Introduction to Alternating Current and Voltage

11

Chapter Outline

Chapter Objectives

- Identify a sinusoidal waveform and measure its characteristics
- Determine the various voltage and current values of a sine wave
- Describe angular relationships of sine waves
- Mathematically analyze a sinusoidal waveform
- Use a phasor to represent a sine wave
- Apply the basic circuit laws to resistive ac circuits
- Describe how an alternator generates electricity
- Explain how ac motors convert electrical energy into rotational motion
- Identify the characteristics of basic nonsinusoidal waveforms
- Use an oscilloscope to measure waveforms

Key Terms

- Waveform
- Sine wave
- Cycle
- Period (T)
- Frequency (f)
- Hertz (Hz)
- Oscillator
- Function generator
- Instantaneous value
- Peak value
- Amplitude
- Peak-to-peak value
- rms value
- Average value
- Degree
- Radian
- Phase
- Phasor
- Angular velocity
- Induction motor
- Synchronous motor
- Squirrel cage
- Slip
- Pulse
- Rise time (t_r)
- Fall time (t_f)
- Pulse width (t_W)
- Periodic
- Duty cycle
- Ramp
- Fundamental frequency
- Harmonics
- Oscilloscope

Application Activity Preview

In this application activity, you will learn to measure voltage signals in an AM receiver using an oscilloscope.

Visit the Companion Website

Study aids for this chapter are available at
http://www.pearsonhighered.com/careersresources/

Introduction

In the preceding chapters, you have studied resistive circuits with dc currents and voltages. This chapter provides an introduction to ac circuit analysis in which time-varying electrical signals, particularly the sine wave, are studied. An electrical signal is a voltage or current that changes in some consistent manner with time.

An alternating voltage is one that changes polarity at a certain rate, and an alternating current is one that changes direction at a certain rate. The sinusoidal waveform (sine wave) is the most common and fundamental type because all other types of repetitive waveforms can be broken down into composite sine waves. The sine wave is a periodic waveform which means that it repeats at fixed intervals. The use of phasors to represent sine waves is discussed.

Special emphasis is given to the sinusoidal waveform (sine wave) because of its fundamental importance in ac circuit analysis. Alternators, which generate sine waves, and ac motors are introduced. Other types of repetitive waveforms are also introduced, including pulse, triangular, and sawtooth. The use of the oscilloscope for displaying and measuring waveforms is introduced.

11–1 The Sinusoidal Waveform

The sinusoidal waveform or *sine wave* is based on the mathematical sine function from trigonometry but in electrical work it is defined as an alternating current (ac) or alternating voltage. It is also referred to as a sinusoidal wave or, simply, sinusoid. The electrical service provided by the power company is in the form of sinusoidal voltage and current. In addition, other types of repetitive **waveforms** are composites of many integer multiples of a fundamental sine wave. In this section, we will focus on the sine wave itself.

After completing this section, you should be able to

- **Identify a sinusoidal waveform and measure its characteristics**
  - Determine the period
  - Determine the frequency
  - Relate the period and the frequency
  - Describe two types of electronic signal generators.

▲ **FIGURE 11–1**

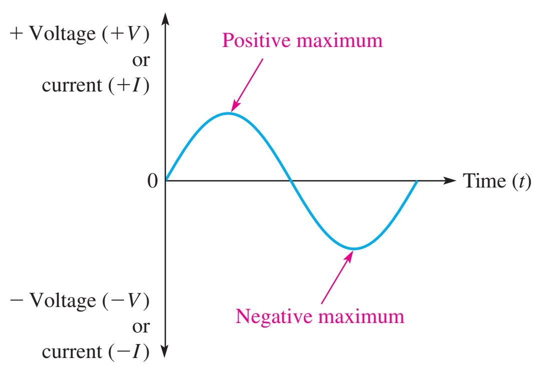
Symbol for a sinusoidal voltage source.

Sinusoidal voltages are produced by two types of sources: rotating electrical machines (ac generators) or electronic oscillator circuits, which are used in instruments commonly known as electronic signal generators. Figure 11–1 shows the symbol used to represent either source of sinusoidal voltage. AC generators are covered in Section 11–7, and electronic signal generators and function generators are discussed at the end of this section.

Figure 11–2 is a graph showing the general shape of a **sine wave**, which is generally either an alternating current or an alternating voltage. Voltage (or current) is displayed on the vertical axis and time (t) is displayed on the horizontal axis. Notice how the voltage (or current) varies with time. Starting at zero, the voltage (or current) increases to a positive maximum (peak), returns to zero, and then increases to a negative maximum (peak) before returning again to zero, thus completing one full cycle. The complete wave consists of two alternations. (An alternation is defined as the portion of the cycle between zero crossings during which the signal polarity does not change.)

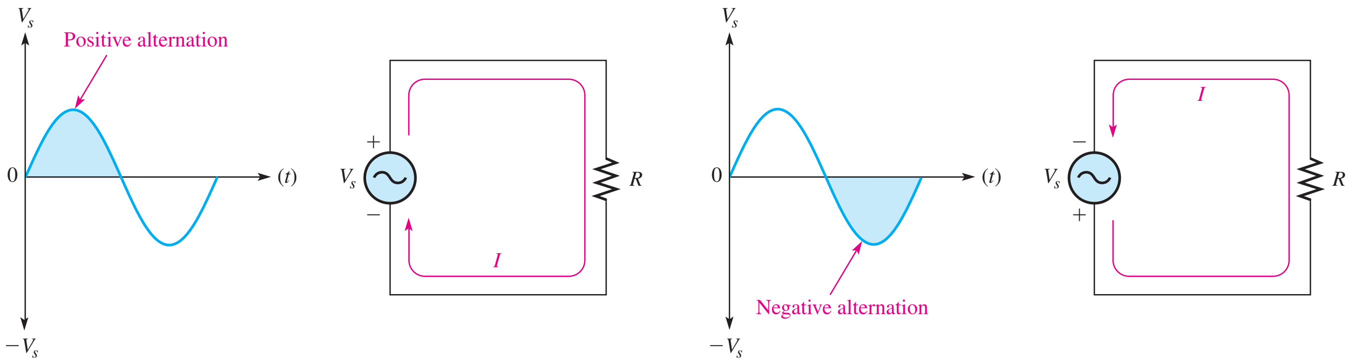
► **FIGURE 11–2**

Graph of one cycle of a sine wave.



Polarity of a Sine Wave

As mentioned, a sine wave changes polarity at its zero value; that is, it alternates between positive and negative values. When a sinusoidal voltage source (V_s) is applied to a resistive circuit, as in Figure 11–3, an alternating sinusoidal current results. When the voltage changes polarity, the current correspondingly changes direction as indicated.



(a) During a positive alternation of voltage, current is in the direction shown.

(b) During a negative alternation of voltage, current reverses direction, as shown.

▲ **FIGURE 11–3**

Alternating current and voltage.

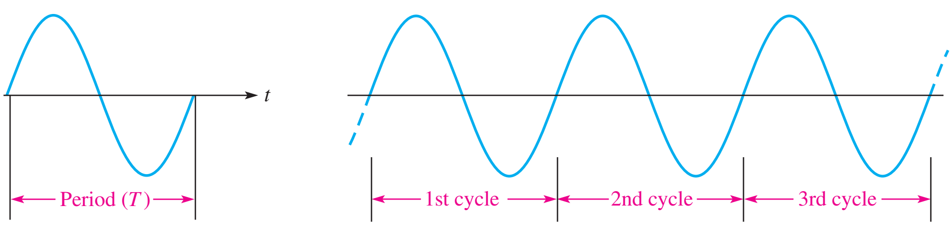
During the positive alternation of the applied voltage V_s, the current is in the direction shown in Figure 11–3(a). During a negative alternation of the applied voltage, the current is in the opposite direction, as shown in Figure 11–3(b). The combined positive and negative alternations make up one **cycle** of a sine wave.

Period of a Sine Wave

A sine wave varies with time (t) in a definable manner.

The time required for a sine wave to complete one full cycle is called the period (T).

Figure 11–4(a) illustrates the period of a sine wave. Typically, a sine wave continues to repeat itself in identical cycles, as shown in Figure 11–4(b). Since all cycles of a repetitive sine wave are the same, the period is always a fixed value for a given sine wave. The period of a sine wave can be measured from any point in a given cycle to the corresponding point in the next cycle.



(a) (b)

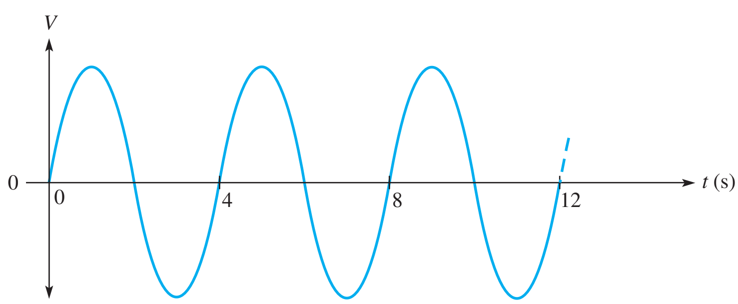
◀ **FIGURE 11–4**

The period of a sine wave is the same for each cycle.

EXAMPLE 11–1

What is the period of the sine wave in Figure 11–5?

▶ **FIGURE 11–5**



Solution As shown in Figure 11–5, it takes four seconds (4 s) to complete each cycle. Therefore, the period is 4 s.

$$T = \mathbf{4\ s}$$

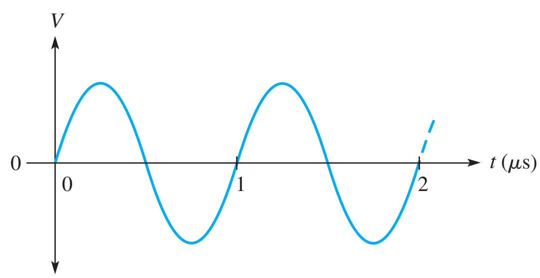
*Related Problem** What is the period if the sine wave goes through five cycles in 12 s?

*Answers are at the end of the chapter.

EXAMPLE 11–2

Show three possible ways to measure the period of the sine wave in Figure 11–6. How many cycles are shown?

FIGURE 11–6



Solution **Method 1:** The period can be measured from one zero crossing to the corresponding zero crossing in the next cycle (the slope must be the same at the corresponding zero crossings).

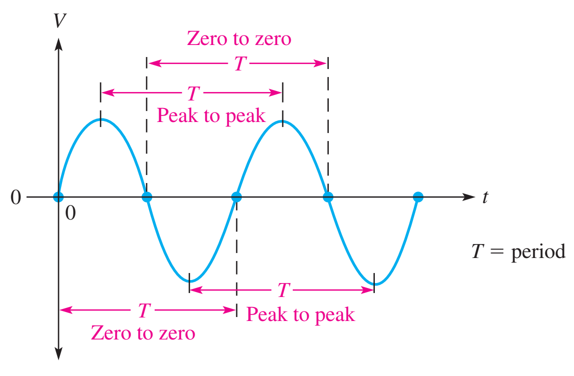
Method 2: The period can be measured from the positive peak in one cycle to the positive peak in the next cycle.

Method 3: The period can be measured from the negative peak in one cycle to the negative peak in the next cycle.

These measurements are indicated in Figure 11–7, where **two cycles of the sine wave** are shown. Keep in mind that you obtain the same value for the period no matter which corresponding points on the waveform you use.

FIGURE 11–7

Measurement of the period of a sine wave.

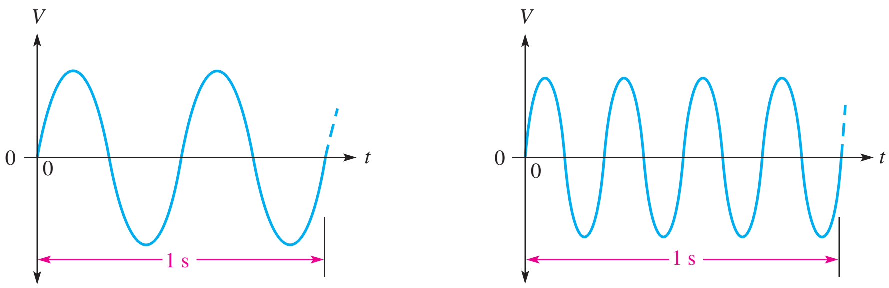


Related Problem If a positive peak occurs at 1 ms and the next positive peak occurs at 2.5 ms, what is the period?

Frequency of a Sine Wave

Frequency (f) is the number of cycles that a sine wave completes in one second.

The more cycles completed in one second, the higher the frequency. Frequency (f) is measured in units of hertz. One **hertz (Hz)** is equivalent to one cycle per second; 60 Hz is 60 cycles per second, for example. Figure 11–8 shows two sine waves. The sine wave in part (a) completes two full cycles in one second. The one in part (b) completes four cycles in one second. Therefore, the sine wave in part (b) has twice the frequency of the one in part (a).



(a) Lower frequency: fewer cycles per second   (b) Higher frequency: more cycles per second

▲ **FIGURE 11–8**

Illustration of frequency.

HISTORY NOTE

Heinrich Rudolf Hertz 1857–1894

Hertz, a German physicist, was the first to broadcast and receive electromagnetic (radio) waves. He produced electromagnetic waves in the laboratory and measured their parameters. Hertz also proved that the nature of the reflection and refraction of electromagnetic waves was the same as that of light. The unit of frequency (hertz) is named in his honor. It replaced the older *cycle per second* (cps) in 1960. The older unit was more descriptive of the term frequency. (Photo credit: Deutsches Museum, courtesy AIP Emilio Segrè Visual Archives.)

Relationship of Frequency and Period

The formulas for the relationship between frequency (f) and period (T) are as follows:

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

Equation 11–1

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

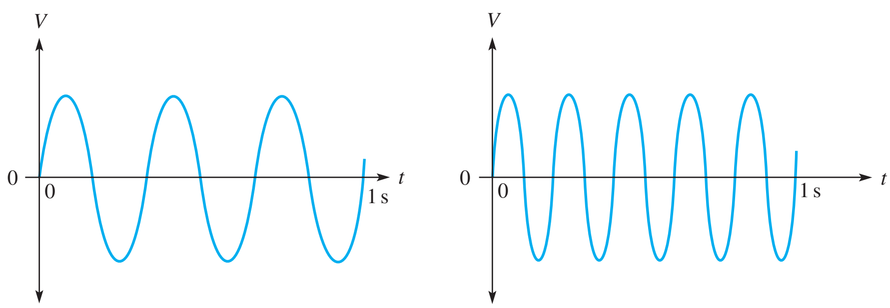
Equation 11–2

There is a reciprocal relationship between f and T. Knowing one, you can calculate the other with the x^{-1} or $1/x$ key on your calculator. This inverse relationship makes sense because a sine wave with a longer period goes through fewer cycles in one second than one with a shorter period.

EXAMPLE 11–3

Which sine wave in Figure 11–9 has a higher frequency? Determine the frequency and the period of both waveforms.

► **FIGURE 11–9**



(a)   (b)

Solution The sine wave in Figure 11–9(b) has the higher frequency because it completes more cycles in 1 s than does the sine wave in part (a).

In Figure 11–9(a), three cycles are completed in 1 s; therefore,

$$f = \mathbf{3\ Hz}$$

One cycle takes 0.333 s (one-third second), so the period is

$$T = 0.333\ \text{s} = \mathbf{333\ ms}$$

In Figure 11–9(b), five cycles are completed in 1 s; therefore,

$$f = \mathbf{5\ Hz}$$

One cycle takes 0.2 s (one-fifth second), so the period is

$$T = 0.2\ \text{s} = \mathbf{200\ ms}$$

Related Problem If the time between negative peaks of a given sine wave is 50 μs, what is the frequency?

EXAMPLE 11–4

The period of a certain sine wave is 10 ms. What is the frequency?

Solution Use Equation 11–1.

$$f = \frac{1}{T} = \frac{1}{10\ \text{ms}} = \frac{1}{10 \times 10^{-3}\ \text{s}} = \mathbf{100\ Hz}$$

Related Problem A certain sine wave goes through four cycles in 20 ms. What is the frequency?

EXAMPLE 11–5

The frequency of a sine wave is 60 Hz. What is the period?

Solution Use Equation 11–2.

$$T = \frac{1}{f} = \frac{1}{60\ \text{Hz}} = \mathbf{16.7\ ms}$$

Related Problem If $T = 15\ \mu$s, what is f?

Electronic Signal Generators

A signal generator is an instrument that electronically produces sine waves for use in testing or controlling electronic circuits and systems. All signal generators consist basically of an **oscillator**, which is an electronic circuit that produces repetitive waves. There are a variety of signal generators, ranging from special-purpose instruments that produce only one type of waveform in a limited frequency range, to programmable instruments that produce a wide range of frequencies and a variety of waveforms. All generators have controls for adjusting the amplitude and frequency.

Function Generators and Arbitrary Function Generators A **function generator** is a type of signal generator that produces more than one type of waveform. Typically, a conventional function generator can generate sine, square, and triangle waveforms as well as pulses. An arbitrary function generator has many more waveforms and added capabilities available than conventional function generators. These include multiple outputs and various output modes such as repetitive, burst, or the ability to simulate certain common signals. The Tektronix AFG1022 Arbitrary Function Generator is shown in Figure 11–10(a). This generator has dual channel outputs and has 50 built-in

(a) An arbitrary function generator (b) An arbitrary waveform generator

▲ FIGURE 11–10

Typical signal generators. Copyright © Tektronix, Inc. Reproduced by permission.

waveforms available with a wide range of frequencies that can be selected. A generator like this allows the user to simulate various conditions for test.

Arbitrary Waveform Generators An arbitrary waveform generator has even more capability than an arbitrary function generator. In addition to all of the standard outputs, an arbitrary waveform generator can synchronize multiple independent channels. This capability is useful in testing complex systems. The output can be defined by a mathematical function, a graphical input from the user, or can be a waveform captured and stored in a digital oscilloscope. The Tektronix AWG5200, shown in Figure 11–10(b), is an example of a multiple channel arbitrary waveform generator.

SECTION 11–1 CHECKUP
Answers are at the end of the chapter.

1. Describe one cycle of a sine wave.
2. At what point does a sine wave change polarity?
3. How many maximum points does a sine wave have during one cycle?
4. How is the period of a sine wave measured?
5. Define *frequency,* and state its unit.
6. Determine f when $T = 5\,\mu s$.
7. Determine T when $f = 120$ Hz.
8. What is the difference between an arbitrary function generator and an arbitrary waveform generator?

11–2 SINUSOIDAL VOLTAGE AND CURRENT VALUES

Five ways to express the value of a sine wave in terms of its voltage or its current magnitude are instantaneous, peak, peak-to-peak, rms, and average values.

After completing this section, you should be able to

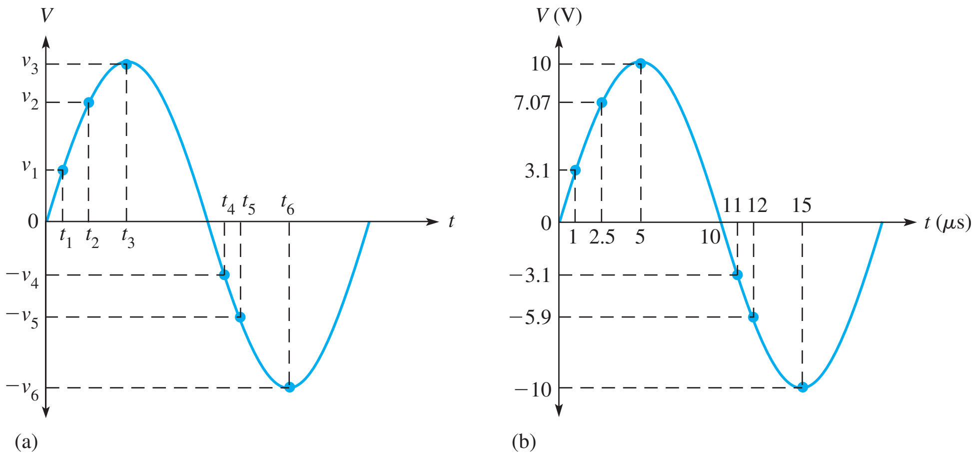
- **Determine the various voltage and current values of a sine wave**
  - Find the instantaneous value at any point
  - Find the peak value
  - Find the peak-to-peak value
  - Define *rms*
  - Explain why the average value is always zero over a complete cycle
  - Find the half-cycle average value

Instantaneous Value

Figure 11–11 illustrates that at any point in time on a sine wave, the voltage (or current) has an **instantaneous value**. This instantaneous value is different at different points along the curve. Instantaneous values are positive during the positive alternation and negative during the negative alternation. Instantaneous values of voltage and current are symbolized by lowercase v and i, respectively. The curve in part (a) shows voltage only, but it applies equally for current when the v's are replaced with i's. An example of instantaneous values is shown in part (b) where the instantaneous voltage is 3.1 V at 1 μs, 7.07 V at 2.5 μs, 10 V at 5 μs, 0 V at 10 μs, −3.1 V at 11 μs, and so on.

▶ FIGURE 11–11

Instantaneous values.

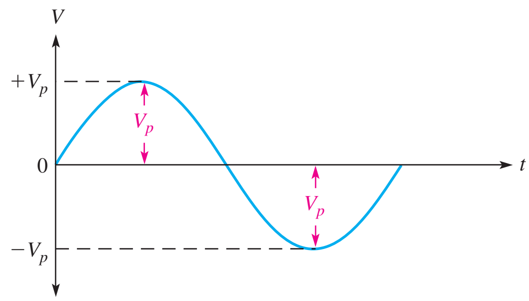


Peak Value

The **peak value** of a sine wave is the value of voltage (or current) at the positive or the negative maximum (peak) with respect to zero. Since the positive and negative peak values are equal in **magnitude**, a sine wave is characterized by a single peak value. This is illustrated in Figure 11–12. For a given sine wave, the peak value is constant and is represented by V_p or I_p. The peak value is also called the **amplitude**. The amplitude is measured from the mean or average value for a sine wave (in this case 0 V).

▶ FIGURE 11–12

Peak values.

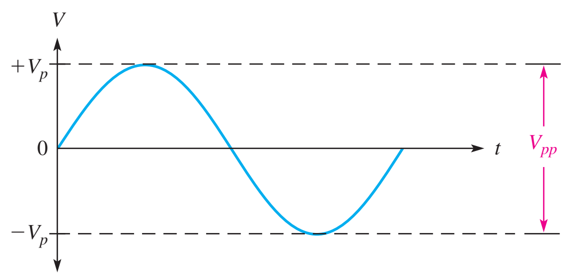


Peak-to-Peak Value

The **peak-to-peak value** of a sine wave, as shown in Figure 11–13, is the voltage or current from the positive peak to the negative peak. It is always twice the peak value as

▶ FIGURE 11–13

Peak-to-peak value.



expressed in the following equations. Peak-to-peak voltage or current values are represented by V_{pp} or I_{pp}.

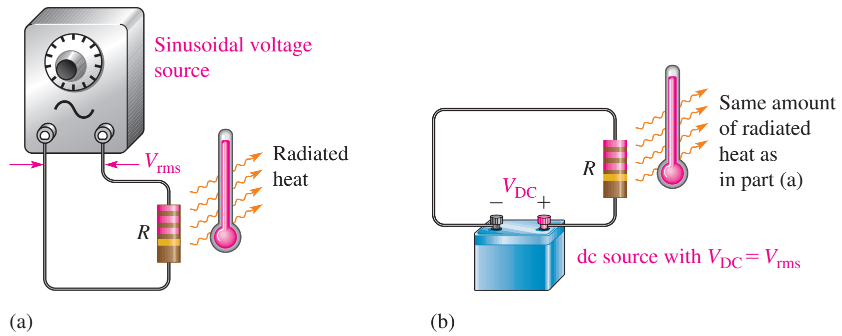
$$V_{pp} = 2V_p \qquad \text{Equation 11–3}$$

$$I_{pp} = 2I_p \qquad \text{Equation 11–4}$$

RMS Value

The term *rms* stands for *root mean square.* Most ac voltmeters display rms voltage. The 120 V at your wall outlet is an rms value. The **rms value**, also referred to as the **effective value**, of a sinusoidal voltage is actually a measure of the heating effect of the sine wave. For example, when a resistor is connected across an ac (sinusoidal) voltage source, as shown in Figure 11–14(a), a certain amount of heat is generated by the power in the resistor. Figure 11–14(b) shows the same resistor connected across a dc voltage source. The value of the dc voltage can be adjusted so that the resistor gives off the same amount of heat as it does when connected to the ac source.

