency measured?

1-4.   HERTZ (Hz)

Ref: 1.20

1-5.   The number of cycles generated in one complete revolution of an alternator equals half the number of _____.

1-5.   POLES

Ref: 1.27

1-6.   What is the frequency of the output of a four-pole alternator running at 1800 revolutions per minute?

1-6.   60 Hz

Ref: 1.28 to 1.31

1-7.   Do motors running on 50 Hz run faster or slower than motors running on 60 Hz?

1-7.   SLOWER

Ref: 1.35

1-8.   Peak-to-peak value is defined as the distance from the _____ point on a waveform to the _____ point.

1-8.   MAXIMUM; MINIMUM

Ref: 1.40

Average Values

1.41   The potential difference and the current are always changing in an ac circuit. How can you measure these values without specifying a specific instant in time? One way is to calculate an average of the changing value.

1.42   A simple average would be zero, because every point above the horizontal axis is matched by a corresponding point below the axis. Such an average would be useless.

1.43   Therefore, the average is calculated in a different way. The average is based on the area between the horizontal axis and the curve. For each half cycle, the average value is defined as the height of a rectangle that has an area equal to the area bounded by the curve and the horizontal axis.

1.44   Figure 1-9 shows such an area. When the curve is a sine curve, the height of the rectangle is 0.637 times the height at the peak of the curve.

Effective Values

1.45   If you connect an ac source across a simple resistor, the source will drive current through the resistor. The resistor will increase in temperature, and release heat to the surroundings. The ac source is said to be equivalent to a dc source if the dc source has the right potential difference. The right potential difference is defined as being sufficient to produce heat in a resistor at the same rate as the ac source.

1.46   This physical definition has a matching mathematical definition. To calculate an effective value mathematically, you perform the following steps:

1. Calculate the square of each value on the sine curve.

2. Add all these squares and divide by the total number of squares to find the *mean* (the proper mathematical name for this kind of average) of the squares.

3. Calculate the square root of the mean.

1.47   The result of this calculation, called the *effective value*, is also called the *root mean square* of all the values on the curve. It is abbreviated RMS. The name root mean square comes from the fact that you are calculating the square *root* of the *mean* of the *squares* of all the individual values.

1.48   The RMS value of potential difference or current for a sine wave is always the same fraction of the peak value. It is always 0.707 times the amplitude. The fraction 0.707 is not an arbitrary number. It equals half the square root of two.

1.49   When an ac current or potential difference is specified, it is always the RMS value, unless stated otherwise. For example, the potential difference between electrical ground and a standard 120 V ac line is a sine wave having an amplitude of about 165 to 170 V. The potential difference between two such lines in a 240 V circuit is a sine wave having an amplitude of about 330 to 340 V.

Fig. 1-9. Average ac potential difference
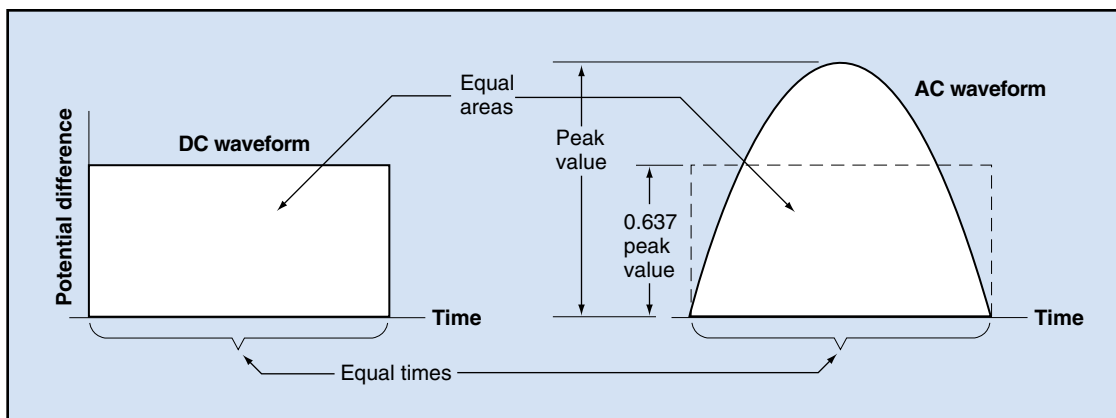
Energy Storage

1.50   In 1820, the Danish physicist Hans Christian Oersted showed that a conductor carrying an electric current produces a magnetic field. Any variation in the current in a conductor produces a corresponding change in its magnetic field.

