

2

DIODES AND APPLICATIONS

CHAPTER OUTLINE

- 2-1 Diode Operation
 - 2-2 Voltage-Current ($V-I$) Characteristics of a Diode
 - 2-3 Diode Models
 - 2-4 Half-Wave Rectifiers
 - 2-5 Full-Wave Rectifiers
 - 2-6 Power Supply Filters and Regulators
 - 2-7 Diode Limiters and Clampers
 - 2-8 Voltage Multipliers
 - 2-9 The Diode Datasheet
 - 2-10 Troubleshooting
- Application Activity
GreenTech Application 2: *Solar Power*

CHAPTER OBJECTIVES

- ◆ Use a diode in common applications
- ◆ Analyze the voltage-current ($V-I$) characteristic of a diode
- ◆ Explain how the three diode models differ
- ◆ Explain and analyze the operation of half-wave rectifiers
- ◆ Explain and analyze the operation of full-wave rectifiers
- ◆ Explain and analyze power supply filters and regulators
- ◆ Explain and analyze the operation of diode limiters and clampers
- ◆ Explain and analyze the operation of diode voltage multipliers
- ◆ Interpret and use diode datasheets
- ◆ Troubleshoot diodes and power supply circuits

KEY TERMS

- ◆ Diode
- ◆ Bias
- ◆ Forward bias
- ◆ Reverse bias
- ◆ $V-I$ characteristic
- ◆ DC power supply
- ◆ Rectifier
- ◆ Filter
- ◆ Regulator
- ◆ Half-wave rectifier
- ◆ Peak inverse voltage (PIV)
- ◆ Full-wave rectifier
- ◆ Ripple voltage
- ◆ Line regulation
- ◆ Load regulation
- ◆ Limiter
- ◆ Clamper
- ◆ Troubleshooting

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INTRODUCTION

In Chapter 1, you learned that many semiconductor devices are based on the pn junction. In this chapter, the operation and characteristics of the diode are covered. Also, three diode models representing three levels of approximation are presented and testing is discussed. The importance of the diode in electronic circuits cannot be overemphasized. Its ability to conduct current in one direction while blocking current in the other direction is essential to the operation of many types of circuits. One circuit in particular is the ac rectifier, which is covered in this chapter. Other important applications are circuits such as diode limiters, diode clampers, and diode voltage multipliers. A datasheet is discussed for specific diodes.

APPLICATION ACTIVITY PREVIEW

You have the responsibility for the final design and testing of a power supply circuit that your company plans to use in several of its products. You will apply your knowledge of diode circuits to the Application Activity at the end of the chapter.

2-1 DIODE OPERATION

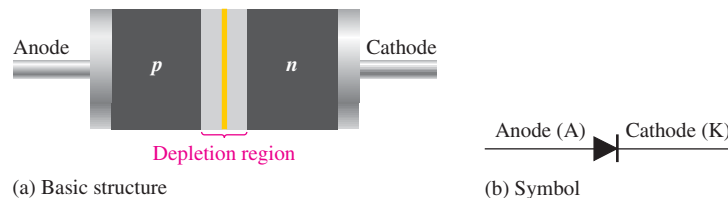
Similar to the solar cell in Chapter 1, a diode is a two-terminal semiconductor device formed by two doped regions of silicon separated by a pn junction. In this chapter, the most common category of diode, known as the general-purpose diode, is covered. Other names, such as rectifier diode or signal diode, depend on the particular type of application for which the diode was designed. You will learn how to use a voltage to cause the diode to conduct current in one direction and block it in the other direction. This process is called *biasing*.