The rms value of a sinusoidal voltage is equal to the dc voltage that produces the same amount of heat in a resistance as does the sinusoidal voltage.



▲ FIGURE 11–14

When the same amount of heat is produced in both setups, the sinusoidal voltage has an rms value equal to the dc voltage.

The peak value of a sine wave can be converted to the corresponding rms value using the following relationships, derived in Appendix B, for either voltage or current:

$$V_{rms} = 0.707V_p \qquad \text{Equation 11–5}$$

$$I_{rms} = 0.707I_p \qquad \text{Equation 11–6}$$

Using these formulas, you can also determine the peak value if you know the rms value.

$$V_p = \frac{V_{rms}}{0.707}$$

$$V_p = 1.414V_{rms} \qquad \text{Equation 11–7}$$

Similarly,

$$I_p = 1.414I_{rms} \qquad \text{Equation 11–8}$$

To get the peak-to-peak value, simply double the peak value.

$$V_{pp} = 2.828V_{rms} \qquad \text{Equation 11–9}$$

and

$$I_{pp} = 2.828I_{rms} \qquad \text{Equation 11–10}$$

Average Value

The average value of a sine wave taken over one complete cycle is always zero because the positive values (above the zero crossing) offset the negative values (below the zero crossing).

To be useful for certain purposes such as measuring types of voltages found in power supplies, the average value of a sine wave is defined over a half-cycle rather than over a full cycle. The **average value** is the total area under the half-cycle curve divided by the distance in radians of the curve along the horizontal axis. The result is derived in Appendix B and is expressed in terms of the peak value as follows for both voltage and current sine waves:

$$V_{avg} = \left(\frac{2}{\pi}\right)V_p$$

Equation 11–11

$$V_{avg} = 0.637V_p$$

$$I_{avg} = \left(\frac{2}{\pi}\right)I_p$$

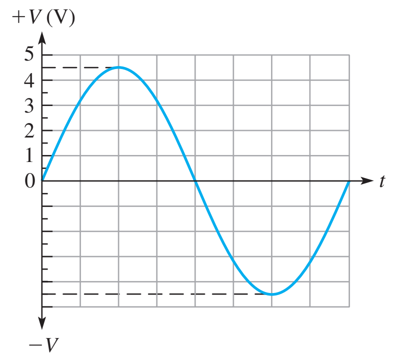
Equation 11–12

$$I_{avg} = 0.637I_p$$

EXAMPLE 11–6

Determine V_p, V_{pp}, V_{rms}, and the half-cycle V_{avg} for the sine wave in Figure 11–15.

► FIGURE 11–15



Solution V_p = **4.5 V** is read directly from the graph. From this, calculate the other values.

$$V_{pp} = 2V_p = 2(4.5\text{ V}) = \mathbf{9\text{ V}}$$
$$V_{rms} = 0.707V_p = 0.707(4.5\text{ V}) = \mathbf{3.18\text{ V}}$$
$$V_{avg} = 0.637V_p = 0.637(4.5\text{ V}) = \mathbf{2.86\text{ V}}$$

Related Problem If $V_p = 25$ V, determine V_{pp}, V_{rms}, and V_{avg} for a voltage sine wave.

SECTION 11–2 CHECKUP

1. Determine V_{pp} in each case when
   (a) $V_p = 1$ V (b) $V_{rms} = 1.414$ V (c) $V_{avg} = 3$ V
2. Determine V_{rms} in each case when
   (a) $V_p = 2.5$ V (b) $V_{pp} = 10$ V (c) $V_{avg} = 1.5$ V
3. Determine the half-cycle V_{avg} in each case when
   (a) $V_p = 10$ V (b) $V_{rms} = 2.3$ V (c) $V_{pp} = 60$ V

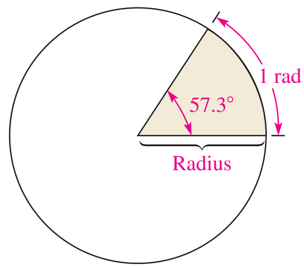
11–3 ANGULAR MEASUREMENT OF A SINE WAVE

As you have seen, sine waves can be measured along the horizontal axis on a time basis; however, since the time for completion of one full cycle or any portion of a cycle is frequency-dependent, it is often useful to specify points on the sine wave in terms of an angular measurement expressed in degrees or radians.

After completing this section, you should be able to

- **Describe angular relationships of sine waves**
  - Show how to measure a sine wave in terms of angles
  - Define *radian*
  - Convert radians to degrees
  - Determine the phase angle of a sine wave

A sinusoidal voltage can be produced by an alternator, which is an ac generator. There is a direct relationship between the rotation of the rotor in an alternator and the sine wave output. Thus, the angular measurement of the rotor's position is directly related to the angle assigned to the sine wave.



▲ FIGURE 11–16

Angular measurement showing relationship of radian (rad) to degrees (°).

Angular Measurement

A **degree** is an angular measurement corresponding to 1/360 of a circle or a complete revolution. A **radian** is the angular measurement along the circumference of a circle that is equal to the radius of the circle. One radian (rad) is equivalent to 57.3°, as illustrated in Figure 11–16. In a 360° revolution, there are 2π radians.

The Greek letter π (pi) represents the ratio of the circumference of any circle to its diameter and has a constant value of approximately 3.1416.

Scientific calculators have a π function so that the actual numerical value does not have to be entered.

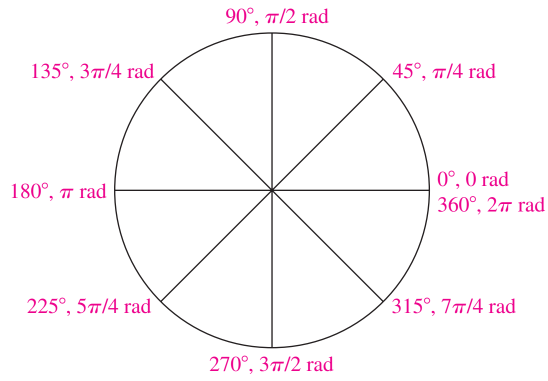
Table 11–1 lists several values of degrees and the corresponding radian values. These angular measurements are illustrated in Figure 11–17.

◄ TABLE 11–1

DEGREES (°)	RADIANS (RAD)
0	0
45	$\pi/4$
90	$\pi/2$
135	$3\pi/4$
180	π
225	$5\pi/4$
270	$3\pi/2$
315	$7\pi/4$
360	2π

▶ FIGURE 11–17

Angular measurements starting at 0° and going counterclockwise.



Radian/Degree Conversion

Degrees can be converted to radians.

Equation 11–13

$$\text{rad} = \left(\frac{\pi \text{ rad}}{180^\circ}\right) \times \text{degrees}$$

Similarly, radians can be converted to degrees.

Equation 11–14

$$\text{degrees} = \left(\frac{180^\circ}{\pi \text{ rad}}\right) \times \text{rad}$$

EXAMPLE 11–7

(a) Convert 60° to radians. **(b)** Convert $\pi/6$ rad to degrees.

Solution **(a)** $\text{Rad} = \left(\dfrac{\pi \text{ rad}}{180^\circ}\right)60^\circ = \boldsymbol{\dfrac{\pi}{3}}\textbf{ rad}$ **(b)** $\text{Degrees} = \left(\dfrac{180^\circ}{\pi \text{ rad}}\right)\left(\dfrac{\pi}{6}\text{ rad}\right) = \mathbf{30^\circ}$

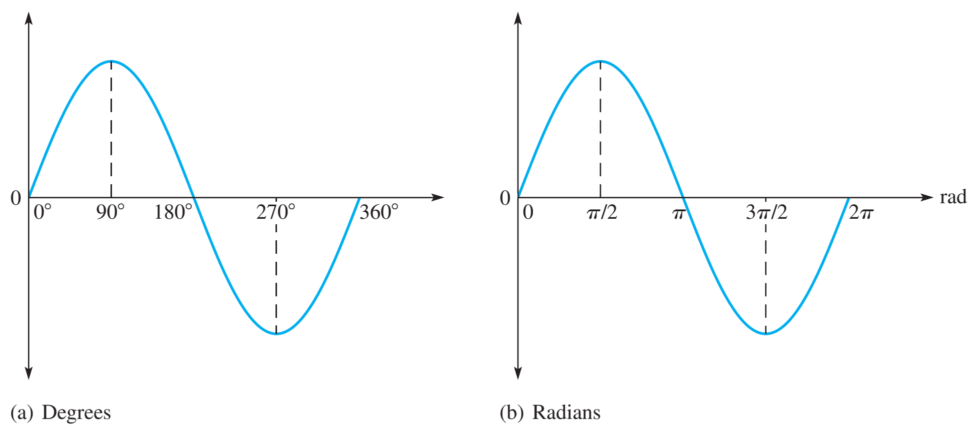
Related Problem **(a)** Convert 15° to radians. **(b)** Convert $5\pi/8$ rad to degrees.

Sine Wave Angles

The angular measurement of a sine wave is based on 360° or 2π rad for a complete cycle. A half-cycle is 180° or π rad; a quarter-cycle is 90° or $\pi/2$ rad; and so on. Figure 11–18(a) shows angles in degrees for a full cycle of a sine wave; part (b) shows the same points in radians.

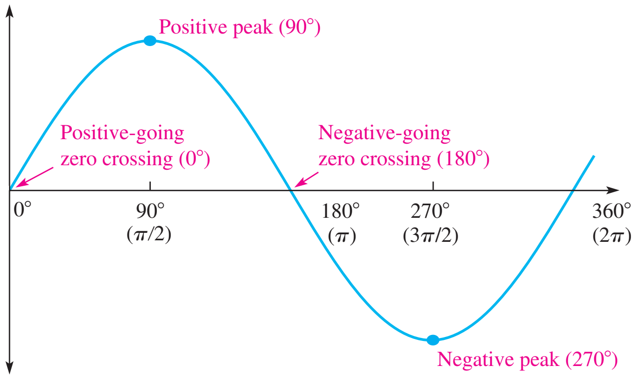
▶ FIGURE 11–18

Sine wave angles.



Phase of a Sine Wave

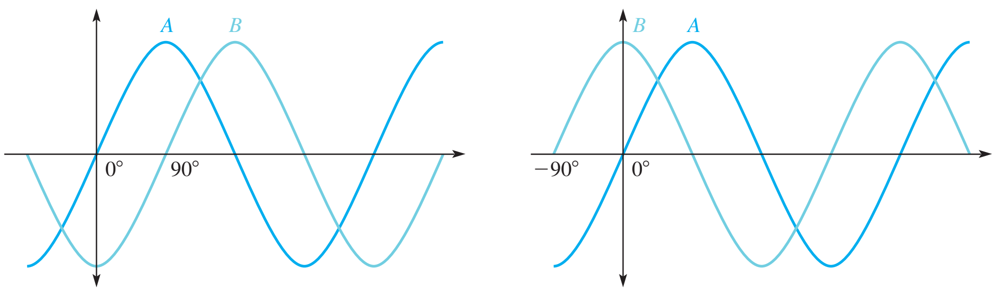
The **phase** of a sine wave is an angular measurement that specifies the position of that sine wave relative to a reference. Figure 11–19 shows one cycle of a sine wave to be used as the reference. Note that the first positive-going crossing of the horizontal axis (zero crossing) is at 0° (0 rad), and the positive peak is at 90° ($\pi/2$ rad). The negative-going zero crossing is at 180° (π rad), and the negative peak is at 270° ($3\pi/2$ rad). The cycle is completed at 360° (2π rad). When the sine wave is shifted left or right with respect to this reference, there is a phase shift.



▲ **FIGURE 11–19**

Phase reference.

Figure 11–20 illustrates phase shifts of a sine wave. In part (a), sine wave B is shifted to the right by 90° ($\pi/2$ rad) with respect to sine wave A. Thus, there is a phase angle of 90° between sine wave A and sine wave B. In terms of time, the positive peak of sine wave B occurs later than the positive peak of sine wave A because time increases to the right along the horizontal axis. In this case, sine wave B is said to **lag** sine wave A by 90° or $\pi/2$ radians. Stated another way, sine wave A leads sine wave B by 90°.



(a) A leads B by 90°, or B lags A by 90°.

(b) B leads A by 90°, or A lags B by 90°.

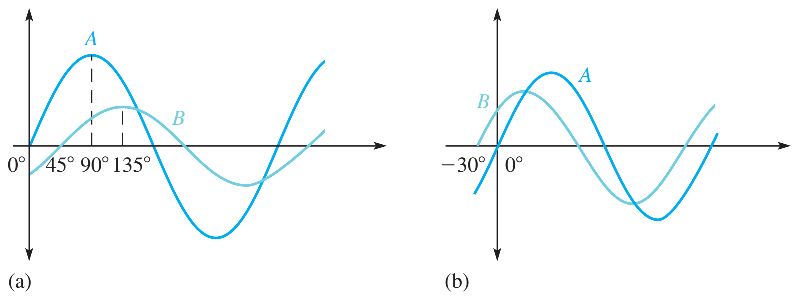
▲ **FIGURE 11–20**

Illustration of a phase shift.

In Figure 11–20(b), sine wave B is shown shifted left by 90° with respect to sine wave A. Thus, again there is a phase angle of 90° between sine wave A and sine wave B. In this case, the positive peak of sine wave B occurs earlier in time than that of sine wave A; therefore, sine wave B is said to **lead** sine wave A by 90°.

EXAMPLE 11–8

What are the phase angles between the two sine waves in parts (a) and (b) of Figure 11–21?



▲ **FIGURE 11–21**

Solution In Figure 11–21(a) the zero crossing of sine wave *A* is at 0°, and the corresponding zero crossing of sine wave *B* is at 45°. There is a 45° phase angle between the two waveforms with sine wave *B* lagging sine wave *A*.

In Figure 11–21(b) the zero crossing of sine wave *B* is at −30°, and the corresponding zero crossing of sine wave *A* is at 0°. There is a 30° phase angle between the two waveforms with sine wave *B* leading sine wave *A*.

Related Problem If the positive-going zero crossing of one sine wave is at 15° and that of the second sine wave is at 23°, what is the phase angle between them?

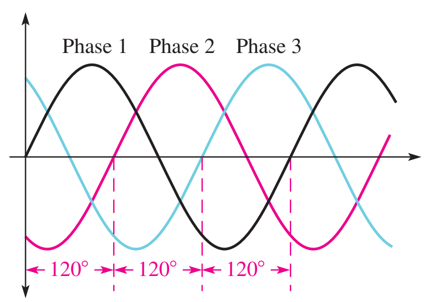
As a practical matter, when you measure the phase shift between two waveforms on an oscilloscope, you should make them appear to have the same amplitude. This is done by taking one of the oscilloscope channels out of vertical calibration and adjusting the corresponding waveform until its apparent amplitude equals that of the other waveform. This procedure eliminates the error caused if both waveforms are not measured at their exact center.

Polyphase Power

One important application of phase-shifted sine waves is in electrical power systems. Electrical utilities generate ac with three phases that are separated by 120°, as shown in Figure 11–22. The reference is called neutral. Normally, three-phase power is delivered to the user with four lines (three hot lines and neutral). There are important advantages to three-phase power for ac motors. Three-phase motors are more efficient and simpler than an equivalent single-phase motor. Motors are discussed further in Section 11–8.

► **FIGURE 11–22**

Three-phase power waveforms.

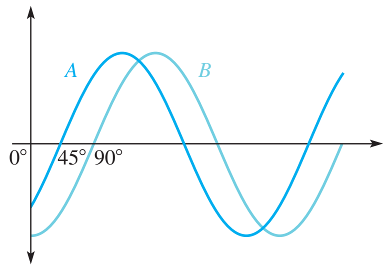


The three phases can be split up by the utility company to supply three separate single-phase systems. If only one of the three phases plus neutral is supplied, the result is standard 120 V, which is single-phase power. Single-phase power is distributed to residential and small commercial buildings; it consists of two 120 V hot lines that are 180° out of phase with each other and a neutral, which is grounded at the service entrance. The two hot lines allow for connecting to 240 V for high-power appliances (dryers, air conditioners).

SECTION 11–3 CHECKUP

1. When the positive-going zero crossing of a sine wave occurs at 0°, at what angle does each of the following points occur?
   (a) Positive peak
   (b) Negative-going zero crossing
   (c) Negative peak
   (d) End of first complete cycle
2. A half-cycle is completed in _______ degrees or _______ radians.
3. A full cycle is completed in _______ degrees or _______ radians.
4. Determine the phase angle between the two sine waves in Figure 11–23.

▶ FIGURE 11–23



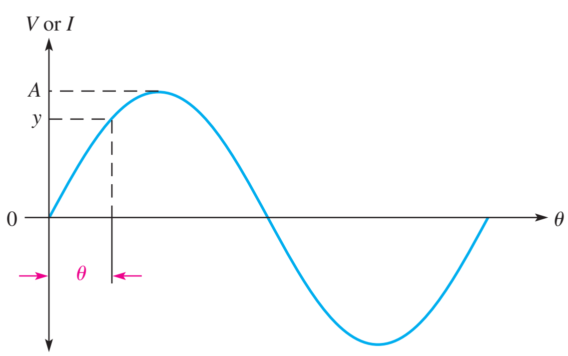
11–4 THE SINE WAVE FORMULA

A sine wave can be graphically represented by voltage or current values on the vertical axis and by angular measurement (degrees or radians) along the horizontal axis. This graph can be expressed mathematically, as you will see.

After completing this section, you should be able to

- **Mathematically analyze a sinusoidal waveform**
  - State the sine wave formula
  - Find instantaneous values using the sine wave formula

A generalized graph of one cycle of a sine wave is shown in Figure 11–24. The sine wave amplitude (A) is the maximum value of the voltage or current on the vertical



◀ FIGURE 11–24

One cycle of a generic sine wave showing amplitude and phase.

axis; angular values run along the horizontal axis. The variable y is an instantaneous value that represents either voltage or current at a given angle, θ. The symbol θ is the Greek letter *theta.*

All electrical sine waves follow a specific mathematical formula. The general expression for the sine wave curve in Figure 11–24 is

Equation 11–15

$$y = A\sin\theta$$

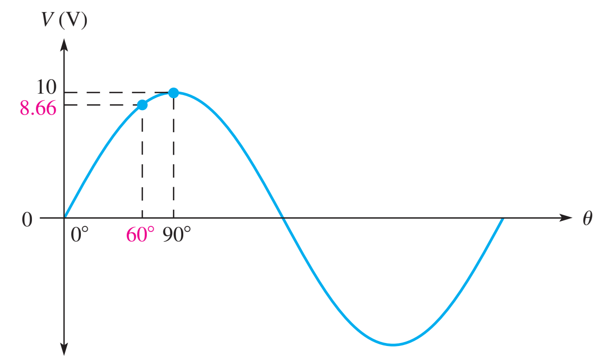
This formula states that any point on the sine wave, represented by an instantaneous value (y), is equal to the maximum value A times the sine (sin) of the angle θ at that point. For example, a certain voltage sine wave has a peak value of 10 V. You can calculate the instantaneous voltage at a point 60° along the horizontal axis as follows, where $y = v$ and $A = V_p$:

$$v = V_p\sin\theta = (10\text{ V})\sin 60° = (10\text{ V})(0.866) = 8.66\text{ V}$$

Figure 11–25 shows this particular instantaneous value of the curve. You can find the sine of any angle on most calculators by first entering the value of the angle and then pressing the SIN key. Verify that your calculator is in the degree mode.

▶ FIGURE 11–25

Illustration of the instantaneous value of a voltage sine wave at $\theta = 60°$.



Expressions for Phase-Shifted Sine Waves

When a sine wave is shifted to the right of the reference (lagging) by a certain angle, ϕ (Greek letter phi), as illustrated in Figure 11–26(a) where the reference is the vertical axis, the general expression is

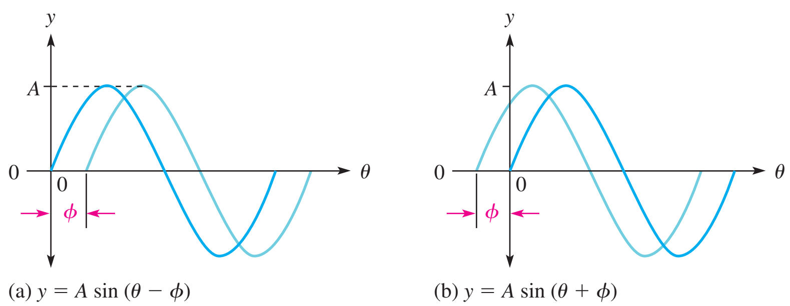
Equation 11–16

$$y = A\sin(\theta - \phi)$$

where y represents instantaneous voltage or current, and A represents the peak value (amplitude). When a sine wave is shifted to the left of the reference (leading) by a certain angle, ϕ, as shown in Figure 11–26(b), the general expression is

Equation 11–17

$$y = A\sin(\theta + \phi)$$



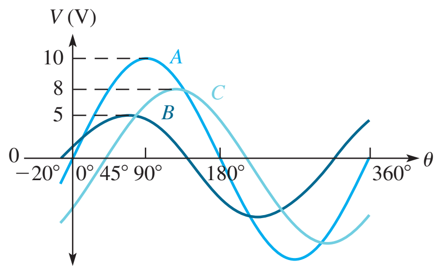
▲ FIGURE 11–26

Shifted sine waves.

EXAMPLE 11–9

Determine the instantaneous value at the 90° reference point on the horizontal axis for each voltage sine wave in Figure 11–27.

▶ **FIGURE 11–27**



Solution Sine wave A is the reference. Sine wave B is shifted left by 20° with respect to A, so it leads. Sine wave C is shifted right by 45° with respect to A, so it lags.

$$v_A = V_p \sin\theta$$
$$= (10\text{ V})\sin(90°) = (10\text{ V})(1) = \mathbf{10\ V}$$
$$v_B = V_p \sin(\theta + \phi_B)$$
$$= (5\text{ V})\sin(90° + 20°) = (5\text{ V})\sin(110°) = (5\text{ V})(0.9397) = \mathbf{4.70\ V}$$
$$v_C = V_p \sin(\theta - \phi_C)$$
$$= (8\text{ V})\sin(90° - 45°) = (8\text{ V})\sin(45°) = (8\text{ V})(0.7071) = \mathbf{5.66\ V}$$

Related Problem A voltage sine wave has a peak value of 20 V. What is its instantaneous value at 65° from its zero crossing?

SECTION 11–4 CHECKUP

1. Calculate the instantaneous value at 120° for the voltage sine wave in Figure 11–25.
2. Determine the instantaneous value at 45° of a voltage sine wave that leads the reference by 10° ($V_p = 10$ V).
3. Find the instantaneous value of 90° of a voltage sine wave that leads the reference by 25° ($V_p = 5$ V).

11–5 INTRODUCTION TO PHASORS

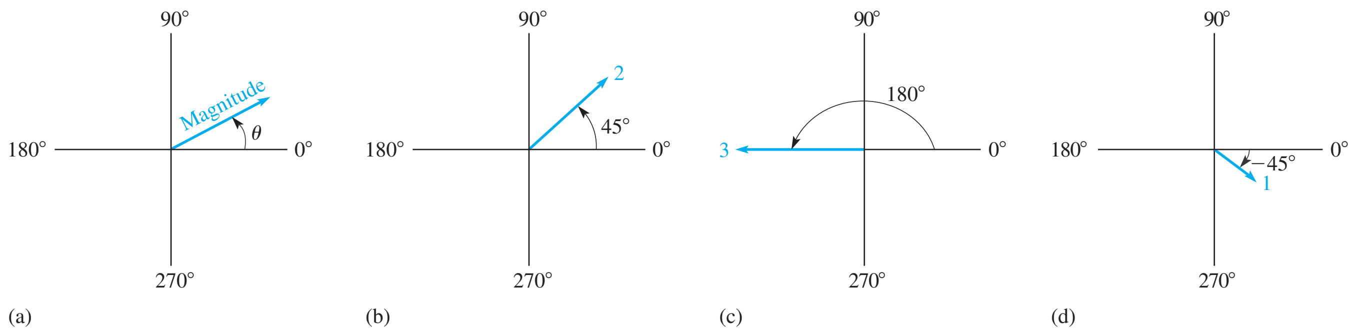
Phasors provide a graphic means for representing quantities that have both magnitude and direction (angular position). Phasors are especially useful for representing sine waves in terms of their magnitude and phase angle and also for the analysis of reactive circuits discussed in later chapters.

After completing this section, you should be able to

- **Use a phasor to represent a sine wave**
  - Define *phasor*
  - Explain how phasors are related to the sine wave formula
  - Draw a phasor diagram
  - Discuss angular velocity

You may already be familiar with vectors. In math and science, a vector is any quantity with both magnitude and direction. Examples of vector quantities are force, velocity, and acceleration. The simplest way to describe a vector is to assign a magnitude and an angle to a quantity.