- When the current increases, energy is stored in the magnetic field.

- When the current decreases, the stored energy returns to the electric conductor.

These changes are especially important in inductors.

1.51   Energy is also stored electrically in the space between conductors that differ in electric potential.

- As the potential difference increases between the conductors, more energy is stored in the space.

- As the potential difference decreases, the stored energy is returned to the conductors.

These changes are especially important in capacitors.

Faraday's Law

1.52   Any change in the magnetic field surrounding a conductor induces a potential difference across the conductor. If the conductor forms a closed path, current is produced. If not, current is not produced.

1.53   The importance of the induced potential difference is greatest when the conductor is in the shape of a coil. The potential difference induced across a coil depends on the number of turns of wire in the coil and the rate at which the magnetic field changes.

1.54   The scientific law that governs the relationship between the induced potential difference and the magnetic field is known as *Faraday's law*. It is named in honor of the English scientist Michael Faraday, who developed the first understanding of electromagnetic induction during the 1830s. According to Faraday's law, any conductor located in a changing magnetic field has a potential difference induced across it that is proportional to the rate at which the field is changing.

Basic Circuit Concepts

1.55   The basic laws governing electric circuits are fundamental laws of nature. They describe the flow of electricity in any circuit.

1.56   Two laws, Ohm's law and Joule's law, describe the effects of electrical resistance.

- *Ohm's law* expresses the relationship among current, resistance, and potential difference. This law states that the current in a conductor is proportional to the potential difference across it. The constant of proportionality is called the *resistance* of the conductor. Mathematically, the law is written as follows:

$$E = I \times R$$

where E = potential difference across the conductor

I = current in the conductor

R = resistance of the conductor, the constant of proportionality between the potential difference and the current.

- *Joule's law* expresses the relationship between the current in a resistor and the rate at which it produces heat. This law states that the amount of heat produced depends on the length of time the current flows, the resistance of the resistor, and the amount of current it carries.

$$H = I^2 \times R \times t$$

where H = amount of heat produced

I = current in the resistor

R = resistance of the resistor

t = time the current flows

1.57   *Lenz's law* expresses the relationship between the direction of the electric current induced in a conductor and the direction of the change in the magnetic field that induces the current. According to Lenz's law, the direction of the induced current is such that

Fig. 1-10. Kirchhoff's point rule
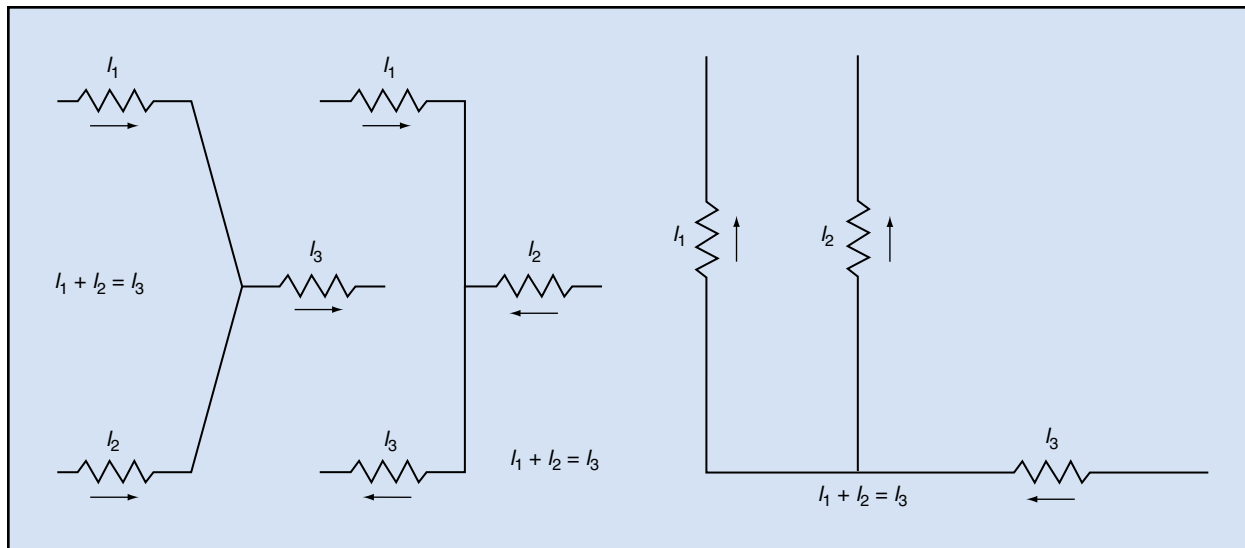
its magnetic field opposes the direction of the change in the magnetic field that induces the current.

1.58   This law is named in honor of the Russian physicist Heinrich Lenz. Lenz performed experiments in electromagnetic induction and developed his law in the 1830s, at about the same time Faraday was doing similar work in England and Joseph Henry was doing similar work in the United States.

1.59   *Kirchhoff's rules*, which are stated below, are important in solving complex electric circuits. There are two rules. They both apply to specific sections of a circuit.

- Kirchhoff's *point rule* says that the sum of the currents flowing toward any point in an electric circuit must equal the sum of the currents flowing away from that point. This rule is shown in Fig. 1-10.

- Kirchhoff's *loop rule* says that the sum of the potential differences of all the sources

Fig. 1-11. Kirchhoff's loop rule
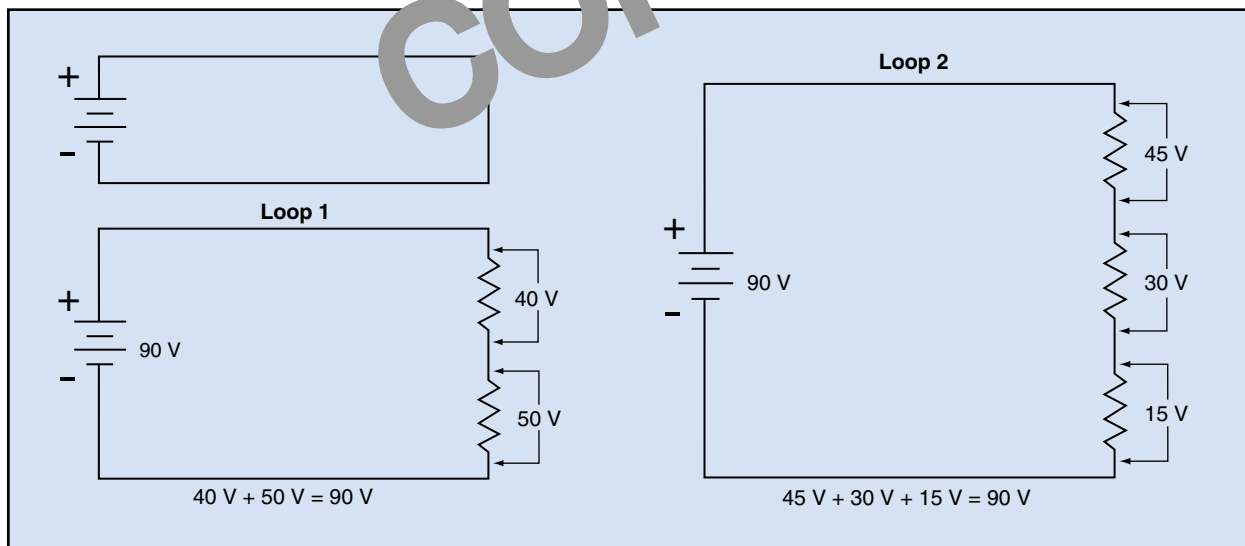
around a loop (within a circuit) equals the sum of all the voltage drops across all the resistors in the loop. This rule is shown in Fig. 1-11.

1.60   With these two rules, you can write a set of mathematical equations for a circuit and solve for several currents and voltage drops. Solving the equations may not be easy, but it is possible to arrive at a solution.

1.61   Many ac circuits consist of pure resistance. They lack both capacitance and inductance. For example, resistors, lamps, and heating elements have very little inductance or capacitance and are considered to be pure resistance. You can apply all the dc rules and laws to ac circuits if the circuits contain only resistance.

1.62   When you apply the dc rules and laws to ac circuits, you must use the RMS values of ac current and potential difference. All the ac values specified in technical documents are RMS values.