In electronics, a **phasor** is a rotating vector. Examples of phasors are shown in Figure 11–28. The length of the phasor "arrow" represents the magnitude of a quantity. The angle, θ (relative to 0°), represents the angular position, as shown in part (a) for a positive angle. The specific phasor example in part (b) has a magnitude of 2 and a phase angle of 45°. The phasor in part (c) has a magnitude of 3 and a phase angle of 180°. The phasor in part (d) has a magnitude of 1 and a phase angle of −45° (or +315°). Notice that positive angles are measured counterclockwise (CCW) from the reference (0°) and negative angles are measured clockwise (CW) from the reference.



▲ FIGURE 11–28

Examples of phasors.

Phasor Representation of a Sine Wave

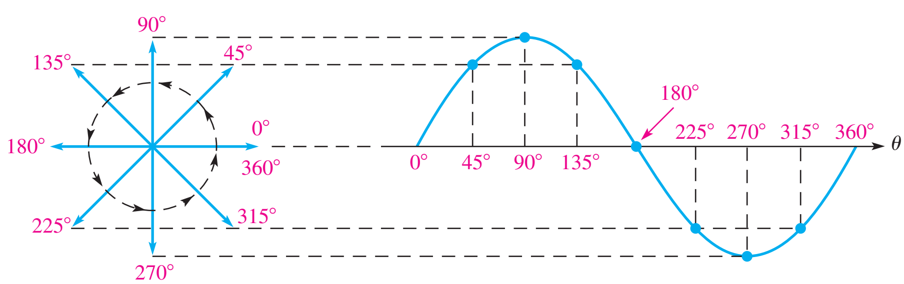
A full cycle of a sine wave can be represented by rotation of a phasor through 360 degrees.

The instantaneous value of the sine wave at any point is equal to the vertical distance from the tip of the phasor to the horizontal axis.

Figure 11–29 shows how the phasor traces out the sine wave as it goes from 0° to 360°. You can relate this concept to the rotation in an ac generator. Notice that the length of the phasor is equal to the peak value of the sine wave (observe the 90° and the 270° points). The angle of the phasor measured from 0° is the corresponding angular point on the sine wave.

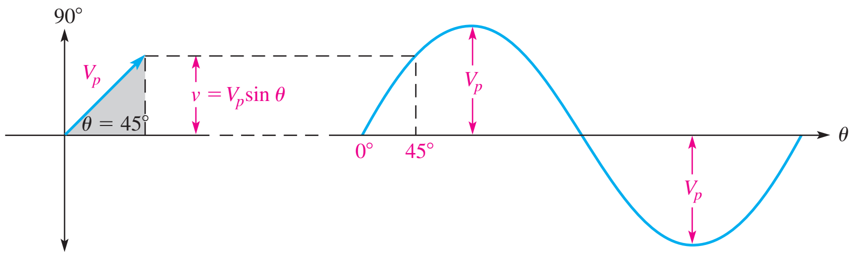
► FIGURE 11–29

Sine wave represented by rotational phasor motion.



Phasors and the Sine Wave Formula

Let's examine a phasor representation at one specific angle. Figure 11–30 shows a voltage phasor at an angular position of 45° and the corresponding point on the sine wave. The instantaneous value of the sine wave at this point is related to both the position and the length of the phasor. As previously mentioned, the vertical distance



▲ FIGURE 11–30

Right triangle derivation of sine wave formula.

from the phasor tip down to the horizontal axis represents the instantaneous value of the sine wave at that point.

Notice that when a vertical line is drawn from the phasor tip down to the horizontal axis, a right triangle is formed, as shown shaded in Figure 11–30. The length of the phasor is the hypotenuse of the triangle, and the vertical projection is the opposite side. From trigonometry,

> **The opposite side of a right triangle is equal to the hypotenuse times the sine of the angle θ.**

The length of the phasor is the peak value of the sinusoidal voltage, V_p. Thus, the opposite side of the triangle, which is the instantaneous value, can be expressed as

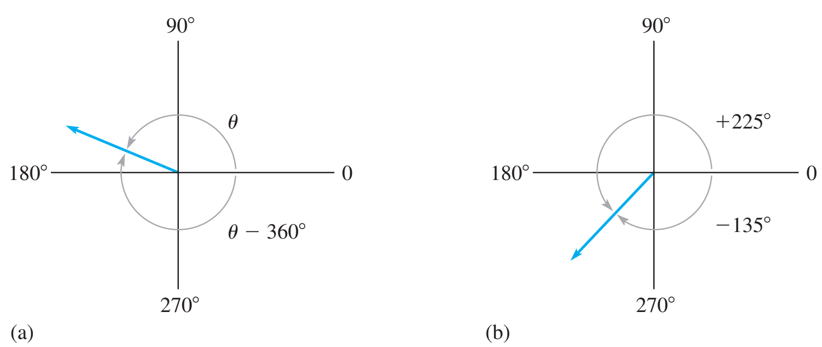
$$v = V_p \sin \theta$$

Recall that this formula is the one stated earlier for calculating instantaneous sinusoidal voltage. A similar formula applies to a sinusoidal current.

$$i = I_p \sin \theta$$

Positive and Negative Phasor Angles

The position of a phasor at any instant can be expressed as a positive angle, as you have seen, or as an equivalent negative angle. Positive angles are measured counterclockwise from 0°. Negative angles are measured clockwise from 0°. For a given positive angle θ, the corresponding negative angle is $\theta - 360°$, as illustrated in Figure 11–31(a). In part (b), a specific example is shown. The angle of the phasor in this case can be expressed as +225° or −135°.

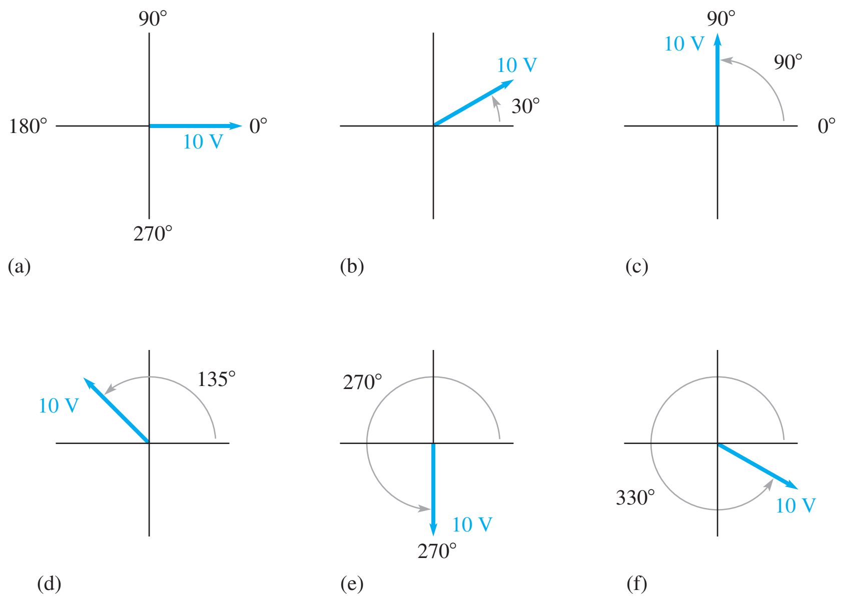


▲ FIGURE 11–31

Positive and negative phasor angles.

EXAMPLE 11–10

For the phasor in each part of Figure 11–32, determine the instantaneous voltage value. Also express each positive angle shown as an equivalent negative angle. The length of each phasor represents the peak value of the sinusoidal voltage.



▲ FIGURE 11–32

Solution

(a) $v = (10\text{ V})\sin 0° = (10\text{ V})(0) = \mathbf{0\ V}$

$0° - 360° = \mathbf{-360°}$

(b) $v = (10\text{ V})\sin 30° = (10\text{ V})(0.5) = \mathbf{5\ V}$

$30° - 360° = \mathbf{-330°}$

(c) $v = (10\text{ V})\sin 90° = (10\text{ V})(1) = \mathbf{10\ V}$

$90° - 360° = \mathbf{-270°}$

(d) $v = (10\text{ V})\sin 135° = (10\text{ V})(0.707) = \mathbf{7.07\ V}$

$135° - 360° = \mathbf{-225°}$

(e) $v = (10\text{ V})\sin 270° = (10\text{ V})(-1) = \mathbf{-10\ V}$

$270° - 360° = \mathbf{-90°}$

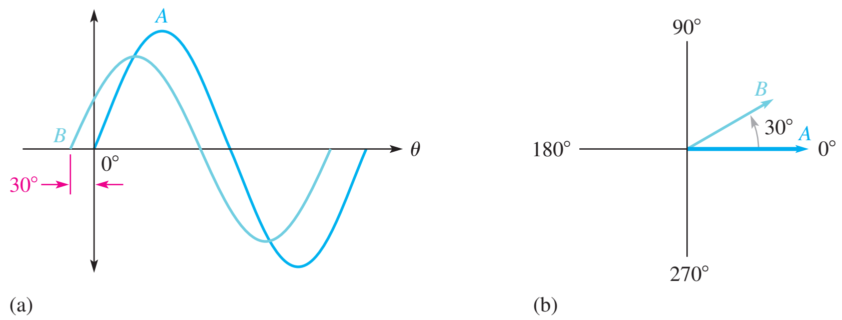
(f) $v = (10\text{ V})\sin 330° = (10\text{ V})(-0.5) = \mathbf{-5\ V}$

$330° - 360° = \mathbf{-30°}$

Related Problem If a phasor is at 45° and its length represents 15 V, what is the instantaneous sine wave value?

Phasor Diagrams

A phasor diagram can be used to show the relative relationship of two or more sine waves of the same frequency. A phasor in a *fixed position* is used to represent a complete sine wave because once the phase angle between two or more sine waves of the same frequency or between the sine wave and a reference is established, the phase angle remains constant throughout the cycles. For example, the two sine waves in Figure 11–33(a) can be represented by a phasor diagram, as shown in part (b). As you can see, sine wave B leads sine wave A by 30° and has less amplitude than sine wave A, as indicated by the lengths of the phasors.

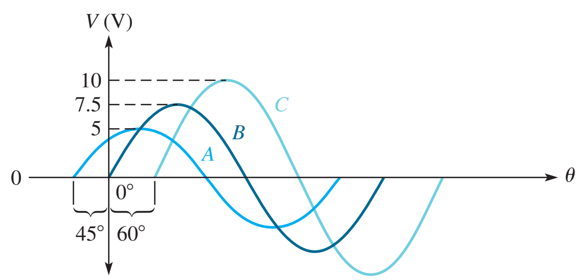


▲ **FIGURE 11–33**

Example of a phasor diagram representing sinusoidal waveforms.

EXAMPLE 11–11

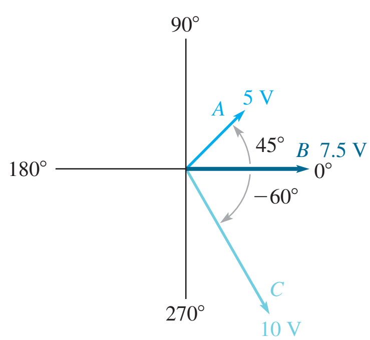
Use a phasor diagram to represent the sine waves in Figure 11–34.



▲ **FIGURE 11–34**

Solution The phasor diagram representing the sine waves is shown in Figure 11–35. The length of each phasor represents the peak value of the sine wave.

► **FIGURE 11–35**



Related Problem Describe a phasor to represent a 5 V peak sine wave that lags sine wave C in Figure 11–34 by 25°.

Angular Velocity of a Phasor

As you have seen, one cycle of a sine wave is traced out when a phasor is rotated through 360 degrees or 2π radians. The faster it is rotated, the faster the sine wave cycle is traced out. Thus, the period and frequency are related to the velocity of rotation of the phasor. The velocity of rotation is called the **angular velocity** and is designated ω (the small Greek letter omega).

When a phasor rotates through 2π radians, one complete cycle is traced out. Therefore, the time required for the phasor to go through 2π radians is the period of the sine wave. Because the phasor rotates through 2π radians in a time equal to the period, T, the angular velocity can be expressed as

$$\omega = \frac{2\pi}{T}$$

Since $f = 1/T$,

Equation 11–18

$$\omega = 2\pi f$$

When a phasor is rotated at an angular velocity ω, then ωt is the angle through which the phasor has passed at any instant. Therefore, the following relationship can be stated:

Equation 11–19

$$\theta = \omega t$$

Substituting $2\pi f$ for ω results in $\theta = 2\pi ft$. With this relationship between angle and time, the equation for the instantaneous value of a sinusoidal voltage, $v = V_p \sin \theta$, can be written as

Equation 11–20

$$v = V_p \sin 2\pi ft$$

You can calculate the instantaneous value at any point in time along the sine wave curve if you know the frequency and peak value. The unit of $2\pi ft$ is the radian so your calculator must be in the radian mode.

EXAMPLE 11–12

What is the value of a sinusoidal voltage at 3 μs from the positive-going zero crossing when $V_p = 10$ V and $f = 50$ kHz?

Solution

$$v = V_p \sin 2\pi ft$$
$$= (10\text{ V}) \sin [2\pi(50\text{ kHz})(3 \times 10^{-6}\text{ s})] = \mathbf{8.09\ V}$$

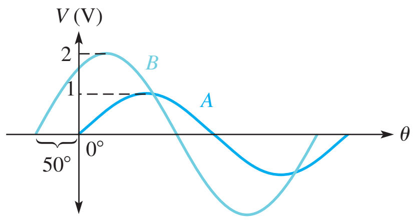
Related Problem What is the value of a sinusoidal voltage at 12 μs from the positive-going zero crossing when $V_p = 50$ V and $f = 10$ kHz?

SECTION 11–5 CHECKUP

1. What is a phasor?
2. What is the angular velocity of a phasor representing a sine wave with a frequency of 1,500 Hz?
3. A certain phasor has an angular velocity of 628 rad/s. To what frequency does this correspond?

4. Draw a phasor diagram to represent the two sine waves in Figure 11–36. Use peak values.

▶ FIGURE 11–36



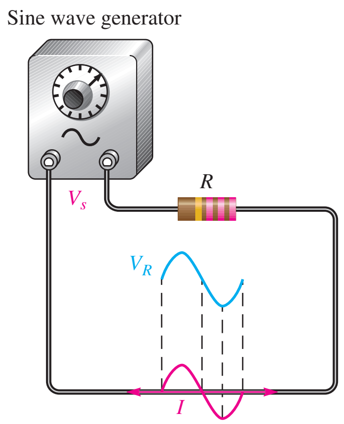
11–6 ANALYSIS OF AC CIRCUITS

When a time-varying ac voltage such as a sinusoidal voltage is applied to a circuit, the circuit laws and power formulas that you studied earlier still apply. Ohm's law, Kirchhoff's laws, and the power formulas apply to ac circuits in the same way that they apply to dc circuits.

After completing this section, you should be able to

- **Apply the basic circuit laws to resistive ac circuits**
  - Apply Ohm's law to resistive circuits with ac sources
  - Apply Kirchhoff's voltage law and current law to resistive circuits with ac sources
  - Determine power in resistive ac circuits
  - Determine total voltages that have both ac and dc components

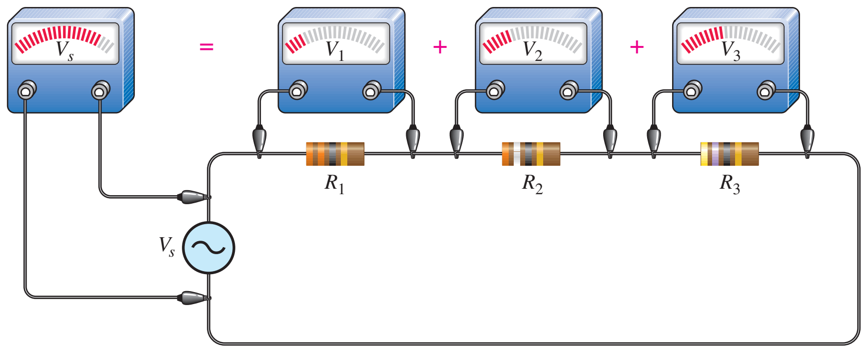
If a sinusoidal voltage is applied across a resistor as shown in Figure 11–37, there is a sinusoidal current. The current is zero when the voltage is zero and is maximum when the voltage is maximum. When the voltage changes polarity, the current reverses direction. As a result, the voltage and current are said to be in phase with each other.



◀ FIGURE 11–37

A sinusoidal voltage produces a sinusoidal current.

When you use Ohm's law in ac circuits, remember that both the voltage and the current must be expressed consistently, that is, both as peak values, both as rms values, both as average values, and so on. Kirchhoff's voltage and current laws apply to ac circuits as well as to dc circuits. Figure 11–38 illustrates Kirchhoff's voltage law in a resistive circuit that has a sinusoidal voltage source. The source voltage is the sum of all the voltage drops across the resistors, just as in a dc circuit.



▲ **FIGURE 11–38**

Illustration of Kirchhoff's voltage law in an ac circuit.

Power in resistive ac circuits is determined the same as for dc circuits except that you must use rms values of current and voltage. Recall that the rms value of a sine wave voltage is equivalent to a dc voltage of the same value in terms of its heating effect. The general power formulas are restated for a resistive ac circuit as

$$P = V_{rms}I_{rms}$$

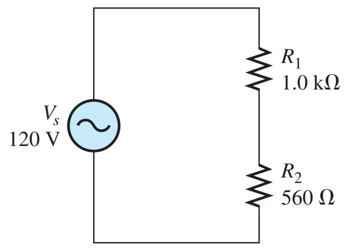
$$P = \frac{V_{rms}^2}{R}$$

$$P = I_{rms}^2 R$$

EXAMPLE 11–13

Determine the rms voltage across each resistor and the rms current in Figure 11–39. The source voltage is given as an rms value. Also determine the total power.

► **FIGURE 11–39**



Solution The total resistance of the circuit is

$$R_{tot} = R_1 + R_2 = 1.0\text{ k}\Omega + 560\ \Omega = 1.56\text{ k}\Omega$$

Use Ohm's law to find the rms current.

$$I_{rms} = \frac{V_{s(rms)}}{R_{tot}} = \frac{120\text{ V}}{1.56\text{ k}\Omega} = \mathbf{76.9\ mA}$$

The rms voltage drop across each resistor is

$$V_{1(\text{rms})} = I_{\text{rms}}R_1 = (76.9 \text{ mA})(1.0 \text{ k}\Omega) = \mathbf{76.9 \text{ V}}$$

$$V_{2(\text{rms})} = I_{\text{rms}}R_2 = (76.9 \text{ mA})(560 \ \Omega) = \mathbf{43.1 \text{ V}}$$

The total power is

$$P_{tot} = I^2_{\text{rms}}R_{tot} = (76.9 \text{ mA})^2(1.56 \text{ k}\Omega) = \mathbf{9.23 \text{ W}}$$

Related Problem Repeat this example for a source voltage of 10 V peak.

MultiSim

Use Multisim files E11-13A and E11-13B to verify the calculated results in this example and to confirm your calculations for the related problem.

EXAMPLE 11–14

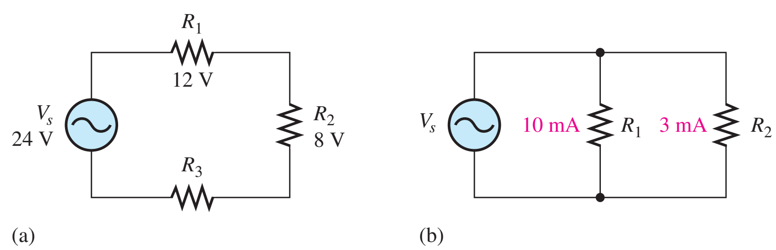
All values in Figure 11–40 are given in rms.

(a) Find the unknown peak voltage drop in Figure 11–40(a).

(b) Find the total rms current in Figure 11–40(b).

(c) Find the total power in Figure 11–40(b) if $V_{\text{rms}} = 24$ V.

▶ FIGURE 11–40



Solution **(a)** Use Kirchhoff's voltage law to find V_3.

$$V_s = V_1 + V_2 + V_3$$

$$V_{3(\text{rms})} = V_{s(\text{rms})} - V_{1(\text{rms})} - V_{2(\text{rms})} = 24 \text{ V} - 12 \text{ V} - 8 \text{ V} = 4 \text{ V}$$

Convert rms to peak.

$$V_{3(p)} = 1.414V_{3(\text{rms})} = 1.414(4 \text{ V}) = \mathbf{5.66 \text{ V}}$$

(b) Use Kirchhoff's current law to find I_{tot}.

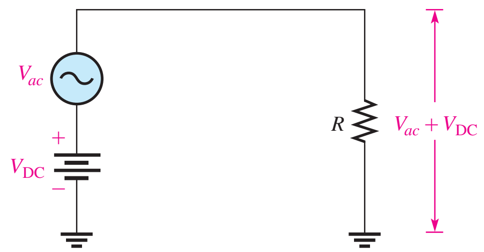
$$I_{tot(\text{rms})} = I_{1(\text{rms})} + I_{2(\text{rms})} = 10 \text{ mA} + 3 \text{ mA} = \mathbf{13 \text{ mA}}$$

(c) $P_{tot} = V_{\text{rms}}I_{\text{rms}} = (24 \text{ V})(13 \text{ mA}) = \mathbf{312 \text{ mW}}$

Related Problem A series circuit with three resistors has the following voltage drops: $V_{1(\text{rms})} = 3.50$ V, $V_{2(p)} = 4.25$ V, $V_{3(\text{avg})} = 1.70$ V. Determine the peak-to-peak source voltage.

Superimposed DC and AC Voltages

In many practical circuits, you will find both dc and ac voltages combined. An example of this is in amplifier circuits where ac signal voltages are superimposed on dc operating voltages. This is a common application of the superposition theorem studied in Chapter 8.

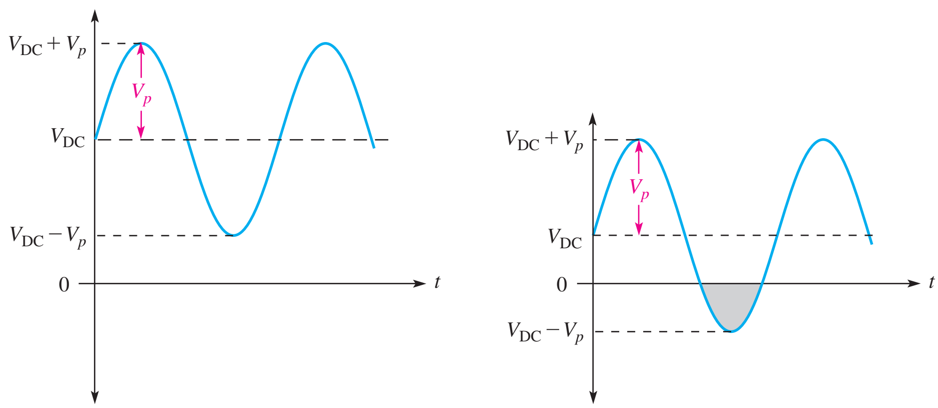


▶ FIGURE 11–41

Superimposed dc and ac voltages.

Figure 11–41 shows a dc source and an ac source in series. These two voltages will add algebraically to produce an ac voltage "riding" on a dc level, as measured across the resistor.

If V_{DC} is greater than the peak value of the sinusoidal voltage, the combined voltage is a sine wave that never reverses polarity and is therefore nonalternating. This voltage, for which the amplitude periodically varies over time but never changes polarity, is commonly referred to as pulsating dc. That is, the sine wave is riding on a dc level, as shown in Figure 11–42(a). If V_{DC} is less than the peak value of the sine wave, the sine wave will be negative during a portion of its lower half-cycle, as illustrated in Figure 11–42(b), and is therefore alternating. In either case, the sine wave will reach a maximum voltage equal to $V_{DC} + V_p$, and it will reach a minimum voltage equal to $V_{DC} - V_p$.



(a) $V_{DC} > V_p$. The sine wave never goes negative.

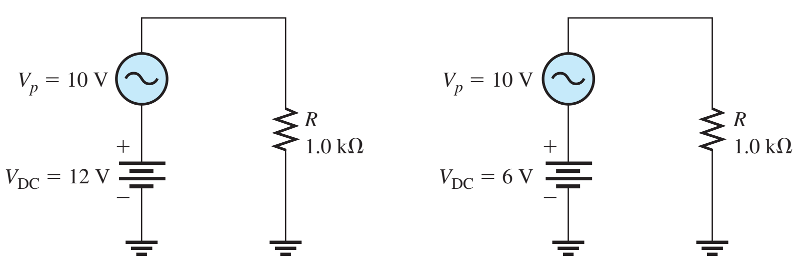
(b) $V_{DC} < V_p$. The sine wave reverses polarity during a portion of its cycle, as indicated by the gray area.

▲ FIGURE 11–42

Sine waves with dc levels.

EXAMPLE 11–15

Determine the maximum and minimum voltage across the resistor in each circuit of Figure 11–43.



(a) (b)

▲ FIGURE 11–43

Solution In Figure 11–43(a), the maximum voltage across R is

$$V_{max} = V_{DC} + V_p = 12\text{ V} + 10\text{ V} = \mathbf{22\text{ V}}$$

The minimum voltage across R is

$$V_{min} = V_{DC} - V_p = 12\text{ V} - 10\text{ V} = \mathbf{2\text{ V}}$$

Therefore, $V_{R(tot)}$ is a nonalternating sine wave that varies from +22 V to +2 V, as shown in Figure 11–44(a).

In Figure 11–43(b), the maximum voltage across R is

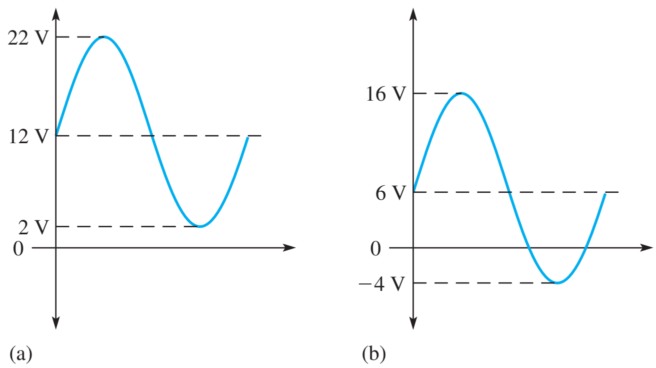
$$V_{max} = V_{DC} + V_p = 6\text{ V} + 10\text{ V} = \mathbf{16\text{ V}}$$

The minimum voltage across R is

$$V_{min} = V_{DC} - V_p = \mathbf{-4\text{ V}}$$

Therefore, $V_{R(tot)}$ is an alternating sine wave that varies from +16 V to −4 V, as shown in Figure 11–41(b).

► FIGURE 11–44



Related Problem Explain why the waveform in Figure 11–44(a) is nonalternating but the waveform in part (b) is considered to be alternating.

MultiSim

Use Multisim files E11-15A and E11-15B to verify the calculated results in this example.

SECTION 11–6 CHECKUP

1. A sinusoidal voltage with a half-cycle average value of 12.5 V is applied to a circuit with a resistance of 330 Ω. What is the peak current in the circuit?
2. The peak voltage drops in a series resistive circuit are 6.2 V, 11.3 V, and 7.8 V. What is the rms value of the source voltage?
3. What is the maximum positive value of the resulting total voltage when a sine wave with $V_p = 5$ V is added to a dc voltage of +2.5 V?
4. Will the resulting voltage in Question 3 alternate polarity?
5. If the dc voltage in Question 3 is −2.5 V, what is the maximum positive value of the resulting total voltage?

11–7 The Alternator (AC Generator)

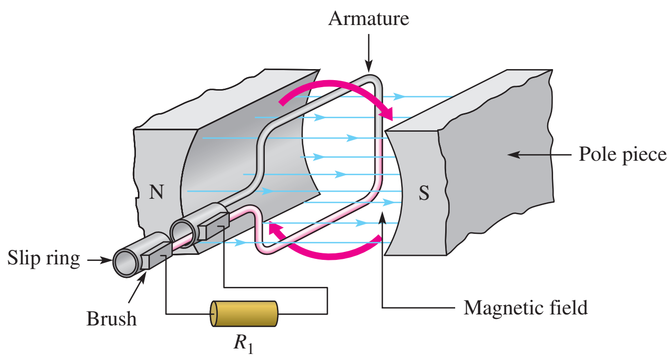
An **alternator** is an ac generator that converts energy of motion into electrical energy. Although it is similar to a dc generator, the alternator is more efficient than the dc generator. Alternators are widely used in vehicles, boats, and other applications even when dc is the final output.

After completing this section, you should be able to

- **Describe how an alternator generates electricity**
  - Identify the main parts of an alternator, including the rotor, stator, and slip rings
  - Explain why the output of a rotating-field alternator is taken from the stator
  - Describe the purpose of the slip rings
  - Explain how an alternator can be used to produce dc

Simplified Alternator

Both the dc generator and the alternator, which generates ac voltage, are based on the principle of electromagnetic induction that produces a voltage when there is relative motion between a magnetic field and a conductor. For a simplified alternator, a single rotating loop passes permanent magnetic poles. The natural voltage that is generated by a rotating loop is ac. In an alternator, instead of the split rings used in a dc generator, solid rings called slip rings are used to connect to the rotor, and the output is ac. The simplest form of an alternator has the same appearance as a dc generator (see Figure 10–35) except for the slip rings, as shown in Figure 11–45.



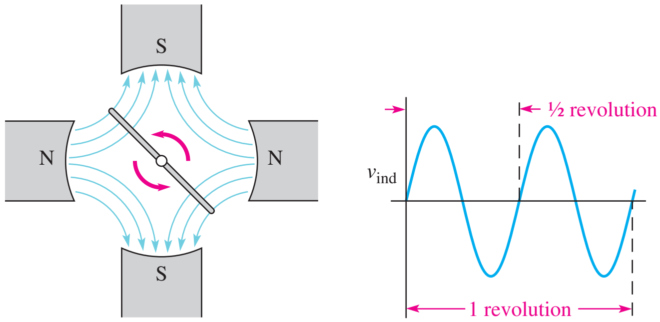
▲ **FIGURE 11–45**

A simplified alternator.

Frequency

In the simplified alternator in Figure 11–45, each revolution of the loop produces one cycle of a sine wave. The positive and negative peaks occur when the loop cuts the maximum number of flux lines. The rate the loop spins determines the time for one complete cycle and the frequency. If it takes 1/60 of a second to make a revolution, the period of the sine wave is 1/60 of a second and the frequency is 60 Hz. Thus, the faster the loop rotates, the higher the frequency.

Another way of achieving a higher frequency is to use more magnetic poles. When four poles are used instead of two, as shown in Figure 11–46, the conductor passes under a north and a south pole during one-half a revolution, which doubles the frequency.



▲ FIGURE 11–46

Four poles produce twice the frequency of two poles for the same rotational speed.

Alternators can have many more poles, depending on the requirements, some have as many as 100. The number of poles and the speed of the rotor determine the frequency in accordance with the following equation:

$$f = \frac{Ns}{120}$$

Equation 11–21

where f is the frequency in hertz, N is the number of poles, and s is the rotational speed in revolutions per minute.

EXAMPLE 11–16

Assume a large alternator is turned by a turbine at 300 rpm and has 24 poles. What is the output frequency?

Solution

$$f = \frac{Ns}{120} = \frac{(24)(300 \text{ rpm})}{120} = \mathbf{60\ Hz}$$

Related Problem At what speed must the rotor move to produce a 50 Hz output?

Practical Alternators

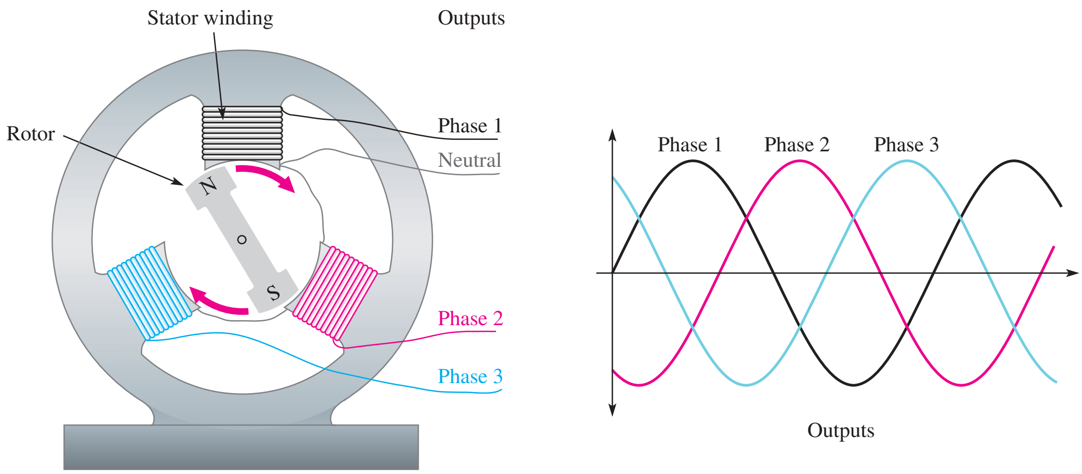
The single loop used in our simplified alternator produces only a tiny voltage. In a practical alternator, hundreds of loops are wound on a magnetic core, which forms the rotor. Practical alternators usually have fixed windings surrounding the rotor instead of permanent magnets. Depending on the type of alternator, these fixed windings can either provide the magnetic field (in which case they are called field windings) or act as the fixed conductors that produce the output (in which case they are the armature windings).

Rotating-Armature Alternators In a rotating-armature alternator, the magnetic field is stationary and is supplied by permanent magnets or electromagnets operated from dc. With electromagnets, field windings are used instead of permanent magnets and provide a fixed magnetic field that interacts with the rotor coils. Power is generated in the rotating assembly and supplied to the load through the slip rings.

In a rotating-armature alternator, the rotor is the component from which power is taken. In addition to hundreds of windings, the practical rotating-armature alternator usually has many pole pairs in the stator that alternate as north and south poles, which serve to increase the output frequency.

Rotating-Field Alternator The rotating-armature alternator is generally limited to low-power applications because all output current must pass through the slip rings and brushes. To avoid this problem, rotating-field alternators take the output from the stator coils and use a rotating magnet, hence the name. Small alternators may have a permanent magnet for a rotor, but most use an electromagnet formed by a wound rotor. A relatively small amount of dc is supplied to the rotor (through the slip rings) to power the electromagnet. As the rotating magnetic field sweeps by the stator windings, power is generated in the stator. The stator is therefore the armature in this case.

Figure 11–47 shows how a rotating-field alternator can generate three-phase sine waves. (For simplicity, a permanent magnet is shown for the rotor.) AC is generated in each winding as the north pole and the south pole of the rotor alternately sweep by a stator winding. If the north pole generates the positive portion of the sine wave, the south pole will generate the negative portion; thus, one rotation produces a complete sine wave. Each winding has a sine wave output; but because the windings are separated by 120°, the three sine waves are also shifted by 120°. This produces the three-phase output as shown. Most alternators generate three-phase voltage because it is more efficient to produce and is widely used in industry. If the final output is dc, three-phase is easier to convert to dc.



▲ **FIGURE 11–47**

The rotor shown is a permanent magnet that produces a strong magnetic field. As it sweeps by each stator winding, a sine wave is produced across that winding. The neutral is the reference.

Rotor Current

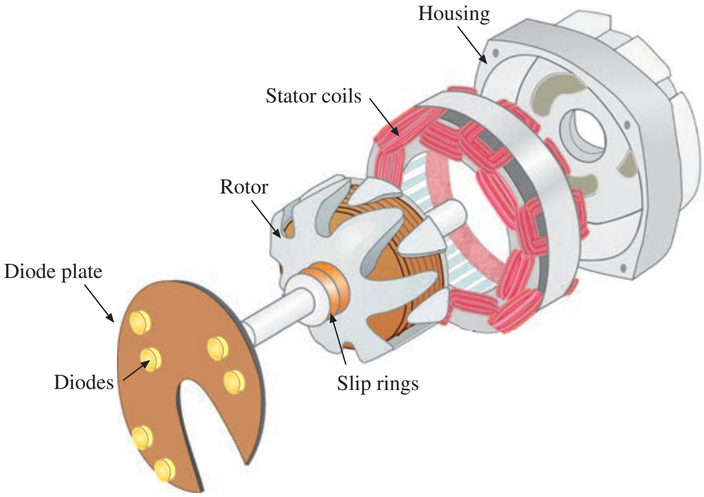
A wound rotor offers important control advantages to alternators. A wound rotor enables control over the strength of the magnetic field by controlling the rotor current and hence the output voltage. For wound rotors, dc must be supplied to the rotor. This current is usually supplied through brushes and slip rings, which are made of a continuous ring of material (unlike a commutator, which is segmented). Because the brushes need to pass only the magnetizing rotor current, they last longer and are smaller than the brushes in an equivalent dc generator, which pass all of the output current.

In wound-rotor alternators, the only current through the brushes and slip rings is the dc that is used to maintain its magnetic field. The dc is usually derived from a small portion of the output current, which is taken from the stator and converted to dc. Large alternators, such as in power stations, may have a separate dc generator, called an **exciter,** to supply current to the field coils. An exciter can respond very fast to changes in output voltage to keep the alternator's output constant, an important consideration in high-power alternators. Some exciters are set up using a stationary field with the armature on the rotating main shaft. The result is a brushless system because the exciter output is on the rotating shaft. A brushless system eliminates the primary maintenance issue with large alternators in cleaning, repairing, and replacing brushes.

An Application

Alternators are used in nearly all modern automobiles, trucks, tractors, and other vehicles. In vehicles, the output is usually three-phase ac taken from stator windings and then converted to dc with diodes that are housed inside the alternator case. (In alternators, diodes are solid-state devices that allow current in only one direction.) Current to the rotor is controlled by a voltage regulator, which is also internal to the alternator. The voltage regulator keeps the output voltage relatively constant for engine speed changes or changing loads. Alternators have replaced dc generators in automobiles and most other applications because they are more efficient and more reliable.

Important parts of a small alternator, such as you might find in an automobile are shown in Figure 11–48. Like the self-excited generator discussed in Chapter 10, the rotor has a small residual magnetism to begin with, so an ac voltage is generated in the stators as soon as the rotor starts spinning. This ac is converted to dc by a set of diodes. A portion of the dc is used to provide current to the rotor; the rest is available for the loads. The amount of current required by the rotor is much less than the total current from the alternator, so it can easily provide the required current to the load.



▲ **FIGURE 11–48**

Expanded and simplified view of a rotor, stator, and diode plate for a small alternator that produces dc.

In addition to the fact that three-phase voltage is more efficient to produce, it can produce a stable dc output easily by using two diodes in each winding. Since vehicles require dc for the charging system and loads, the output of the alternator is converted to dc internally using a diode array mounted on a diode plate. Thus, a standard three-phase automotive alternator will normally have six diodes inside to convert the output to dc. (Some alternators have six independent stator coils and 12 diodes.)

SECTION 11–7 CHECKUP

1. What two factors affect the frequency of an alternator?
2. What is the advantage of taking the output from the stator in a rotating-field alternator?
3. What is an exciter?
4. What is the purpose of the diodes in an automobile alternator?

11–8 The AC Motor

Motors are electromagnetic devices that represent the most common loads for ac in power applications. AC motors are used to operate household appliances such as heat pumps, refrigerators, washers, dryers, and vacuums. In industry, ac motors are used in many applications to move and process materials as well as refrigeration and heating units, machining operations, pumps, and much more. In this section, the two major types of ac motors, induction motors and synchronous motors, are introduced.

After completing this section, you should be able to

- **Explain how ac motors convert electrical energy into rotational motion**
  - Cite the main differences between induction and synchronous motors
  - Explain how the magnetic field rotates in an ac motor
  - Explain how an induction motor develops torque

AC Motor Classification

The two major classifications of ac motors are induction motors and synchronous motors. Several considerations determine which of these types are best for any given application. These considerations include the speed and power requirements, voltage rating, load characteristics (such as starting torque required), efficiency requirements, maintenance requirements, and operating environment (such as underwater operation or high temperatures).

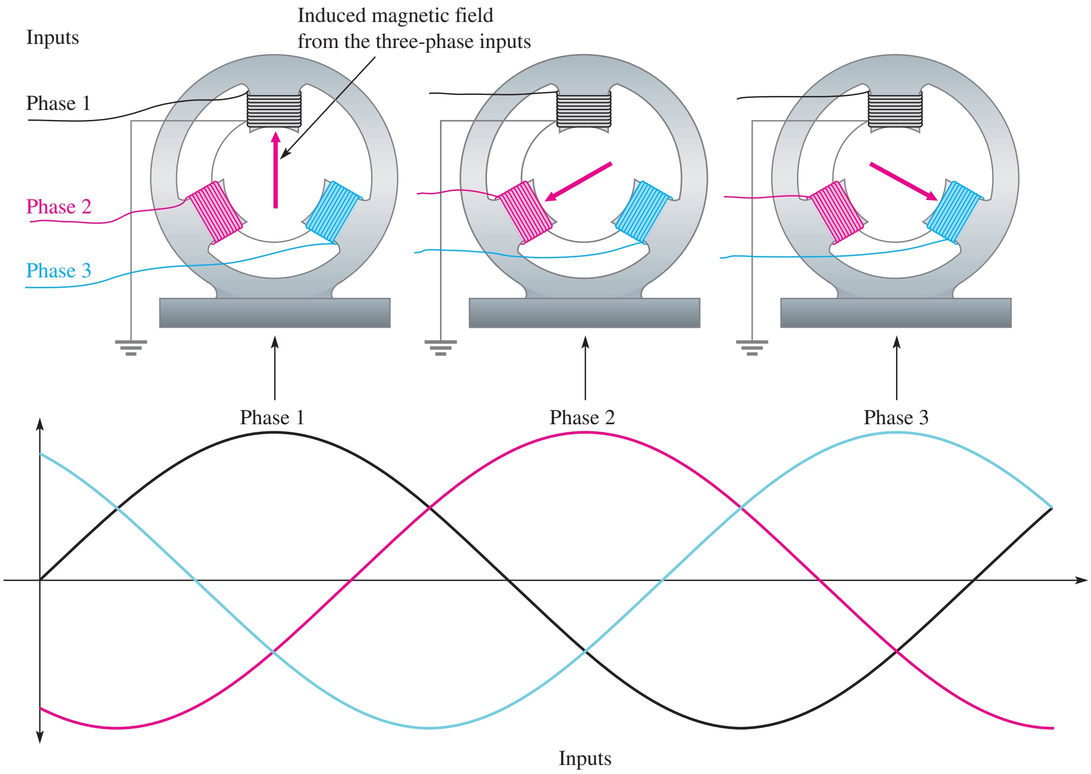
An **induction motor** is so named because a magnetic field induces current in the rotor, creating a magnetic field that interacts with the stator field. Normally, there is no electrical connection to the rotor, so there is no need for slip rings or brushes, which tend to wear out. The rotor current is caused by electromagnetic induction, which also occurs in transformers (covered in Chapter 14), so induction motors are said to work by transformer action.

In a **synchronous motor**, the rotor moves in sync (at the same rate) as the rotating field of the stator. Synchronous motors are used in applications where maintaining constant speed is important. Synchronous motors are not self-starting and must receive starting torque from an external source or from built-in starting windings. Like alternators, synchronous motors use slip rings and brushes to provide current to the rotor.

Rotating Stator Field

Both synchronous and induction ac motors have a similar arrangement for the stator windings, which allow the magnetic field of the stator to rotate. The rotating stator field is equivalent to moving a magnet in a circle except that the rotating field is produced electrically, with no moving parts.

How can the magnetic field in the stator rotate if the stator itself does not move? The rotating field is created by the changing ac itself. Let's look at a rotating field with a three-phase stator, as shown in Figure 11–49. Notice that one of the three phases "dominates" at different times. When phase 1 is at 90°, the current in the phase 1 winding is at a maximum and current in the other windings is smaller. Therefore, the stator magnetic field will be oriented toward the phase-1 stator winding. As the phase-1 current declines, the phase-2 current increases, and the field rotates toward the phase-2 winding. The magnetic field will be oriented toward the phase-2 winding when current in it is a maximum. As the phase-2 current declines, the phase-3 current increases, and the field rotates toward the phase-3 winding. The process repeats as the field returns to



▲ **FIGURE 11–49**

The application of three phases to the stator produces a net magnetic field as shown by the red arrow. The rotor (not shown) moves in response to this field.

the phase-1 winding. Thus, the field rotates at a rate determined by the frequency of the applied voltage. With a more detailed analysis, it can be shown that the magnitude of the field is unchanged; only the direction of the field changes. Although the rotating field in a three-phase motor eliminates the need for an external starter or extra starting windings, larger three-phase motors will generally have an external **motor starter**, which is a device that isolates the motor from the main power source, protects it against short circuits and overloads, and enables progressive start-up to avoid high currents at start-up.

As the stator field moves, the rotor moves in sync with it in a synchronous motor but lags behind in an induction motor. The rate the stator field moves is called the *synchronous speed* of the motor.

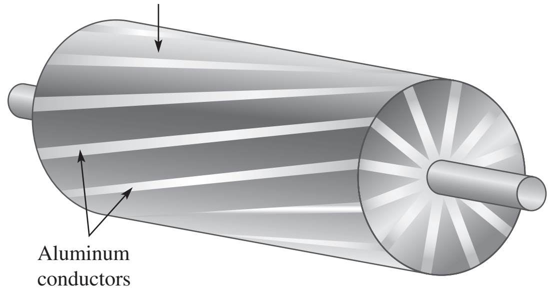
Induction Motors

The theory of operation is essentially the same for both single-phase and three-phase induction motors. Both types use the rotating field described previously, but the single-phase motor requires starting windings or other method to produce torque for starting the motor, whereas the three-phase motor is self-starting. When starting windings are employed in a single-phase motor, they are removed from the circuit by a mechanical centrifugal switch as the motor speeds up.

The core of the induction motor's rotor consists of an aluminum frame that forms the conductors for the circulating current in the rotor. (Some larger induction motors use copper bars.) The aluminum frame is similar in appearance to the exercise wheel for pet squirrels (common in the early 20th century), so it is aptly called a **squirrel cage**, illustrated in Figure 11–50. The aluminum squirrel cage itself is the *electrical* path; it is embedded within a ferromagnetic material to provide a low reluctance

▶ FIGURE 11–50

Diagram of a squirrel-cage rotor.



magnetic path through the rotor. In addition, the rotor has cooling fins that may be molded into the same piece of aluminum as the squirrel cage. The entire assembly must be balanced so that it spins easily and without vibrating.

Operation of an Induction Motor When the magnetic field from the stator moves across the squirrel cage of the inductor, a current is generated in the squirrel cage. This current creates a magnetic field that reacts with the moving field of the stator, causing the rotor to start turning. The rotor will try to "catch up" with the moving field, but cannot, in a condition known as slip. **Slip** is defined as the difference between the synchronous speed of the stator and the rotor speed. The rotor can never reach the synchronous speed of the stator field because, if it did, it would not cut any field lines and the torque would drop to zero. Without torque, the rotor could not turn itself.

Initially, before the rotor starts moving, there is no back emf, so the stator current is high. As the rotor speeds up, it generates a back emf that opposes the stator current. As the motor speeds up, the torque produced balances the load and the current is just enough to keep the rotor turning. The running current is significantly lower than the initial start-up current because of the back emf. If the load on the motor is then increased, the motor will slow down and generate less back emf. This increases the current to the motor and increases the torque it can apply to the load. Thus, an induction motor can operate over a range of speeds and torque. Maximum torque occurs when the rotor is spinning at about 75% of the synchronous speed.

Synchronous Motors

Recall that an induction motor develops no torque if it runs at the synchronous speed, so it must run slower than the synchronous speed, depending on the load. The synchronous motor will run at the synchronous speed and still develop the required torque for different loads. The only way to change the speed of a synchronous motor is to change the frequency.

The fact that synchronous motors maintain a constant speed for all load conditions is a major advantage in certain industrial operations and in applications where clock or timing requirements are involved (such as a telescope drive motor or a chart recorder). In fact, the first application of synchronous motors was in electric clocks (in 1917).

Another important advantage to large synchronous motors is their efficiency. Although their original cost is higher than a comparable induction motor, the savings in power will often pay for the cost difference in a few years.

Operation of a Synchronous Motor Essentially, the rotating stator field of the synchronous motor is identical to that of an induction motor. The primary difference in the two motors is in the rotor. The induction motor has a rotor that is electrically isolated from a supply and the synchronous motor uses a magnet to follow the rotating stator field. Small synchronous motors use a permanent magnet for the rotor; larger motors use an electromagnet. When an electromagnet is used, dc is supplied from an external source via slip rings as in the case of the alternator.