1-9. An ac source is said to be _____ to a dc source if they both produce heat in a resistor at the same rate.	1-9. EQUIVALENT Ref: 1.45
1-10. The RMS value of potential difference always equals _____ times the amplitude.	1-10. 0.707 Ref: 1.48
1-11. Any variation in the _____ in a conductor produces a change in its magnetic field.	1-11. CURRENT Ref: 1.50
1-12. Any change in the magnetic field surrounding a conductor induces a(n) _____ across the conductor.	1-12. POTENTIAL DIFFERENCE Ref: 1.52
1-13. The potential difference induced across a coil depends on the _____ in the coil and on the rate that the _____ changes.	1-13. NUMBER OF TURNS; MAGNETIC FIELD Ref: 1.53
1-14. Ohm's law says that the _____ in a conductor is proportional to the _____ across it.	1-14. CURRENT; POTENTIAL DIFFERENCE Ref: 1.56
1-15. You can apply all the dc rules and laws to an ac circuit if the circuit contains only _____.	1-15. RESISTANCE Ref: 1.61
1-16. When you apply dc rules and laws to ac circuits, you must use the _____ values of ac current and potential difference.	1-16. RMS Ref: 1.62

Answer the following questions by marking an "X" in the box next to the best answer.

1-1.   On a waveform, what is represented along the horizontal axis?

☐   a.   AC potential difference
☐   b.   Current
☐   c.   DC potential difference
☐   d.   Time

1-2.   Amplitude is the distance from

☐   a.   maximum to maximum
☐   b.   maximum to minimum
☐   c.   zero to maximum
☐   d.   zero to midpoint

1-3.   In a four-pole alternator, the magnetic poles are spaced _____ apart.

☐   a.   90°
☐   b.   180°
☐   c.   270°
☐   d.   360°

1-4.   The number of cycles produced in one complete revolution of the rotor in an alternator equals _____ the number of poles.

☐   a.   0.707 times
☐   b.   exactly
☐   c.   half
☐   d.   twice

1-5.   What is the frequency of the output of a two-pole alternator running at 6000 rpm?

☐   a.   50 Hz
☐   b.   60 Hz
☐   c.   100 Hz
☐   d.   120 Hz

1-6.   To find the root mean square, you calculate the square root of the mean of all the squares of

☐   a.   all individual values
☐   b.   the amplitude
☐   c.   the maximum negative values
☐   d.   the peak-to-peak values

1-7.   The root mean square of potential difference or current for a sine wave is 0.707 times the

☐   a.   amplitude
☐   b.   average value
☐   c.   maximum negative value
☐   d.   peak-to-peak value

1-8.   The importance of an induced potential difference is greatest when the conductor is in the shape of a(n)

☐   a.   closed loop
☐   b.   coil
☐   c.   open loop
☐   d.   straight line

1-9.   Joule's law says the amount of heat produced in a resistor depends in part on the amount of

☐   a.   current in the resistor
☐   b.   frequency of the ac source
☐   c.   magnetic field produced in the resistor
☐   d.   potential difference across the source

1-10.   You can apply all the dc rules and laws to ac circuits if the circuits contain only

☐   a.   capacitance
☐   b.   conductance
☐   c.   inductance
☐   d.   resistance

SUMMARY

AC circuits are more complex than dc circuits. In ac circuits, the current and the potential difference are always changing. These changes are often shown on a graph called a waveform. The current, potential difference, or other electrical value is always represented by the height of the graph, measured on the vertical axis. The time at which the changes occur is represented along the horizontal axis. The ac waveform is called a sine wave.

Most ac equipment is designed to operate on an input that has a specific frequency. The frequency is the number of cycles an electrical system goes through in a unit of time. Frequency is measured in units of hertz, abbreviated Hz.

You can use Ohm's law, Joule's law, Lenz's law, and Kirchhoff's rules when working with ac circuits. However, you must use RMS values for potential difference and current. RMS stands for root mean square. To arrive at an RMS value, you must calculate the square of each value on the sine curve. In principle, each value on the sine curve is squared; the squares are added together; the sum is divided by the number of squares to get the mean (average); and the square root of the mean is calculated. The result value equals the peak value on the sine curve multiplied by 0.707 (half the square root of 2).

Answers to Self-Check Quiz

1-1.   d.   Time. Ref: 1.09

1-2.   c.   Zero to maximum. Ref: 1.17

1-3.   a.   90°. Ref: 1.25

1-4.   c.   Half. Ref: 1.27

1-5.   c.   100 Hz. Ref: 1.28 to 1.31

1-6.   a.   All individual values. Ref: 1.47

1-7.   a.   Amplitude. Ref: 1.48

1-8.   b.   Coil. Ref: 1.53

1-9.   a.   Current in the resistor. Ref: 1.56

1-10.   d.   Resistance. Ref: 1.61