SECTION 11–8 CHECKUP

1. What is the main difference between an induction motor and a synchronous motor?
2. What happens to the magnitude of the rotating stator field as it moves?
3. What is the purpose of a motor starter?
4. What is the purpose of a squirrel cage?
5. With reference to motors, what does the term *slip* mean?

11–9 NONSINUSOIDAL WAVEFORMS

Sine waves are important in electronics, but they are by no means the only type of ac or time-varying waveform. Two other major types of waveforms are the pulse waveform and the triangular waveform.

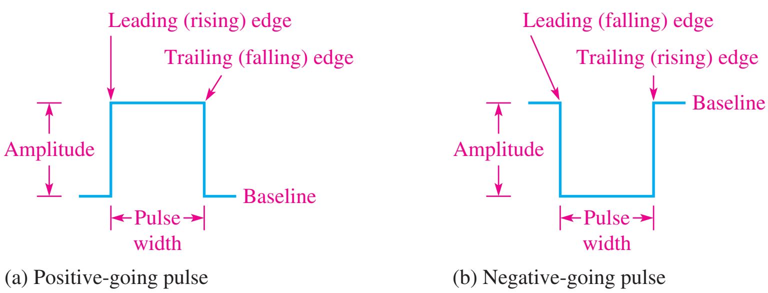
After completing this section, you should be able to

- **Identify the characteristics of basic nonsinusoidal waveforms**
  - Discuss the properties of a pulse waveform
  - Define *duty cycle*
  - Discuss the properties of triangular and sawtooth waveforms
  - Discuss the harmonic content of a waveform

Pulse Waveforms

Basically, a **pulse** can be described as a very rapid transition **(leading edge)** from one voltage or current level **(baseline)** to an amplitude level, and then, after an interval of time, a very rapid transition **(trailing edge)** back to the original baseline level. The transitions in level are also called *steps.* An ideal pulse consists of two opposite-going steps of equal amplitude. When the leading or trailing edge is positive-going, it is called a **rising edge**. When the leading or trailing edge is negative-going, it is called a **falling edge**.

Figure 11–51(a) shows an ideal positive-going pulse consisting of two equal but opposite instantaneous steps separated by an interval of time called the *pulse width*. Part (b) of Figure 11–51 shows an ideal negative-going pulse. The height of the pulse measured from the baseline is its voltage (or current) amplitude.



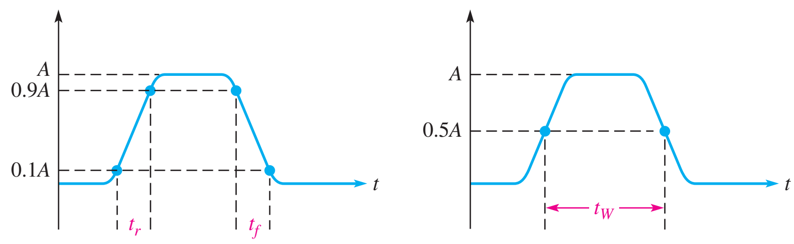
▲ FIGURE 11–51

Ideal pulses.

In many applications, analysis is simplified by treating all pulses as ideal (composed of instantaneous steps and perfectly rectangular in shape). Actual pulses, however, are never ideal. All pulses possess certain characteristics that cause them to be different from the ideal.

In practice, pulses cannot change from one level to another instantaneously. Time is always required for a transition (step), as illustrated in Figure 11–52(a). As you can see, there is an interval of time during the rising edge in which the pulse is going from its lower value to its higher value. This interval is called the *rise time*, t_r.

Rise time is the time required for the pulse to go from 10% of its amplitude to 90% of its amplitude.



(a) Rise and fall times (b) Pulse width

▲ FIGURE 11–52

Nonideal pulse.

The interval of time during the falling edge in which the pulse is going from its higher value to its lower value is called the *fall time*, t_f.

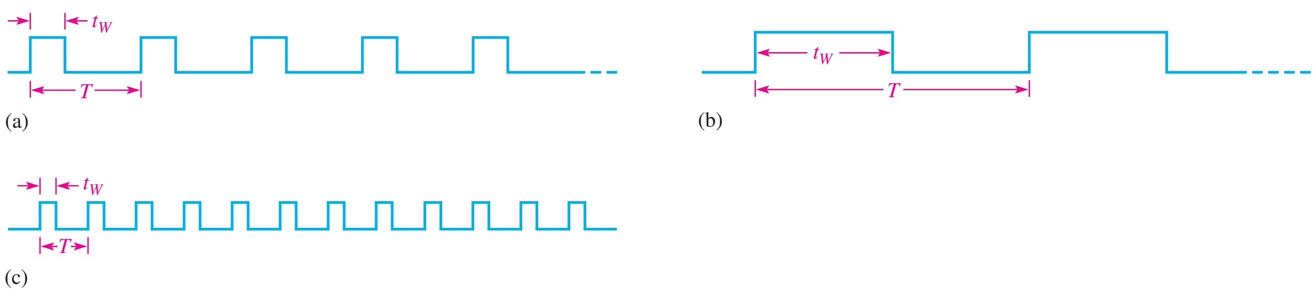
Fall time is the time required for the pulse to go from 90% of its amplitude to 10% of its amplitude.

Pulse width, t_W, also requires a precise definition for the nonideal pulse because the rising and falling edges are not vertical.

Pulse width is the time between the point on the rising edge, where the value is 50% of amplitude, to the point on the falling edge, where the value is 50% of amplitude.

Pulse width is shown in Figure 11–52(b).

Repetitive Pulses Any waveform that repeats itself at fixed intervals is **periodic**. Some examples of periodic pulse waveforms are shown in Figure 11–53. Notice that, in each case, the pulses repeat at regular intervals. The rate at which the pulses repeat is the **pulse repetition frequency (*PRF*) or pulse repetition rate (*PRR*)**, which is the fundamental frequency of the waveform. The frequency can be expressed in hertz or in pulses per second. The time from one pulse to the corresponding point on the next pulse is the period, T. The relationship between frequency and period is the same as with the sine wave, $f = 1/T$.



▲ FIGURE 11–53

Repetitive pulse waveforms.

An important characteristic of repetitive pulse waveforms is the duty cycle.

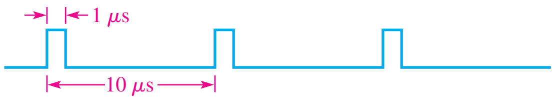
The duty cycle is the ratio of the pulse width (t_W) to the period (T) and is usually expressed as a percentage.

$$\text{percent duty cycle} = \left(\frac{t_W}{T}\right)100\% \qquad \textbf{Equation 11–22}$$

EXAMPLE 11–17

Determine the period, frequency, and duty cycle for the pulse waveform in Figure 11–54.

▶ FIGURE 11–54



Solution

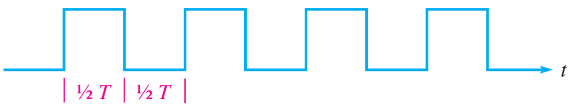
$$T = \mathbf{10\ \mu s}$$

$$f = \frac{1}{T} = \frac{1}{10\ \mu\text{s}} = \mathbf{100\ kHz}$$

$$\text{percent duty cycle} = \left(\frac{1\ \mu\text{s}}{10\ \mu\text{s}}\right)100\% = \mathbf{10\%}$$

Related Problem A certain pulse waveform has a frequency of 200 kHz and a pulse width of 0.25 μs. Determine the duty cycle.

Square Waves A square wave is a pulse waveform with a duty cycle of 50%. Thus, the pulse width is equal to one-half of the period. A square wave is shown in Figure 11–55.



◀ FIGURE 11–55

Square wave.

The Average Value of a Pulse Waveform The average value (V_{avg}) of a pulse waveform is equal to its baseline value plus its duty cycle times its amplitude. The lower level of a positive-going waveform or the upper level of a negative-going waveform is taken as the baseline. The formula is as follows:

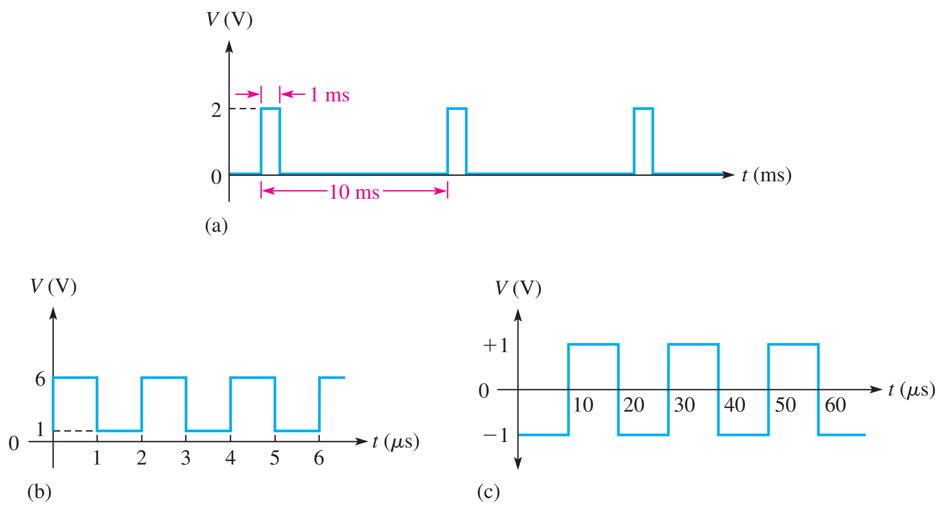
$$V_{avg} = \text{baseline} + (\text{duty cycle})(\text{amplitude}) \qquad \textbf{Equation 11–23}$$

The following example illustrates the calculation of the average value.

EXAMPLE 11–18

Determine the average value of each of the waveforms in Figure 11–56.

▶ FIGURE 11–56



Solution In Figure 11–56(a), the baseline is at 0 V, the amplitude is 2 V, and the duty cycle is 10%. The average value is

$$V_{avg} = \text{baseline} + (\text{duty cycle})(\text{amplitude})$$
$$= 0\text{ V} + (0.1)(2\text{ V}) = \mathbf{0.2\text{ V}}$$

The waveform in Figure 11–56(b) has a baseline of +1 V, an amplitude of 5 V, and a duty cycle of 50%. The average value is

$$V_{avg} = \text{baseline} + (\text{duty cycle})(\text{amplitude})$$
$$= 1\text{ V} + (0.5)(5\text{ V}) = 1\text{ V} + 2.5\text{ V} = \mathbf{3.5\text{ V}}$$

Figure 11–56(c) shows a square wave with a baseline of −1 V and an amplitude of 2 V. The average value is

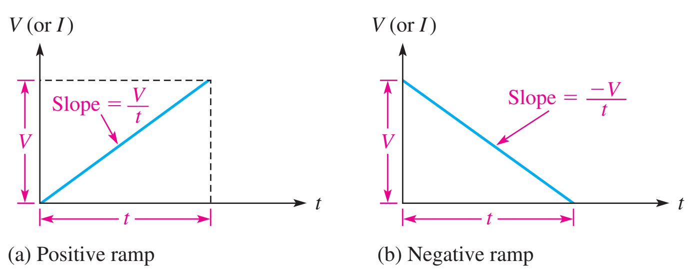
$$V_{avg} = \text{baseline} + (\text{duty cycle})(\text{amplitude})$$
$$= -1\text{ V} + (0.5)(2\text{ V}) = -1\text{ V} + 1\text{ V} = \mathbf{0\text{ V}}$$

This is an alternating square wave, and, as with an alternating sine wave, it has an average of zero.

Related Problem If the baseline of the waveform in Figure 11–56(a) is shifted to 1 V, what is the average value?

Triangular and Sawtooth Waveforms

Triangular and sawtooth waveforms are formed by voltage or current ramps. A **ramp** is a linear increase or decrease in the voltage or current. Figure 11–57 shows both positive- and negative-going ramps. In part (a), the ramp has a positive slope; in part (b), the ramp has a negative slope. The slope of a voltage ramp is $\pm V/t$ and is expressed in units of V/s. The slope of a current ramp is $\pm I/t$ and is expressed in units of A/s.



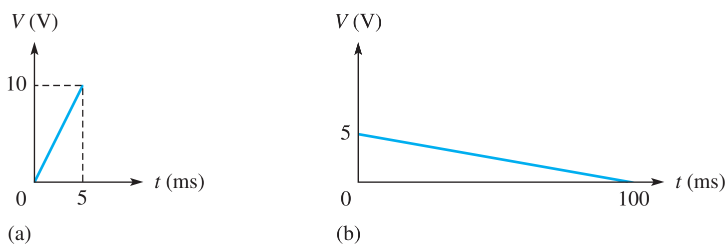
▲ FIGURE 11–57

Voltage ramps.

EXAMPLE 11–19

What are the slopes of the voltage ramps in Figure 11–58?

► FIGURE 11–58



Solution In Figure 11–58(a), the voltage increases from 0 V to +10 V in 5 ms. Thus, $V = 10$ V and $t = 5$ ms. The slope is

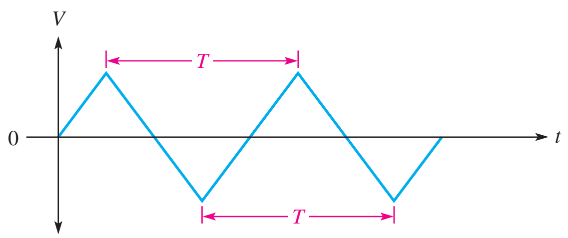
$$\frac{V}{t} = \frac{10\text{ V}}{5\text{ ms}} = \mathbf{2\ V/ms}$$

In Figure 11–58(b), the voltage decreases from +5 V to 0 V in 100 ms. Thus, $V = -5$ V and $t = 100$ ms. The slope is

$$\frac{V}{t} = \frac{-5\text{ V}}{100\text{ ms}} = \mathbf{-0.05\ V/ms}$$

Related Problem A certain voltage ramp has a slope of +12 V/μs. If the ramp starts at zero, what is the voltage at 0.01 ms?

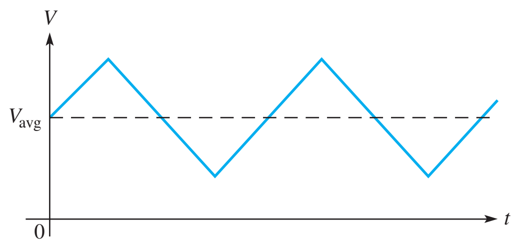
Triangular Waveforms Figure 11–59 shows that a **triangular waveform** is composed of positive-going and negative-going ramps having equal slopes. The period of this waveform is measured from one peak to the next corresponding peak, as illustrated. This particular triangular waveform is alternating and has an average value of zero.



◀ FIGURE 11–59

Alternating triangular waveform with a zero average value.

Figure 11–60 depicts a triangular waveform with a nonzero average value. The frequency for triangular waves is determined in the same way as for sine waves, that is, $f = 1/T$.

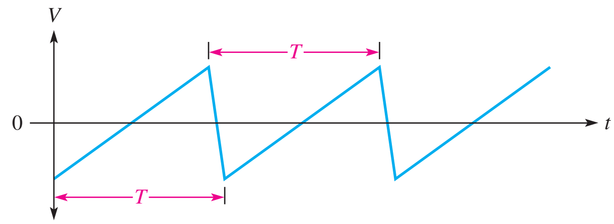


◀ FIGURE 11–60

Nonalternating triangular waveform with a nonzero average value.

Sawtooth Waveforms The **sawtooth waveform** is actually a special case of the triangular wave consisting of two ramps, one of much longer duration than the other. Sawtooth waveforms are used in many electronic systems. For example, the electron beam that sweeps across the screen of a cathode ray tube (CRT) TV, creating the picture, or analog oscilloscope creating the signal image, is controlled by sawtooth voltages and currents. The slow ramp sweeps the electron beam from left to right (the beam trace) to create the image on the CRT screen, and the fast ramp returns the beam to the left side of the screen much more quickly (the beam retrace) for the next trace. One sawtooth wave produces the horizontal beam movement, and the other produces the vertical beam movement. A sawtooth voltage is sometimes called a *sweep voltage*.

Figure 11–61 is an example of a sawtooth wave. Notice that it consists of a positive-going ramp of relatively long duration, followed by a negative-going ramp of relatively short duration.



▲ FIGURE 11–61

Alternating sawtooth waveform.

Harmonics

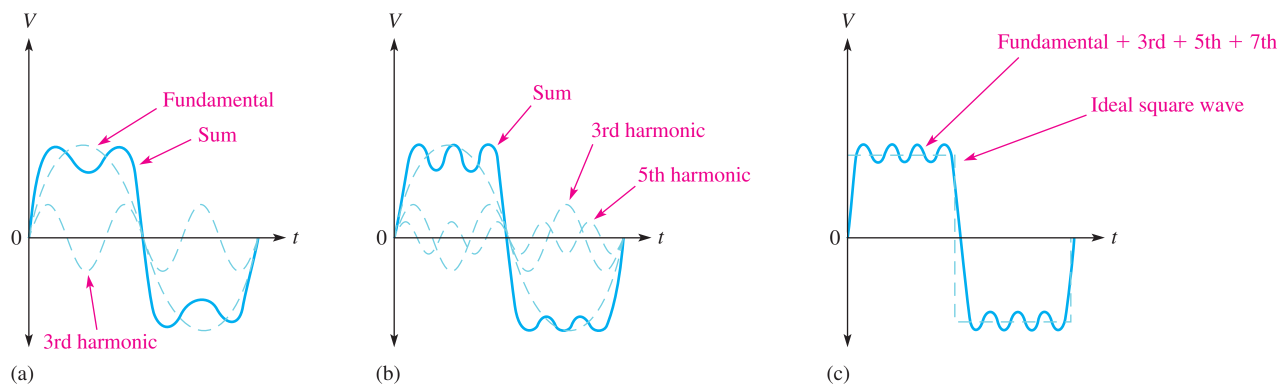
A repetitive nonsinusoidal waveform is composed of a fundamental frequency and harmonic frequencies. The **fundamental frequency** is the repetition rate of the waveform, and the **harmonics** are higher frequency sine waves that are multiples of the fundamental.

Odd Harmonics *Odd harmonics* are frequencies that are odd multiples of the fundamental frequency of a waveform. For example, a 1 kHz square wave consists of a fundamental of 1 kHz and odd harmonics of 3 kHz, 5 kHz, 7 kHz, and so on. The 3 kHz frequency in this case is called the third harmonic, the 5 kHz frequency is the fifth harmonic, and so on.

Even Harmonics *Even harmonics* are frequencies that are even multiples of the fundamental frequency. For example, if a certain wave has a fundamental of 200 Hz, the second harmonic is 400 Hz, the fourth harmonic is 800 Hz, the sixth harmonic is 1,200 Hz, and so on. These are even harmonics.

Composite Waveform Any variation from a pure sine wave produces harmonics. A nonsinusoidal wave is a composite of the fundamental and the harmonics. Some types of waveforms have only odd harmonics, some have only even harmonics, and some contain both. The shape of the wave is determined by its harmonic content. Generally, only the fundamental and the first few harmonics are of significant importance in determining the wave shape.

A square wave is an example of a waveform that consists of a fundamental and only odd harmonics. When the instantaneous values of the fundamental and each odd harmonic are added algebraically at each point, the resulting curve will have the shape of a square wave, as illustrated in Figure 11–62. In part (a) of the figure, the fundamental and the third harmonic produce a wave shape that begins to resemble a square wave. In part (b), the fundamental, third, and fifth harmonics produce a closer resemblance. When the seventh harmonic is included, as in part (c), the resulting wave shape becomes even more like a square wave. As more harmonics are included, a periodic square wave is approached.

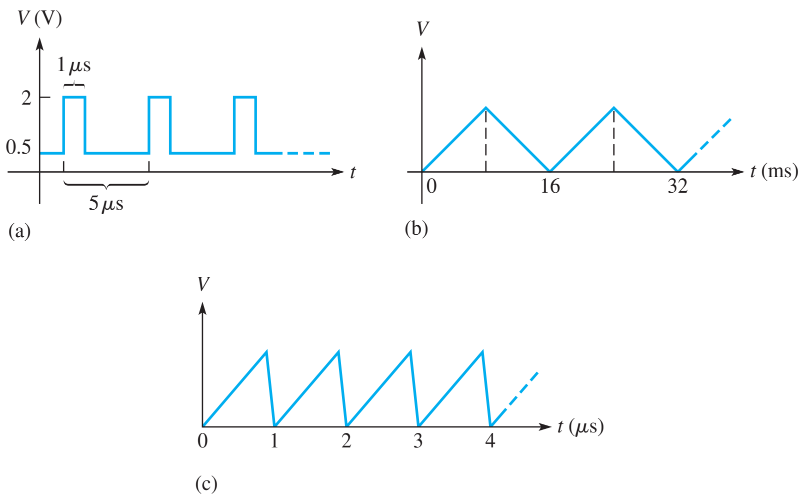


▲ FIGURE 11–62

Odd harmonics produce a square wave.

SECTION 11–9 CHECKUP

1. Define the following parameters:
   (a) rise time (b) fall time (c) pulse width
2. In a certain repetitive pulse waveform, the pulses occur once every millisecond. What is the frequency of this waveform?
3. Determine the duty cycle, amplitude, and average value of the waveform in Figure 11–63(a).
4. What is the period of the triangular wave in Figure 11–63(b)?
5. What is the frequency of the sawtooth wave in Figure 11–63(c)?



▲ FIGURE 11–63

6. Define *fundamental frequency.*
7. What is the second harmonic of a fundamental frequency of 1 kHz?
8. What is the fundamental frequency of a square wave having a period of 10 μs?

11–10 THE OSCILLOSCOPE

The oscilloscope (scope for short) is a widely used and versatile test instrument for observing and measuring waveforms.

After completing this section, you should be able to

- **Use an oscilloscope to measure waveforms**
  - Recognize common oscilloscope controls
  - Measure the amplitude of a waveform
  - Measure the period and frequency of a waveform

The **oscilloscope** is a measurement instrument that traces a graph of a measured electrical signal on its screen (display). In most applications, the display shows the signal as a function of time. Typically, the vertical axis of the display represents voltage, and the horizontal axis represents time. You can measure amplitude, period, and frequency of a signal using an oscilloscope. Also, you can determine the pulse width, duty cycle, rise time, and fall time of a pulse waveform. Nearly all scopes can display at

▲ FIGURE 11–64

A high-end oscilloscope that can display eight channels at once. Copyright © 2018 Tektronix, Inc. "All Rights Reserved" "Reproduced by permission".

least two signals on the screen at one time, enabling you to observe their time relationship. Many scopes have the ability to show four six, or eight channels simultaneously. A mixed signal (digital and analog) oscilloscope is shown in Figure 11–64.

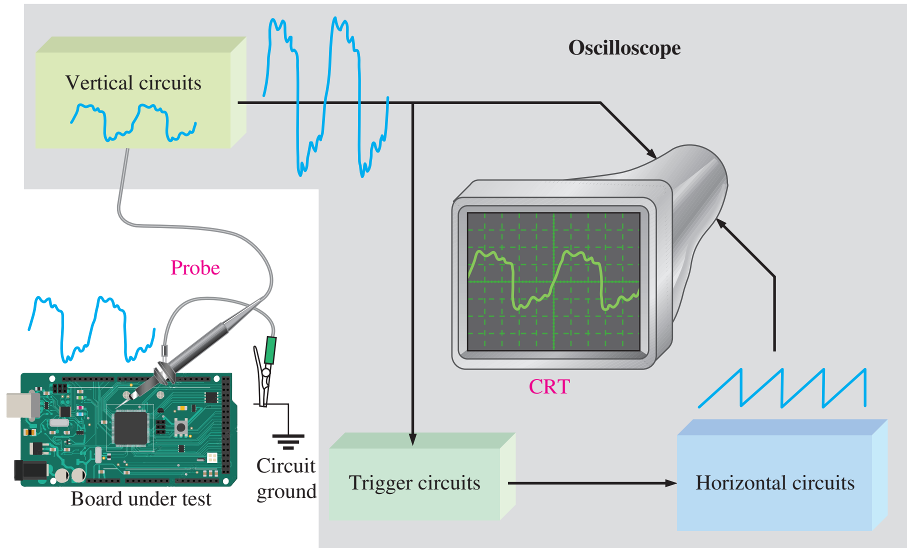
Two basic types of oscilloscopes, digital and analog, can be used to view digital waveforms. The digital scope converts the measured waveform to digital information by a sampling process in an analog-to-digital converter (ADC). The sampled information is processed and used to reconstruct the waveform on a raster type display. The analog scope works by applying the measured waveform directly to control the up and down motion of the electron beam on a cathode ray tube (CRT) as it sweeps across the screen. As a result, the beam traces out the waveform directly on the screen in real time.

The digital scope is able to store measured waves, and it is usually referred to as a digital storage oscilloscope (DSO). DSOs are much more versatile and automated than analog scopes and are much more widely used than analog scopes. While repetitive signals can be observed on either type of oscilloscope, digital scopes can capture and store both repetitive and non-repetitive waves. They can show signals that may happen only once, such as signals from destructive testing. (Specialized analog storage scopes can also store waveforms.) Digital scopes can also make automated measurements such as frequency, period, and peak-to-peak voltage. Measured values can be displayed as selected by the user.

The fundamental controls for either type of oscilloscope can be grouped into three areas: vertical, horizontal, and trigger. If you understand the basic functions of these controls, you can operate either type of scope. Analog scopes will include display controls. Digital scopes will include controls for automated measurements and storage functions. These are described in more detail in the following paragraphs.

Basic Operation of Analog Oscilloscopes

To measure a voltage, a probe must be connected from the scope to the point in a circuit at which the voltage is present. Generally, a $\times 10$ probe is used that reduces (attenuates) the signal amplitude by 10. The purpose of the probe is to couple the signal to the scope with minimum distortion, avoid noise pickup, and extend measurements to higher frequencies than are possible without the probe. The ground on the probe is connected to a nearby ground on the circuit board. The signal goes through the probe into the vertical circuits where it is either further attenuated or amplified, depending on the actual amplitude and on where you set the vertical control of the scope. The vertical circuits then drive the vertical deflection plates of the CRT. Also, the signal goes to the trigger circuits that trigger the horizontal circuits to initiate repetitive horizontal sweeps of the electron beam across the screen using a sawtooth waveform. There are many sweeps per second so that the beam appears to form a continuous line across the screen in the shape of the waveform. This basic operation is illustrated in Figure 11–65.

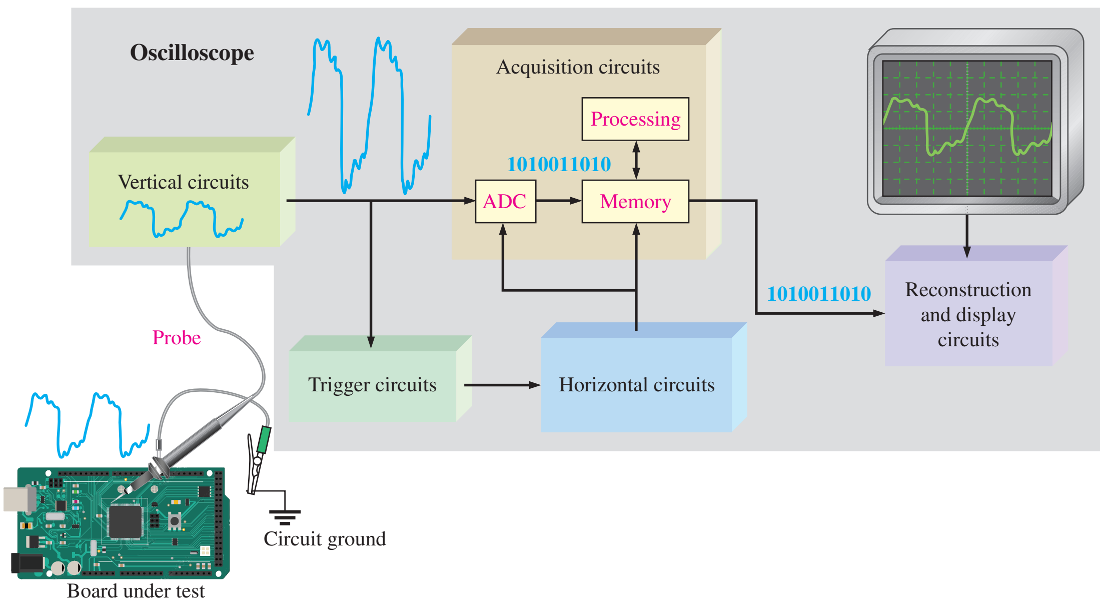


▲ FIGURE 11–65

Block diagram of an analog oscilloscope.

Basic Operation of Digital Oscilloscopes

Some parts of a digital scope are similar to the analog scope. However, the digital scope is more complex than an analog scope and uses a raster screen (a dot matrix structure) rather than the phosphor display of a CRT. There is typically a very slight delay between the acquisition and the displaying of the waveform depending upon how many data points the oscilloscope configuration must acquire and store. The digital scope first acquires the measured analog waveform and converts it to a digital format using an analog-to-digital converter (ADC). The digital data is stored and processed.



▲ FIGURE 11–66

Block diagram of a digital oscilloscope.

The data then goes to the reconstruction and display circuits for display in its original analog form. Figure 11–66 shows a basic block diagram for a digital oscilloscope.

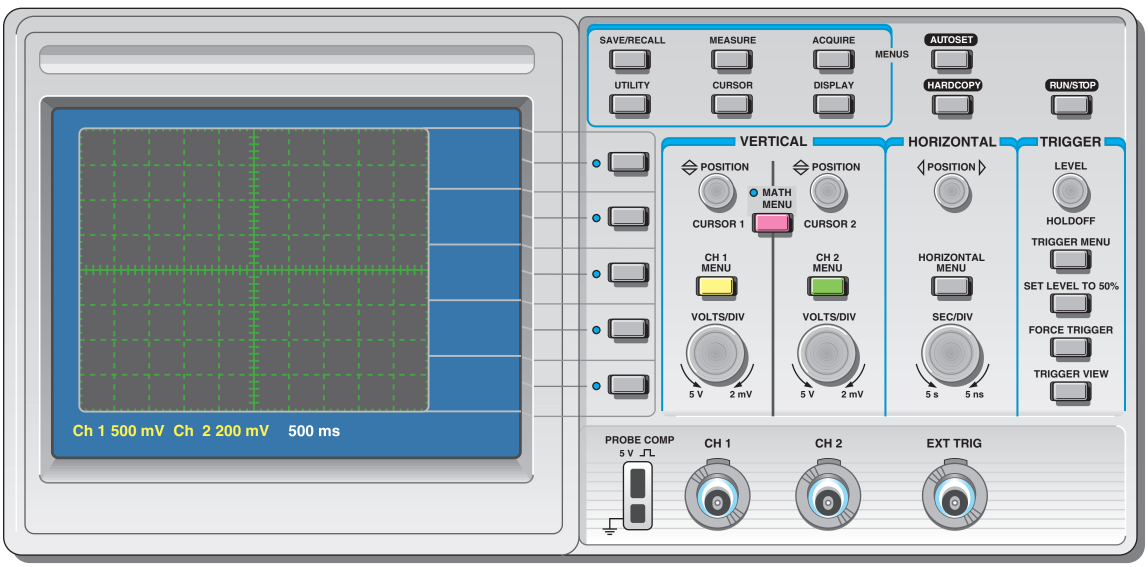
Oscilloscope Controls

A front panel view of a typical dual-channel oscilloscope is shown in Figure 11–67. Instruments vary depending on model and manufacturer, but most have certain common features. For example, the two vertical sections contain a Position control, a channel menu button, and a Volts/Div control. The horizontal section contains a Sec/Div control.

Some of the main controls are now discussed. Refer to the user manual for complete details of your particular scope.

Vertical Controls In the vertical section of the scope in Figure 11–67, there are identical controls for each of the two channels (CH1 and CH2). The Position control lets you move a displayed waveform up or down vertically on the screen. The buttons immediately right of the screen provide for the selection of several items that appear on the screen, such as the coupling modes (ac, dc, or ground), coarse or fine adjustment for the Volts/Div, signal inversion, and other parameters. The Volts/Div control adjusts the number of volts represented by each vertical division on the screen. The Volts/Div setting for each channel is displayed on the bottom of the screen.

Horizontal Controls In the horizontal section, the controls apply to both channels. The Position control lets you move a displayed waveform left or right horizontally on the screen. The Horizontal Menu button provides for the selection of several items that appear on the screen such as the main time base, expanded view of a portion of a waveform, and other parameters. The Sec/Div control adjusts the time represented by each horizontal division or main time base. The Sec/Div setting is displayed at the bottom of the screen.

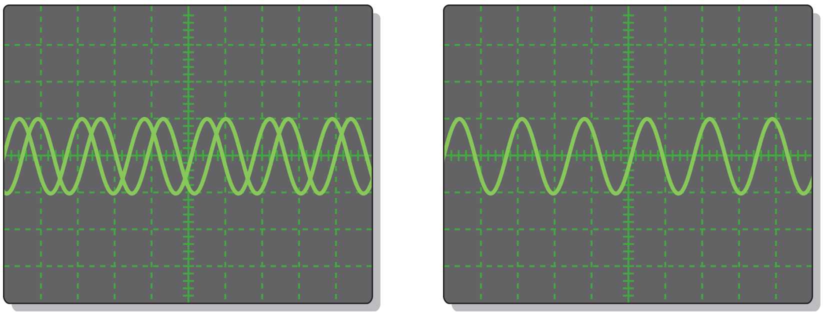


▲ FIGURE 11–67

A typical dual-channel oscilloscope. Numbers below screen indicate the values for each division on the vertical (voltage) and horizontal (time) scales and can be varied using the vertical and horizontal controls on the scope.

Trigger Controls In the Trigger section, the Level control determines the point on the triggering waveform where triggering occurs to initiate the sweep to display input waveforms. The Trigger Menu button provides for the selection of several items that appear on the screen including edge or slope triggering, trigger source, trigger mode, and other parameters. There is also an input for an external trigger signal.

Triggering stabilizes a waveform on the screen and properly triggers on a pulse that occurs only one time or randomly. Also, it allows you to observe time delays between two waveforms. Figure 11–68 compares a triggered to an untriggered signal. The untriggered signal tends to drift across the screen producing what appears to be multiple waveforms.

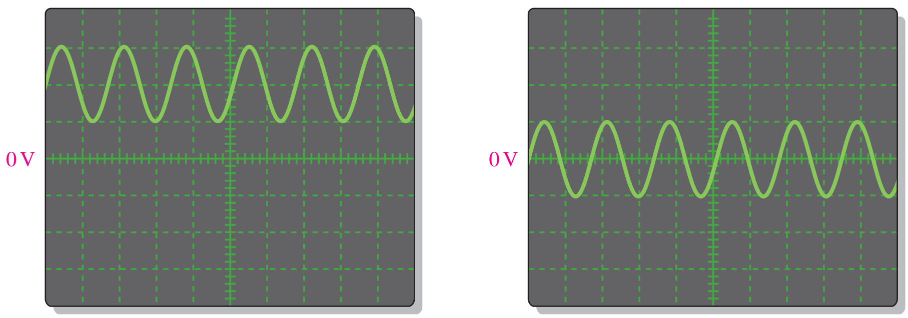


(a) Untriggered waveform display (b) Triggered waveform display

▲ FIGURE 11–68

Comparison of an untriggered and a triggered waveform on an oscilloscope.

Coupling a Signal into the Scope Coupling is the method used to connect a signal voltage to be measured into the oscilloscope. The DC and AC coupling modes are selected from the Vertical menu. DC coupling allows a waveform including its dc component to be displayed. AC coupling blocks the dc component of a signal so that you see the waveform centered at 0 V. The Ground mode allows you to connect the channel input to ground to see where the 0 V reference is on the screen. Figure 11–69 illustrates the result of DC and AC coupling using a sinusoidal waveform that has a dc component.



(a) DC coupled waveform (b) AC coupled waveform

▲ FIGURE 11–69

Displays of the same waveform having a dc component.

A general-purpose standard passive probe is shown in Figure 11–70. It is used for connecting a signal to the scope. The short lead on the side of the probe is a ground lead and allows you to connect the oscilloscope ground to a nearby point in the circuit that is being probed. This helps eliminate stray ground currents and reduces inductance on the ground lead. Since all instruments tend to affect the circuit being measured due to loading, most scope probes provide a high series resistance to minimize loading effects. Probes that have a series resistance 10 times larger than the input resistance of the scope are called ×10 (times 10) probes. Probes with no series resistance are called ×1 (times one) probes. The oscilloscope adjusts its calibration for the attenuation of the type of probe being used. For most measurements, the ×10 probe should be used because it presents a higher resistive load to the circuit under test and can display higher frequencies more accurately. However, if you are measuring very small signals, a ×1 may be the best choice.

FIGURE 11–70

An oscilloscope voltage probe. Copyright © Tektronix, Inc. Reproduced by permission.

The probe has an adjustment that allows you to compensate for the input capacitance of the scope. (Capacitance is discussed in Chapter 12.) Most scopes have a probe compensation output that provides a calibrated square wave for probe compensation. Before making a measurement, you should make sure that the probe is properly compensated to eliminate any distortion introduced. Typically, there is a screw or other means of adjusting compensation on a probe. Figure 11–71 shows scope waveforms for three probe conditions: properly compensated, undercompensated, and overcompensated. If the waveform appears either over- or undercompensated, adjust the probe until the properly compensated square wave is achieved.

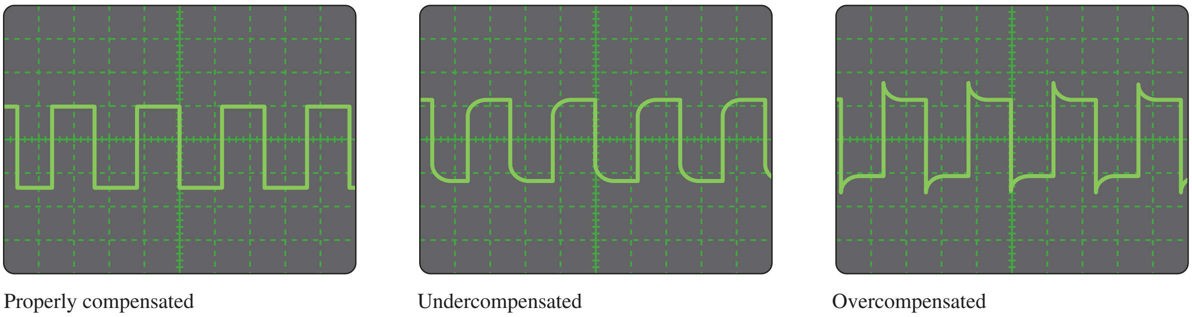
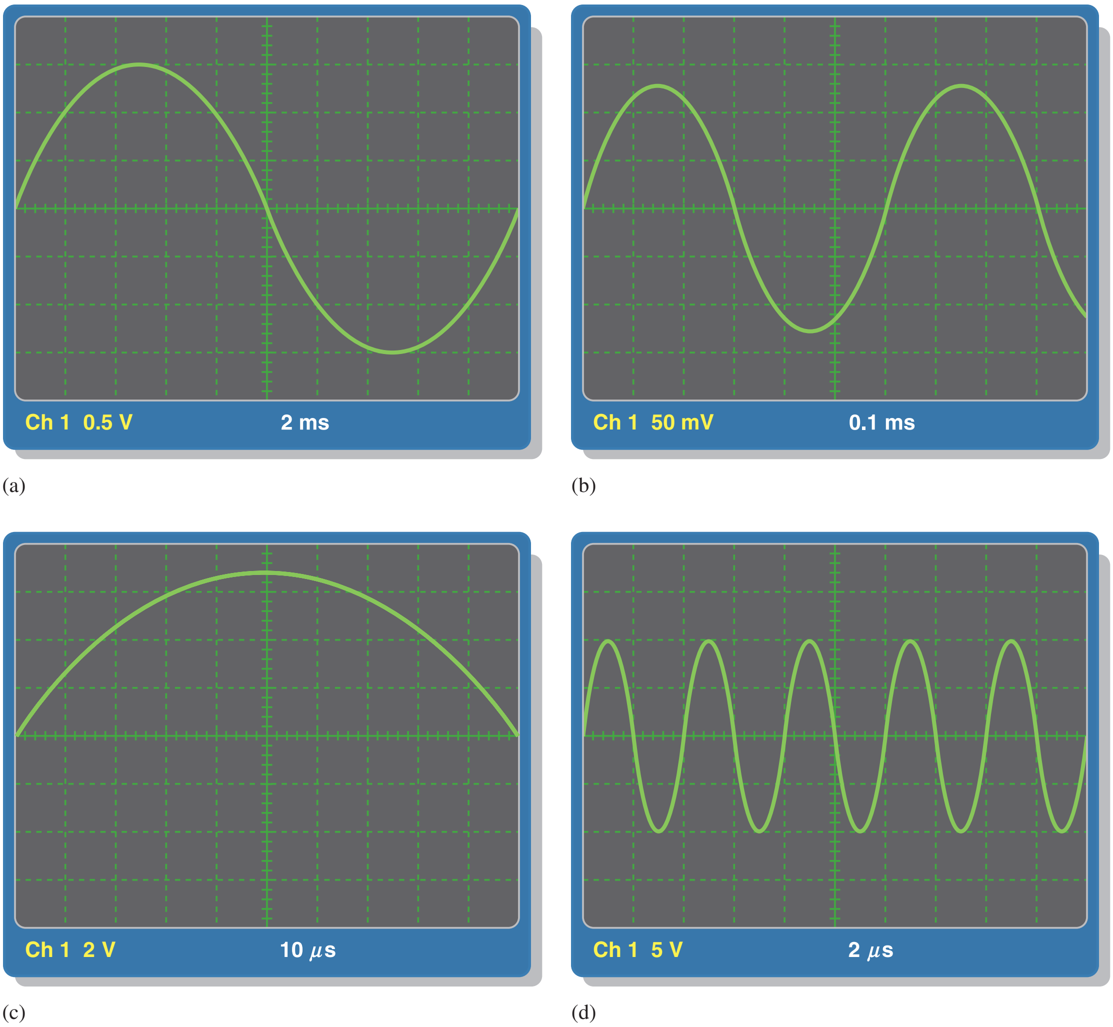


FIGURE 11–71

Probe compensation conditions.

EXAMPLE 11–20

Determine the peak-to-peak value and period of each sine wave in Figure 11–72 from the digital scope screen displays and the settings for Volts/Div and Sec/Div, which are indicated under the screens. Sine waves are centered vertically on the screens.



▲ FIGURE 11–72

Solution Looking at the vertical scale in Figure 11–72(a),

$$V_{pp} = 6 \text{ divisions} \times 0.5 \text{ V/division} = \mathbf{3.0\ V}$$

From the horizontal scale (one cycle covers 10 divisions),

$$T = 10 \text{ divisions} \times 2 \text{ ms/division} = \mathbf{20\ ms}$$

Looking at the vertical scale in Figure 11–72(b),

$$V_{pp} = 5 \text{ divisions} \times 50 \text{ mV/division} = \mathbf{250\ mV}$$

From the horizontal scale (one cycle covers six divisions),

$$T = 6 \text{ divisions} \times 0.1 \text{ ms/division} = 0.6 \text{ ms} = \mathbf{600\ \mu s}$$

Looking at the vertical scale in Figure 11–72(c),

$$V_{pp} = 6.8 \text{ divisions} \times 2 \text{ V/division} = \mathbf{13.6\ V}$$

From the horizontal scale (one-half cycle covers 10 divisions),

$$T = 20 \text{ divisions} \times 10\ \mu\text{s/division} = \mathbf{200\ \mu s}$$

Looking at the vertical scale in Figure 11–72(d),

$$V_{pp} = 4 \text{ divisions} \times 5 \text{ V/division} = \mathbf{20\ V}$$

From the horizontal scale (one cycle covers two divisions),

$$T = 2 \text{ divisions} \times 2\ \mu\text{s/division} = \mathbf{4\ \mu s}$$

Related Problem Determine the rms value and the frequency for each waveform displayed in Figure 11–72.

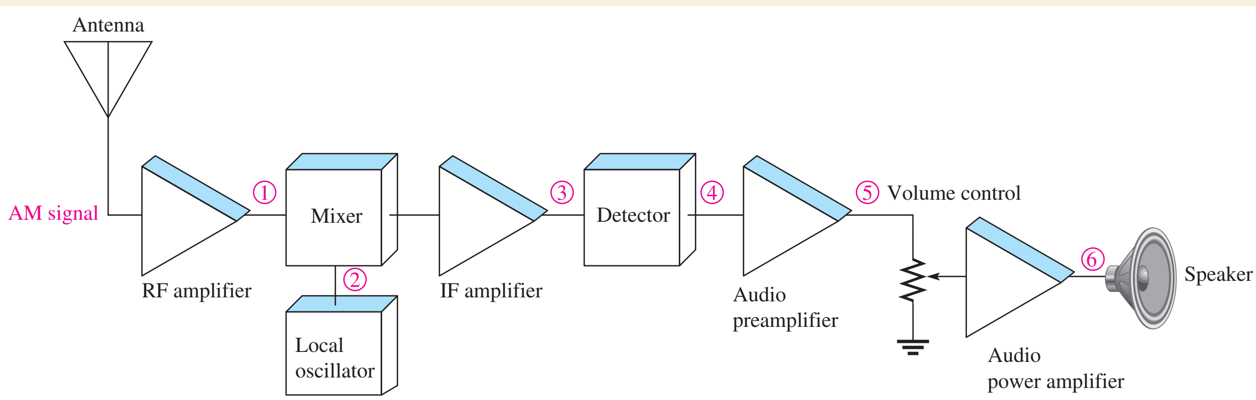
SECTION 11–10 CHECKUP

1. What is the main difference between a digital and an analog oscilloscope?
2. Is voltage read horizontally or vertically on a scope screen?
3. What does the Volts/Div control on an oscilloscope do?
4. What does the Sec/Div control on an oscilloscope do?
5. When should you use a ×10 probe for making a voltage measurement?

Application Activity

As you learned in this chapter, nonsinusoidal waveforms contain a combination of various harmonic frequencies. Each of these harmonics is a sinusoidal waveform with a certain frequency. Certain sinusoidal frequencies are audible; that is, they can be heard by the human ear. A single audible frequency, or pure sine wave, is called a tone and generally falls in the frequency range from about 300 Hz to about 15 kHz. When you hear a tone produced through a speaker, its loudness, or volume, depends on its voltage amplitude. You will use your knowledge of sine wave characteristics and the operation of an oscilloscope to measure the frequency and amplitude of signals at various points in a basic radio receiver.

Actual voice or music signals that are picked up by a radio receiver contain many harmonic frequencies with different voltage values. A voice or music signal is continuously changing,



▲ **FIGURE 11–73**

Simplified block diagram of a basic radio receiver. Circled numbers represent test points.

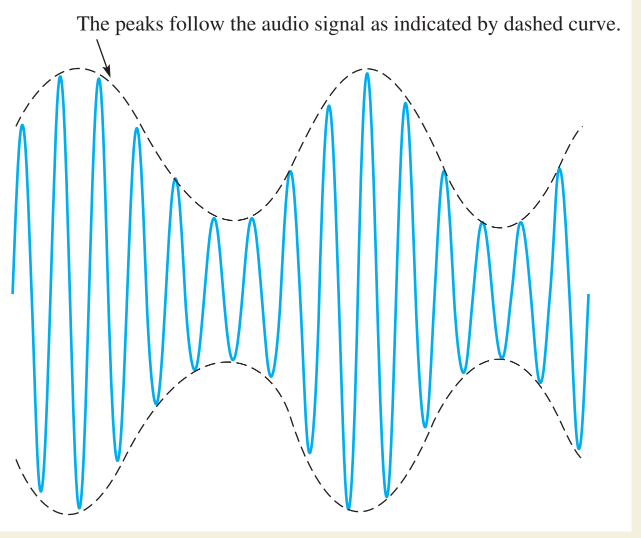


FIGURE 11–74

Example of an amplitude modulated (AM) signal.

so its harmonic content is also changing. However, if a single sinusoidal frequency is transmitted and picked up by the receiver, you will hear a constant tone from the speaker.

Although at this point you do not have the background to study amplifiers and receiver systems in detail, you can observe the signals at various points in the receiver. A block diagram of a typical AM receiver is shown in Figure 11–73. AM stands for amplitude modulation, a topic that will be covered in another course. Figure 11–74 shows what a basic AM signal looks like, and for now that's all you need to know. As you can see, the amplitude of the sinusoidal waveform is changing. The higher radio frequency (RF) signal is called the *carrier*; and its amplitude is varied or modulated by a lower frequency signal, which is the audio (a tone in this case). Normally, however, the audio signal is a complex voice or music waveform.

Oscilloscope Measurements

Signals that are indicated by circled numbers at several test points on the receiver block diagram in Figure 11–73 are displayed on the oscilloscope screen in Figure 11–75 as indicated by the same corresponding circled numbers. In all cases, the upper waveform on the screen is channel 1 and the lower waveform is channel 2. The readings on the bottom of the screen show readings for both channels.

The signal at point 1 is an AM signal, but you can't see the amplitude variation because of the short time base. The waveform is spread out too much to see the modulating audio signal, which causes amplitude variations; so what you see is just one cycle of the carrier. At point 3, the higher carrier frequency is difficult to determine because the time base was selected to allow viewing of one full cycle of the modulating signal. In an AM receiver, this intermediate frequency is 455 kHz. In actual practice, the modulated carrier signal at point 3 cannot easily be viewed on the scope because it contains two frequencies that make it difficult to synchronize in order to obtain a stable pattern. Sometimes external triggering using the modulating signal or TV field is used to obtain a stable display. A stable pattern is shown in this case to illustrate what the modulated waveform looks like.

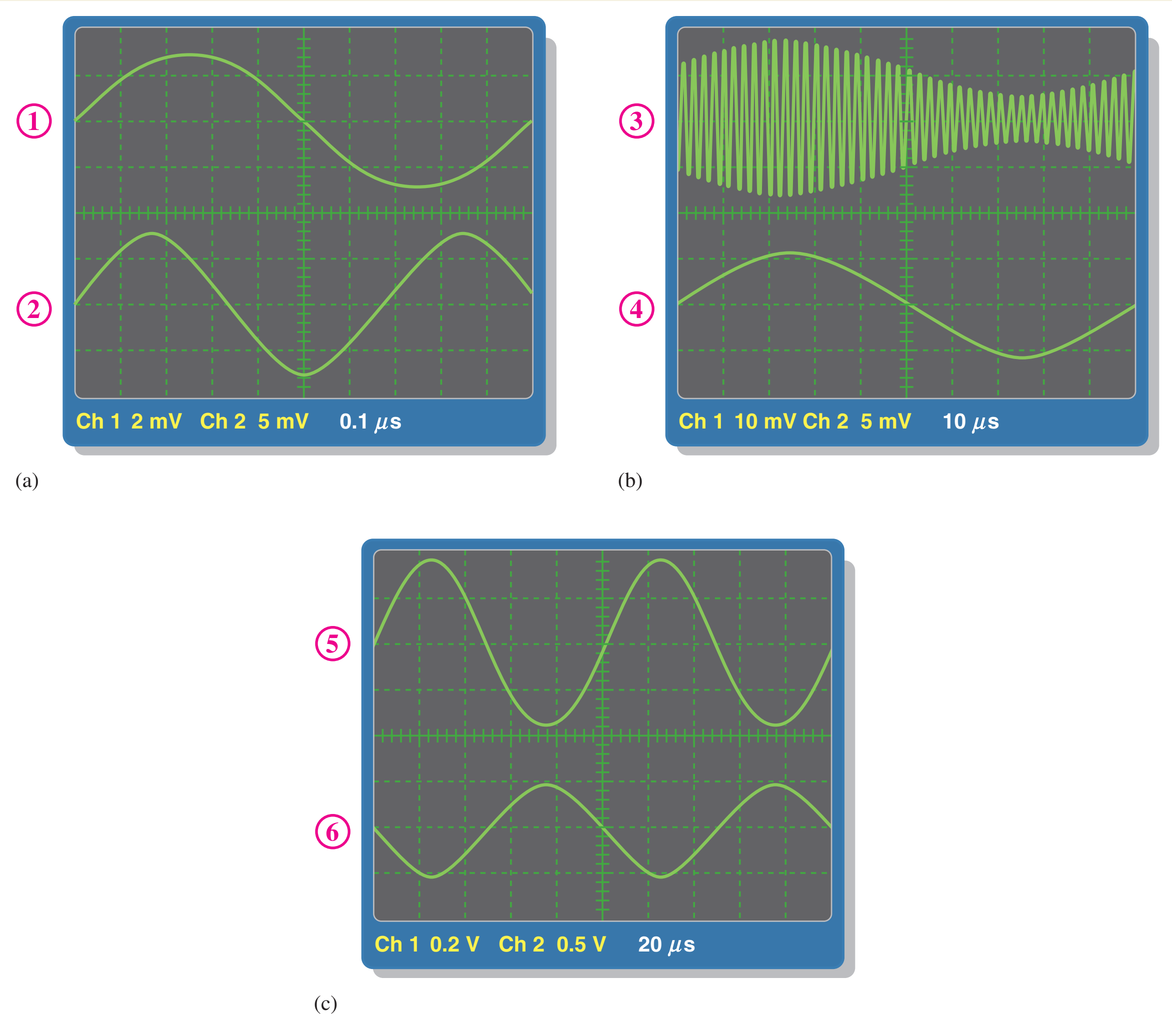
1. For each waveform in Figure 11–75, except point 3, determine the frequency and rms value. The signal at point 4 is the modulating tone extracted by the detector from the higher intermediate frequency (455 kHz).

Amplifier Analysis

2. All voltage amplifiers have a characteristic known as voltage gain. The voltage gain is the amount by which the amplitude of the output signal is greater than the amplitude of the input signal. Using this definition and the appropriate scope measurements, determine the gain of the audio preamplifier in this particular receiver.
3. When an electrical signal is converted to sound by a speaker, the loudness of the sound depends on the amplitude of the signal applied to the speaker. Based on this, explain how the volume control potentiometer is used to adjust the loudness (volume) of the sound and determine the rms amplitude at the speaker.

Review

4. What does RF stand for?
5. What does IF stand for?
6. Which frequency is higher, the carrier or the audio?
7. What is the variable in a given AM signal?

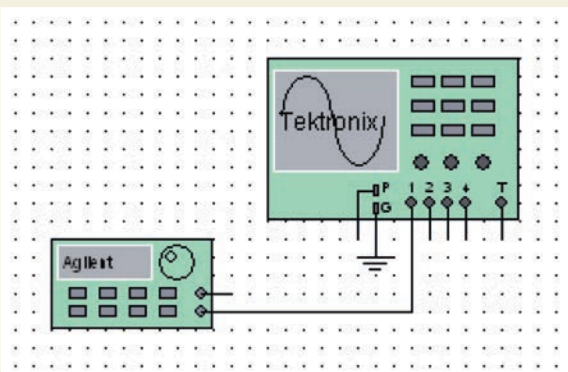


▲ FIGURE 11–75

Circled numbers correspond to the numbered test points in Figure 11–73.

Multisim Analysis

Open your Multisim software. Place an oscilloscope and a function generator on the screen connected as shown in Figure 11–76. Double-click each instrument to see the detailed controls in an expanded view. Select the sine wave function; set the amplitude to 100 mV_{pp} and the frequency to 1 kHz. Verify the values by oscilloscope measurement. Repeat for 1 V and 50 kHz and for 10 V and 1 MHz.



▲ FIGURE 11–76

SUMMARY

- The sine wave is a time-varying, periodic waveform that is based on the mathematical sine function from trigonometry.
- Alternating current changes direction in response to changes in the polarity of the source voltage.
- One cycle of a sine wave consists of a positive alternation and a negative alternation.
- Two common sources of sine waves are the electromagnetic ac generator and the electronic oscillator circuit.
- A full cycle of a sine wave is 360°, or 2π radians. A half-cycle is 180°, or π radian. A quarter-cycle is 90°, or $\pi/2$ radians.
- A sinusoidal voltage can be generated by a conductor rotating in a magnetic field.
- Phase angle is the difference in degrees or radians between a given sine wave and a reference sine wave.
- The angular position of a phasor represents the angle of the sine wave with respect to a 0° reference, and the length or magnitude of a phasor represents the amplitude.
- Alternators (ac generators) produce power when there is relative motion between a magnetic field and a conductor.
- Most alternators take the output from the stator. The rotor provides a moving magnetic field.
- Two major types of ac motors are induction motors and synchronous motors.
- Induction motors have a rotor that turns in response to a rotating field from the stator.
- Synchronous motors move at a constant speed in sync with the field of the stator.
- A pulse consists of a transition from a baseline level to an amplitude level, followed by a transition back to the baseline level.
- A triangle or sawtooth wave consists of positive-going and negative-going ramps.
- Harmonic frequencies are odd or even multiples of the repetition rate of a nonsinusoidal waveform.
- Conversions of sine wave values are summarized in Table 11–2.
- An oscilloscope is an instrument that typically graphs the voltage as a function of time at some point in a circuit.

▶ TABLE 11–2

TO CHANGE FROM	TO	MULTIPLY BY
Peak	rms	0.707
Peak	Peak-to-peak	2
Peak	Average	0.637
rms	Peak	1.414
Peak-to-peak	Peak	0.5
Average	Peak	1.57

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Amplitude (A) The maximum value of a voltage or current measured from the mean for a sine wave.

Angular velocity The rotational rate of a phasor that is related to the frequency of the sine wave that it represents.

Average value The average of a sine wave over one half-cycle. It is 0.637 times the peak value.

Cycle One repetition of a periodic waveform.

Degree The unit of angular measure corresponding to 1/360 of a complete revolution.

Duty cycle A characteristic of a pulse waveform that indicates the percentage of time that a pulse is present during a cycle; the ratio of pulse width to period expressed as either a fraction or as a percentage.

Fall time (t_f) The time interval required for a pulse to change from 90% to 10% of its amplitude.

Frequency (f) A measure of the rate of change of a periodic function; the number of cycles completed in 1 s. The unit of frequency is the hertz.

Function generator An instrument that produces more than one type of waveform.

Fundamental frequency The repetition rate of a waveform.

Harmonics The frequencies contained in a composite waveform, which are integer multiples of the pulse repetition frequency (fundamental).

Hertz (Hz) The unit of frequency. One hertz equals one cycle per second.

Induction motor An ac motor that achieves excitation to the rotor by transformer action.

Instantaneous value The voltage or current value of a waveform at a given instant in time.

Oscillator An electronic circuit that produces a time-varying signal without an external input signal using positive feedback.

Oscilloscope A measurement instrument that traces a graph of a measured electrical signal on its screen.

Peak-to-peak value The voltage or current value of a waveform measured from its minimum to its maximum points.

Peak value The voltage or current value of a waveform at its maximum positive or negative points.

Period (T) The time interval of one complete cycle of a periodic waveform.

Periodic Characterized by a repetition at fixed-time intervals.

Phase The relative angular displacement of a time-varying waveform in terms of its occurrence with respect to a reference.

Phasor A representation of a sine wave in terms of its magnitude (amplitude) and direction (phase angle).

Pulse A type of waveform that consists of two equal and opposite steps in voltage or current separated by a time interval.

Pulse width (t_W) For a nonideal pulse, the time between the 50% points on the leading and trailing edges; the time interval between the opposite steps of an ideal pulse.

Radian A unit of angular measurement. There are 2π radians in one complete 360° revolution. One radian equals 57.3°.

Ramp A type of waveform characterized by a linear increase or decrease in voltage or current.

Rise time (t_r) The time interval required for a pulse to change from 10% to 90% of its amplitude.

rms value The value of a sinusoidal voltage that indicates its heating effect, also known as the effective value. It is equal to 0.707 times the peak value. *rms* stands for root mean square.

Sine wave A type of waveform that follows a cyclic sinusoidal pattern defined by the formula $y = A \sin \theta$.

Slip The difference between the synchronous speed of the stator field and the rotor speed in an induction motor.

Squirrel cage An aluminum frame within the rotor of an induction motor that forms the electrical conductors for a rotating current.

Synchronous motor An ac motor in which the rotor moves at the same rate as the rotating magnetic field of the stator.

Waveform The pattern of variations of a voltage or current showing how the quantity changes with time.

FORMULAS

11–1	$f = \dfrac{1}{T}$	Frequency
11–2	$T = \dfrac{1}{f}$	Period
11–3	$V_{pp} = 2V_p$	Peak-to-peak voltage (sine wave)
11–4	$I_{pp} = 2I_p$	Peak-to-peak current (sine wave)
11–5	$V_{\text{rms}} = 0.707V_p$	Root-mean-square voltage (sine wave)
11–6	$I_{\text{rms}} = 0.707I_p$	Root-mean-square current (sine wave)
11–7	$V_p = 1.414V_{\text{rms}}$	Peak voltage (sine wave)
11–8	$I_p = 1.414I_{\text{rms}}$	Peak current (sine wave)
11–9	$V_{pp} = 2.828V_{\text{rms}}$	Peak-to-peak voltage (sine wave)
11–10	$I_{pp} = 2.828I_{\text{rms}}$	Peak to peak current (sine wave)
11–11	$V_{\text{avg}} = 0.637V_p$	Half-cycle average voltage (sine wave)
11–12	$I_{\text{avg}} = 0.637I_p$	Half-cycle average current (sine wave)
11–13	$\text{rad} = \left(\dfrac{\pi\text{ rad}}{180°}\right) \times \text{degrees}$	Degrees to radian conversion
11–14	$\text{degrees} = \left(\dfrac{180°}{\pi\text{ rad}}\right) \times \text{rad}$	Radian to degrees conversion
11–15	$y = A\sin\theta$	General formula for a sine wave
11–16	$y = A\sin(\theta - \phi)$	Sine wave lagging the reference
11–17	$y = A\sin(\theta + \phi)$	Sine wave leading the reference
11–18	$\omega = 2\pi f$	Angular velocity
11–19	$\theta = \omega t$	Phase angle
11–20	$v = V_p\sin 2\pi ft$	Sine wave voltage
11–21	$f = \dfrac{Ns}{120}$	Frequency of an alternator
11–22	$\text{percent duty cycle} = \left(\dfrac{t_W}{T}\right)100\%$	Duty cycle
11–23	$V_{\text{avg}} = \text{baseline} + (\text{duty cycle})(\text{amplitude})$	Average value of a pulse waveform

TRUE/FALSE QUIZ

Answers are at the end of the chapter.

1. The period of a 60 Hz sine wave is 16.7 ms.
2. The rms and average value of a sine wave are the same.
3. A sine wave with a peak value of 10 V has the same heating effect as a 10 V dc source.
4. The peak value of a sine wave is the same as its amplitude.
5. The number of radians in 360° is 2π.
6. In a three-phase electrical system, the phases are separated by 60°.
7. The purpose of an exciter is to supply dc rotor current to an alternator.
8. In an automotive alternator, the output current is taken from the rotor through slip rings.
9. A maintenance issue with induction motors is brush replacement.
10. A synchronous motor can be used when constant speed is required.
11. A periodic waveform repeats itself at fixed intervals.
12. An oscilloscope probe tends to reduce noise pickup.

SELF-TEST

Answers are at the end of the chapter.

1. The difference between alternating current (ac) and direct current (dc) is
   (a) ac changes value and dc does not **(b)** ac changes direction and dc does not
   (c) both answers (a) and (b) **(d)** neither answer (a) nor (b)
2. During each cycle, a sine wave reaches a peak value
   (a) one time **(b)** two times
   (c) four times **(d)** a number of times depending on the frequency
3. A sine wave with a frequency of 12 kHz is changing at a faster rate than a sine wave with a frequency of
   (a) 20 kHz **(b)** 15,000 Hz **(c)** 10,000 Hz **(d)** 1.25 MHz
4. A sine wave with a period of 2 ms is changing at a faster rate than a sine wave with a period of
   (a) 1 ms **(b)** 0.0025 s **(c)** 1.5 ms **(d)** 1,200 μs
5. When a sine wave has a frequency of 60 Hz, in 10 s it goes through
   (a) 6 cycles **(b)** 10 cycles **(c)** 1/16 cycle **(d)** 600 cycles
6. If the peak value of a sine wave is 10 V, the peak-to-peak value is
   (a) 20 V **(b)** 5 V **(c)** 100 V **(d)** none of these
7. If the peak value of a sine wave is 20 V, the rms value is
   (a) 14.14 V **(b)** 6.37 V **(c)** 7.07 V **(d)** 0.707 V
8. The average value of a 10 V peak sine wave over one complete cycle is
   (a) 0 V **(b)** 6.37 V **(c)** 7.07 V **(d)** 5 V
9. The average half-cycle value of a sine wave with a 20 V peak is
   (a) 0 V **(b)** 6.37 V **(c)** 12.74 V **(d)** 14.14 V
10. One sine wave has a positive-going zero crossing at 10° and another sine wave has a positive-going zero crossing at 45°. The phase angle between the two waveforms is
    (a) 55° **(b)** 35° **(c)** 0° **(d)** none of these
11. The instantaneous value of a 15 A peak sine wave at a point 32° from its positive-going zero crossing is
    (a) 7.95 A **(b)** 7.5 A **(c)** 2.13 A **(d)** 7.95 V
12. A phasor represents
    (a) the magnitude of a quantity **(b)** the magnitude and direction of a quantity
    (c) the phase angle **(d)** the length of a quantity
13. If the rms current through a 10 kΩ resistor is 5 mA, the rms voltage drop across the resistor is
    (a) 70.7 V **(b)** 7.07 V **(c)** 5 V **(d)** 50 V
14. Two series resistors are connected to an ac source. If there are 6.5 V rms across one resistor and 3.2 V rms across the other, the peak source voltage is
    (a) 9.7 V **(b)** 9.19 V **(c)** 13.72 V **(d)** 4.53 V
15. An advantage of a three-phase induction motor is that it
    (a) maintains constant speed for any load **(b)** does not require starting windings
    (c) has a wound rotor **(d)** all of the above
16. The difference in the synchronous speed of the stator field and the rotor speed of a motor is called
    (a) differential speed **(b)** loading **(c)** lag **(d)** slip
17. A 10 kHz pulse waveform consists of pulses that are 10 μs wide. Its duty cycle is
    (a) 100% **(b)** 10% **(c)** 1% **(d)** not determinable
18. The duty cycle of a square wave
    (a) varies with the frequency **(b)** varies with the pulse width
    (c) both answers (a) and (b) **(d)** is 50%

19. A sine wave covers five vertical divisions on a scope and the V/div is set to 0.2 V/div. The peak-to-peak voltage is

(a) 0.2 V **(b)** 0.5 V **(c)** 1.0 V **(d)** 2.0 V

20. On an oscilloscope, the Level control is part of the

(a) trigger controls **(b)** vertical controls

(c) horizontal controls **(d)** display controls

CIRCUIT DYNAMICS QUIZ

Answers are at the end of the chapter.

Refer to Figure 11–81.

1. If the source voltage increases, the voltage across R_3

(a) increases **(b)** decreases **(c)** stays the same

2. If R_4 opens, the voltage across R_3

(a) increases **(b)** decreases **(c)** stays the same

3. If the half-cycle average value of the source voltage is decreased, the rms voltage across R_2

(a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 11–83.

4. If the dc voltage is reduced, the average current through R_L

(a) increases **(b)** decreases **(c)** stays the same

5. If the dc voltage source is reversed, the rms current through R_L

(a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 11–90.

6. If the resistor in the upper left of the protoboard has a color code of blue, gray, brown, gold instead of the color bands shown, the CH2 voltage measured by the oscilloscope

(a) increases **(b)** decreases **(c)** stays the same

7. If the CH2 probe shown connected to the right side of the resistor is moved to the left side of the resistor, the amplitude of the measured voltage

(a) increases **(b)** decreases **(c)** stays the same

8. If the bottom lead of the right-most resistor becomes disconnected, the CH2 voltage

(a) increases **(b)** decreases **(c)** stays the same

9. If the wire connecting the two upper resistors becomes disconnected, altering the loading effect on the input signal source, the CH1 voltage

(a) increases **(b)** decreases **(c)** stays the same

Refer to Figure 11–91.

10. If the right-most resistor has a third band that is orange instead of red, the CH1 voltage

(a) increases **(b)** decreases **(c)** stays the same

11. If the resistor at the upper left opens, the CH1 voltage

(a) increases **(b)** decreases **(c)** stays the same

12. If the resistor at the lower left opens, the CH1 voltage

(a) increases **(b)** decreases **(c)** stays the same

PROBLEMS

More difficult problems are indicated by an asterisk (*).
Answers to odd-numbered problems are at the end of the book.

SECTION 11–1 The Sinusoidal Waveform

1. Calculate the frequency for each of the following values of period:

(a) 1 s **(b)** 0.2 s **(c)** 50 ms **(d)** 1 ms **(e)** 500 μs **(f)** 10 μs

2. Calculate the period of each of the following values of frequency:

(a) 1 Hz **(b)** 60 Hz **(c)** 500 Hz **(d)** 1 kHz **(e)** 200 kHz **(f)** 5 MHz

3. A sine wave goes through 5 cycles in 10 μs. What is its period?

4. A sine wave has a frequency of 50 kHz. How many cycles does it complete in 10 ms?

5. How long does it take a 10 kHz sine wave to complete 100 cycles?

SECTION 11–2 Sinusoidal Voltage and Current Values

6. A sine wave has a peak value of 12 V. Determine the following values:

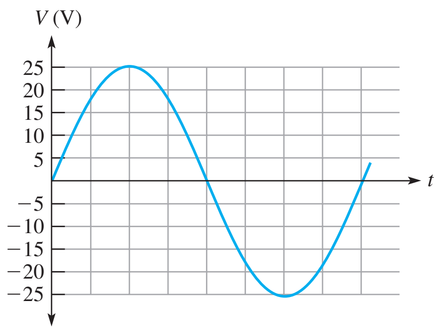
(a) rms **(b)** peak-to-peak **(c)** average

7. A sinusoidal current has an rms value of 5 mA. Determine the following values:

(a) peak **(b)** average **(c)** peak-to-peak

8. For the sine wave in Figure 11–77, determine the peak, peak-to-peak, rms, and average values.

▶ FIGURE 11–77



SECTION 11–3 Angular Measurement of a Sine Wave

9. Convert the following angular values from degrees to radians:

(a) 30° **(b)** 45° **(c)** 78° **(d)** 135° **(e)** 200° **(f)** 300°

10. Convert the following angular values from radians to degrees:

(a) $\pi/8$ rad **(b)** $\pi/3$ rad **(c)** $\pi/2$ rad **(d)** $3\pi/5$ rad **(e)** $6\pi/5$ rad **(f)** 1.8π rad

11. Sine wave A has a positive-going zero crossing at 30°. Sine wave B has a positive-going zero crossing at 45°. Determine the phase angle between the two signals. Which signal leads?

12. One sine wave has a positive peak at 75°, and another has a positive peak at 100°. How much is each sine wave shifted in phase from the 0° reference? What is the phase angle between them?

13. Make a sketch of two sine waves as follows: Sine wave A is the reference, and sine wave B lags A by 90°. Both have equal amplitudes.

SECTION 11–4 The Sine Wave Formula

14. A certain sine wave has a positive-going zero crossing at 0° and an rms value of 20 V. Calculate its instantaneous value at each of the following angles:

(a) 15° **(b)** 33° **(c)** 50° **(d)** 110°
(e) 70° **(f)** 145° **(g)** 250° **(h)** 325°

15. For a particular 0° reference sinusoidal current, the peak value is 100 mA. Determine the instantaneous value at each of the following points:

(a) 35° **(b)** 95° **(c)** 190° **(d)** 215° **(e)** 275° **(f)** 360°

16. For a 0° reference sine wave with an rms value of 6.37 V, determine its instantaneous value at each of the following points:

(a) $\pi/8$ rad **(b)** $\pi/4$ rad **(c)** $\pi/2$ rad **(d)** $3\pi/4$ rad
(e) π rad **(f)** $3\pi/2$ rad **(g)** 2π rad

17. Sine wave A lags sine wave B by 30°. Both have peak values of 15 V. Sine wave A is the reference with a positive-going crossing at 0°. Determine the instantaneous value of sine wave B at 30°, 45°, 90°, 180°, 200°, and 300°.

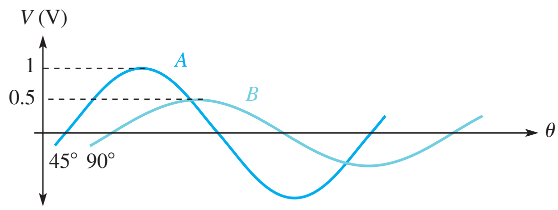
18. Repeat Problem 17 for the case when sine wave A leads sine wave B by 30°.

***19.** A certain sine wave has a frequency of 2.2 kHz and an rms value of 25 V. Assuming a given cycle begins (zero crossing) at $t = 0$ s, what is the change in voltage from 0.12 ms to 0.2 ms?

SECTION 11–5 Introduction to Phasors

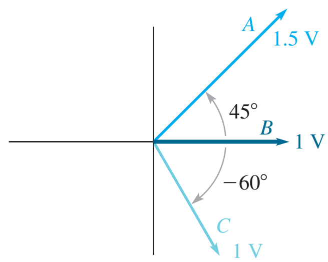
20. Draw a phasor diagram to represent the sine waves in Figure 11–78 with respect to a 0° reference.

▶ FIGURE 11–78



21. Draw the sine waves represented by the phasor diagram in Figure 11–79. The phasor lengths represent peak values.

▶ FIGURE 11–79



22. Determine the frequency for each angular velocity:

(a) 60 rad/s **(b)** 360 rad/s **(c)** 2 rad/s **(d)** 1,256 rad/s

23. Determine the value of sine wave A in Figure 11–78 at each of the following times, measured from the positive-going zero crossing. Assume the frequency is 5 kHz.

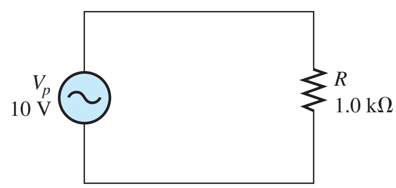
(a) 30 μs **(b)** 75 μs **(c)** 125 μs

SECTION 11–6 Analysis of AC Circuits

24. A sinusoidal voltage is applied to the resistive circuit in Figure 11–80. Determine the following:

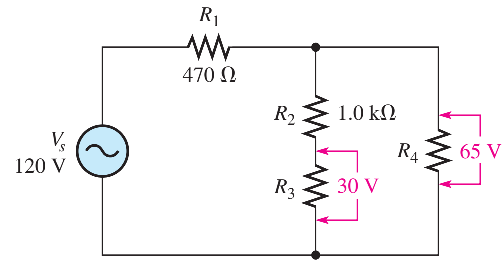
(a) I_{rms} **(b)** I_{avg} **(c)** I_p **(d)** I_{pp} **(e)** i at the positive peak

▶ FIGURE 11–80



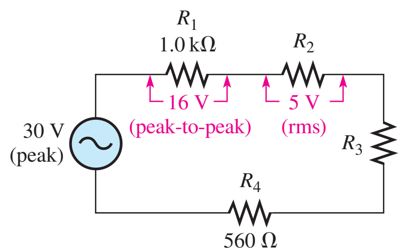
25. Find the half-cycle average values of the voltages across R_1 and R_2 in Figure 11–81. All values shown are rms.

▶ FIGURE 11–81



26. Determine the rms voltage across R_3 in Figure 11–82.

▶ FIGURE 11–82



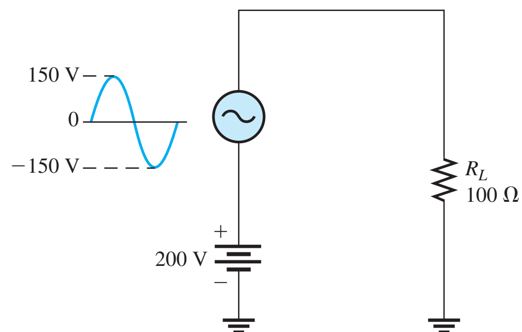
27. A sine wave with an rms value of 10.6 V is riding on a dc level of 24 V. What are the maximum and minimum values of the resulting waveform?

28. How much dc voltage must be added to a 3 V rms sine wave in order to make the resulting voltage nonalternating (no negative values)?

29. A 6 V peak sine wave is riding on a dc voltage of 8 V. If the dc voltage is lowered to 5 V, how far negative will the sine wave go?

***30.** Figure 11–83 shows a sinusoidal voltage source in series with a dc source. Effectively, the two voltages are superimposed. Determine the power dissipation in the load resistor.

▶ FIGURE 11–83



SECTION 11–7 The Alternator (AC Generator)

31. The conductive loop on the rotor of a simple two-pole, single-phase generator rotates at a rate of 250 rps. What is the frequency of the induced output voltage?

32. A certain four-pole generator has a speed of rotation of 3,600 rpm. What is the frequency of the voltage produced by this generator?

33. At what speed of rotation must a four-pole generator be operated to produce a 400 Hz sinusoidal voltage?

34. A common frequency for alternators on aircraft is 400 Hz. How many poles does a 400 Hz alternator have if the speed of rotation is 3,000 rpm?

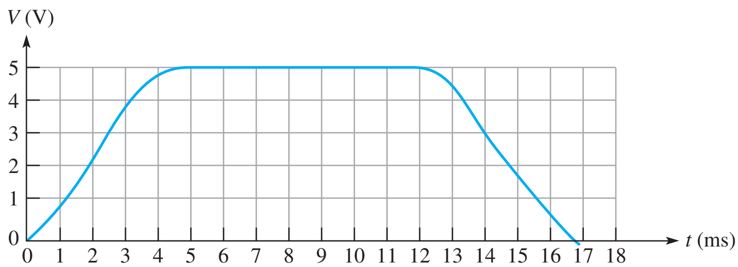
SECTION 11–8 The AC Motor

35. What is the main difference between a one-phase induction motor and a three-phase induction motor?

36. Explain how the field in a three-phase motor rotates if there are no moving parts to the field coils.

SECTION 11–9 Nonsinusoidal Waveforms

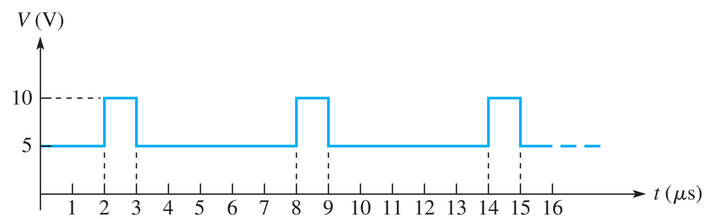
37. From the graph in Figure 11–84, determine the approximate values of t_r, t_f, t_W, and amplitude.



▲ FIGURE 11–84

38. The repetition frequency of a pulse waveform is 2 kHz, and the pulse width is 1 μs. What is the percent duty cycle?

39. Calculate the average value of the pulse waveform in Figure 11–85.

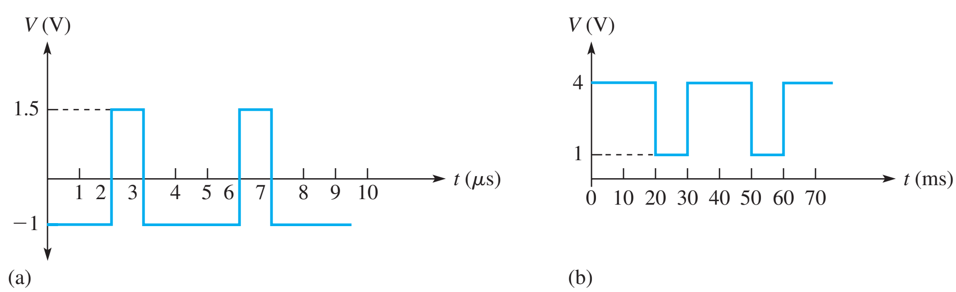


▲ FIGURE 11–85

40. Determine the duty cycle for each waveform in Figure 11–86.

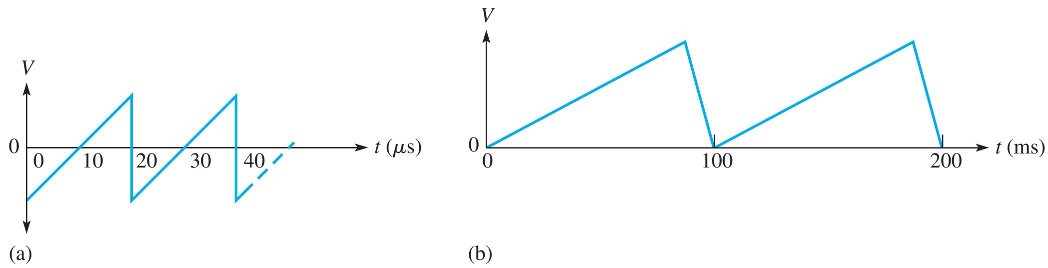
41. Find the average value of each pulse waveform in Figure 11–86.

42. What is the frequency of each waveform in Figure 11–86?



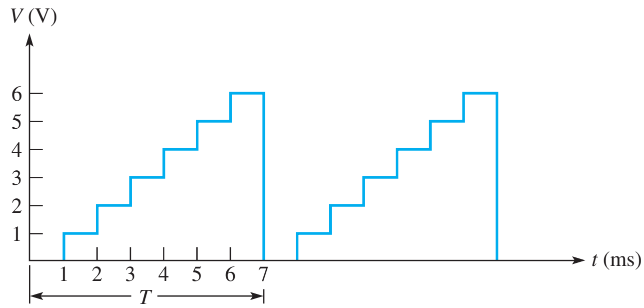
▲ FIGURE 11–86

43. What is the frequency of each sawtooth waveform in Figure 11–87?



▲ FIGURE 11–87

***44.** A nonsinusoidal waveform called a *stairstep* is shown in Figure 11–88. Determine its average value.



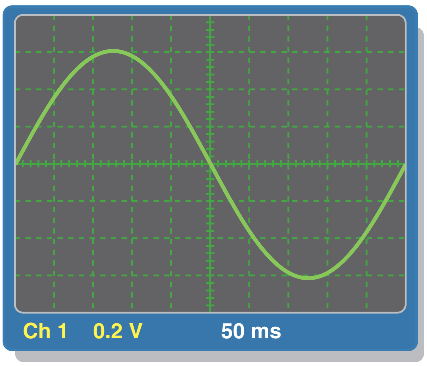
▲ FIGURE 11–88

45. A square wave has a period of 40 μs. List the first six odd harmonics.

46. What is the fundamental frequency of the square wave mentioned in Problem 45?

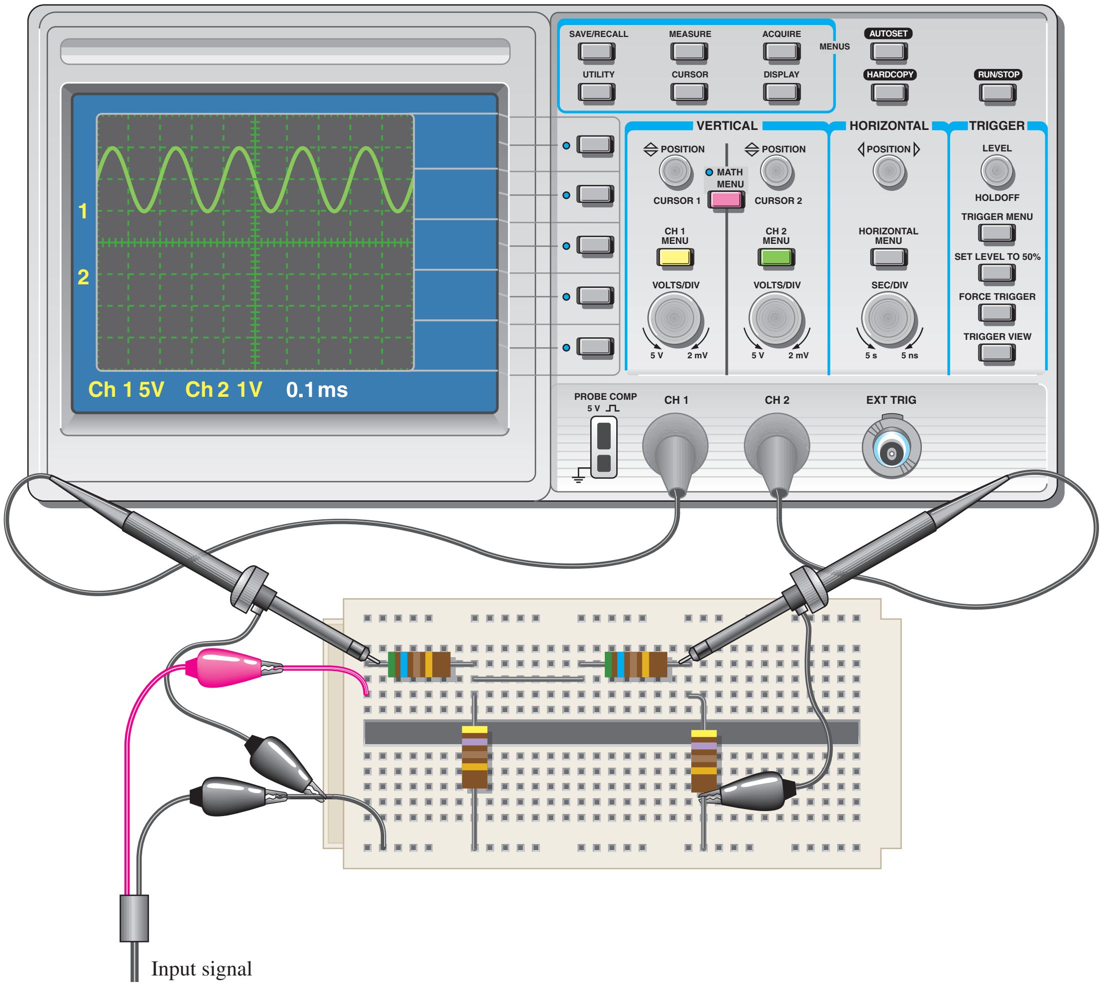
SECTION 11–10 The Oscilloscope

47. Determine the peak value and the period of the sine wave displayed on the scope screen in Figure 11–89.



▲ FIGURE 11–89

***48.** Based on the instrument settings and an examination of the scope display and the protoboard in Figure 11–90, determine the frequency and peak value of the input signal and output signal. The waveform shown is channel 1. Draw the channel 2 waveform as it would appear on the scope with the indicated settings.



▲ FIGURE 11–90

***49.** Examine the protoboard and the oscilloscope display in Figure 11–91 and determine the peak value and the frequency of the unknown input signal.

Multisim Troubleshooting and Analysis

These problems require Multisim.

50. Open file P11-50 and measure the peak and rms voltage across each of the resistors.

51. Open file P11-51 and measure the peak and rms voltage across each of the resistors.

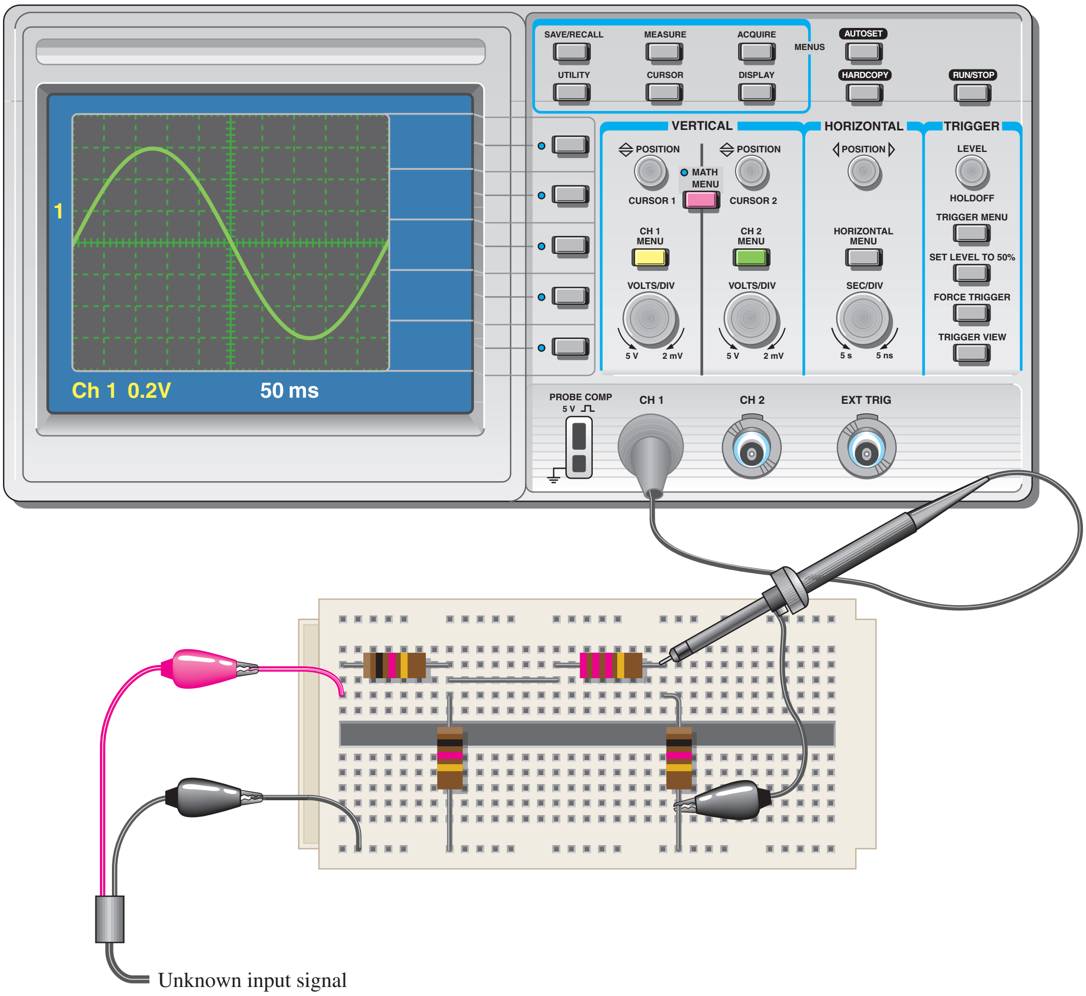
52. Open file P11-52. Determine if there is a fault and, if so, identify the fault.

53. Open file P11-53 and measure the rms current in each branch of the circuit.

54. Open file P11-54. Determine if there is a fault and, if so, identify the fault.

55. Open file P11-55 and measure the total voltage across the resistor using the oscilloscope.

56. Open file P11-56 and measure the total voltage across the resistor using the oscilloscope.



▲ FIGURE 11–91

ANSWERS

SECTION CHECKUPS

SECTION 11–1 The Sinusoidal Waveform

1. One cycle of a sine wave is from the zero crossing through a positive peak, then through zero to a negative peak and back to the zero crossing.
2. A sine wave changes polarity at the zero crossings.
3. A sine wave has two maximum points (peaks) per cycle.
4. The period is from one zero crossing to the next corresponding zero crossing, or from one peak to the next corresponding peak.
5. Frequency is the number of cycles completed in one second; the unit of frequency is the hertz.
6. $f = 1/T = 200$ kHz
7. $T = 1/f = 8.33$ ms
8. An arbitrary function generator has a certain number of built-in waveforms; an arbitrary waveform generator can define outputs from mathematical functions or graphical inputs.

SECTION 11–2 Sinusoidal Voltage and Current Values

1. **(a)** $V_{pp} = 2(1\text{ V}) = 2\text{ V}$ **(b)** $V_{pp} = 2(1.414)(1.414\text{ V}) = 4\text{ V}$
   (c) $V_{pp} = 2(1.57)(3\text{ V}) = 9.42\text{ V}$

2. **(a)** $V_{rms} = (0.707)(2.5\text{ V}) = 1.77\text{ V}$ **(b)** $V_{rms} = (0.5)(0.707)(10\text{ V}) = 3.54\text{ V}$
   (c) $V_{rms} = (0.707)(1.57)(1.5\text{ V}) = 1.66\text{ V}$
3. **(a)** $V_{avg} = (0.637)(10\text{ V}) = 6.37\text{ V}$ **(b)** $V_{avg} = (0.637)(1.414)(2.3\text{ V}) = 2.07\text{ V}$
   (c) $V_{avg} = (0.637)(0.5)(60\text{ V}) = 19.1\text{ V}$

SECTION 11–3 Angular Measurement of a Sine Wave

1. **(a)** Positive peak at 90° **(b)** Negative-going zero crossing at 180°
   (c) Negative peak at 270° **(d)** End of cycle at 360°
2. Half-cycle: 180°; π
3. Full cycle: 360°; 2π
4. $90° - 45° = 45°$

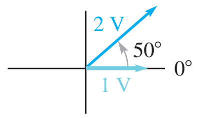
SECTION 11–4 The Sine Wave Formula

1. $v = (10\text{ V})\sin(120°) = 8.66\text{ V}$
2. $v = (10\text{ V})\sin(45° + 10°) = 8.19\text{ V}$
3. $v = (5\text{ V})\sin(90° - 25°) = 4.53\text{ V}$

SECTION 11–5 Introduction to Phasors

1. A graphic representation of the magnitude and angular position of a time-varying quantity
2. 9,425 rad/s
3. 100 Hz
4. See Figure 11–92.

▶ FIGURE 11–92



SECTION 11–6 Analysis of AC Circuits

1. $I_p = V_p/R = (1.57)(12.5\text{ V})/330\ \Omega = 59.5\text{ mA}$
2. $V_{s(rms)} = (0.707)(25.3\text{ V}) = 17.9\text{ V}$
3. $+V_{max} = 5\text{ V} + 2.5\text{ V} = 7.5\text{ V}$
4. Yes, it will alternate.
5. $+V_{max} = 5\text{ V} - 2.5\text{ V} = 2.5\text{ V}$

SECTION 11–7 The Alternator (AC Generator)

1. The number of poles and the rotor speed
2. The brushes do not have to handle the output current.
3. A dc generator that supplies rotor current to larger alternators
4. The diodes convert the ac from the stator to dc for the final output.

SECTION 11–8 The AC Motor

1. The difference is the rotors. In an induction motor, the rotor obtains current by transformer action; in a synchronous motor, the rotor is a permanent magnet or an electromagnet that is supplied current from an external source through slip rings and brushes.
2. The magnitude is constant.
3. A motor starter isolates the motor from the main power source, protects it against short circuits and overloads, and enables progressive start-up to avoid high currents at start-up.
4. The squirrel cage is composed of the electrical conductors that generate current in the rotor.
5. Slip is the difference between the synchronous speed of the stator field and the rotor speed.

SECTION 11–9 Nonsinusoidal Waveforms

1. **(a)** Rise time is the time interval from 10% to 90% of the rising pulse edge;
   (b) Fall time is the time interval from 90% to 10% of the falling pulse edge;
   (c) Pulse width is the time interval from 50% of the leading pulse edge to 50% of the trailing pulse edge.
2. $f = 1/1 \text{ ms} = 1 \text{ kHz}$
3. d.c. $= (1/5)100\% = 20\%$; Ampl. 1.5 V; $V_{avg} = 0.5 \text{ V} + 0.2(1.5 \text{ V}) = 0.8 \text{ V}$
4. $T = 16 \text{ ms}$
5. $f = 1/T = 1/1 \, \mu\text{s} = 1 \text{ MHz}$
6. Fundamental frequency is the repetition rate of the waveform.
7. 2nd harm.: 2 kHz
8. $f = 1/10 \, \mu\text{s} = 100 \text{ kHz}$

SECTION 11–10 The Oscilloscope

1. Analog : Signal drives display directly.
   Digital : Signal is converted to digital for processing and then reconstructed for display.
2. Voltage is measured vertically; time is measured horizontally.
3. The Volts/Div control adjusts the voltage scale.
4. The Sec/Div control adjusts the time scale.
5. Always, unless you are trying to measure a very small, low-frequency signal.

RELATED PROBLEMS FOR EXAMPLES

11–1 2.4 s

11–2 1.5 ms

11–3 20 kHz

11–4 200 Hz

11–5 66.7 kHz

11–6 $V_{pp} = 50 \text{ V}$; $V_{rms} = 17.7 \text{ V}$; $V_{avg} = 15.9 \text{ V}$

11–7 **(a)** $\pi/12$ rad **(b)** 112.5°

11–8 8°

11–9 18.1 V

11–10 10.6 V

11–11 5 V at $-85°$

11–12 34.2 V

11–13 $I_{rms} = 4.53 \text{ mA}$; $V_{1(rms)} = 4.53 \text{ V}$; $V_{2(rms)} = 2.54 \text{ V}$; $P_{tot} = 32.0 \text{ mW}$

11–14 23.7 V

11–15 The waveform in part (a) never goes negative. The waveform in part (b) goes negative for a portion of its cycle.

11–16 250 rpm

11–17 5%

11–18 1.2 V

11–19 120 V

11–20 Part (a) 1.06 V, 50 Hz;
part (b) 88.4 mV, 1.67 kHz;
part (c) 4.81 V, 5 kHz;
part (d) 7.07 V, 250 kHz

TRUE/FALSE QUIZ

1. T **2.** F **3.** F **4.** T **5.** T **6.** F
7. T **8.** F **9.** F **10.** T **11.** T **12.** T

SELF-TEST

1. (b) **2.** (b) **3.** (c) **4.** (b) **5.** (d) **6.** (a) **7.** (a)
8. (a) **9.** (c) **10.** (b) **11.** (a) **12.** (b) **13.** (d) **14.** (c)
15. (b) **16.** (d) **17.** (b) **18.** (d) **19.** (c) **20.** (a)

CIRCUIT DYNAMICS QUIZ

1. (a) **2.** (a) **3.** (b) **4.** (b) **5.** (c) **6.** (b)
7. (a) **8.** (a) **9.** (a) **10.** (a) **11.** (b) **12.** (a)