After completing this section, you should be able to

- **Use a diode in common applications**
- Recognize the electrical symbol for a diode and several diode package configurations
- Apply forward bias to a diode
 - ♦ Define *forward bias* and state the required conditions
 - ♦ Discuss the effect of forward bias on the depletion region
 - ♦ Define *barrier potential* and its effects during forward bias
- Reverse-bias a diode
 - ♦ Define *reverse bias* and state the required conditions
 - ♦ Discuss reverse current and reverse breakdown

The Diode

As mentioned, a **diode** is made from a small piece of semiconductor material, usually silicon, in which half is doped as a p region and half is doped as an n region with a pn junction and depletion region in between. The p region is called the **anode** and is connected to a conductive terminal. The n region is called the **cathode** and is connected to a second conductive terminal. The basic diode structure and schematic symbol are shown in Figure 2-1.



◀ FIGURE 2-1

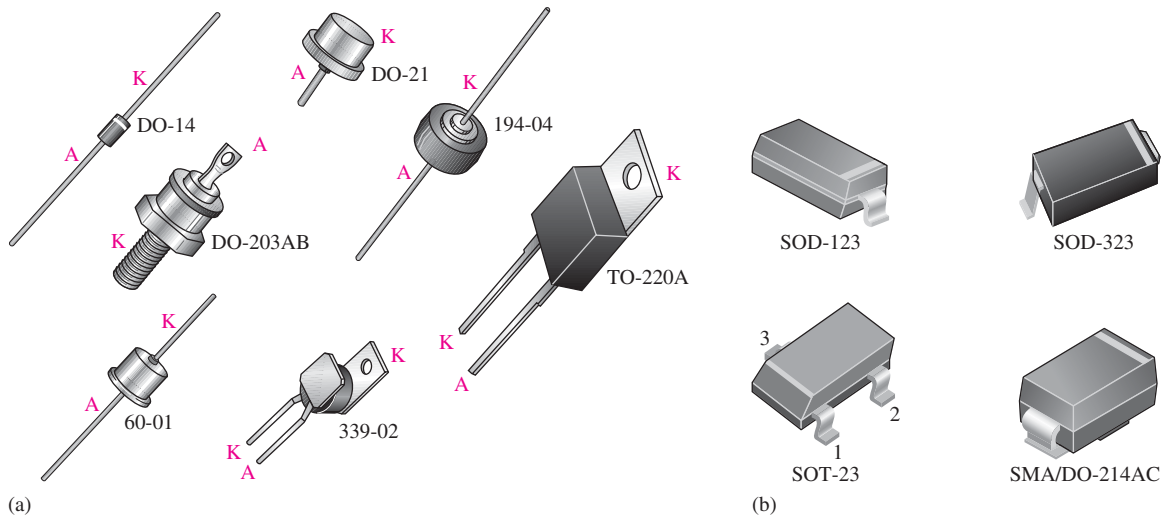
The diode.

Typical Diode Packages Several common physical configurations of through-hole mounted diodes are illustrated in Figure 2-2(a). The anode (A) and cathode (K) are indicated on a diode in several ways, depending on the type of package. The cathode is usually marked by a band, a tab, or some other feature. On those packages where one lead is connected to the case, the case is the cathode.

Surface-Mount Diode Packages Figure 2-2(b) shows typical diode packages for surface mounting on a printed circuit board. The SOD and SOT packages have gull-wing shaped leads. The SMA package has L-shaped leads that bend under the package. The SOD and SMA types have a band on one end to indicate the cathode. The SOT type is a three-terminal package in which there are either one or two diodes. In a single-diode SOT package, pin 1 is usually the anode and pin 3 is the cathode. In a dual-diode SOT package, pin 3 is the common terminal and can be either the anode or the cathode. Always check the datasheet for the particular diode to verify the pin configurations.

GREENTECH NOTE

The diodes covered in this chapter are based on the pn junction just like the solar cell, also known as the photovoltaic cell or PV cell, that was introduced in Chapter 1. A solar cell is basically a diode with a different geometric construction than rectifier and signal diodes. The p and n regions in the solar cell are much thinner to allow light energy to activate the photovoltaic effect, and a solar cell's exposed surface is transparent.



▲ FIGURE 2-2

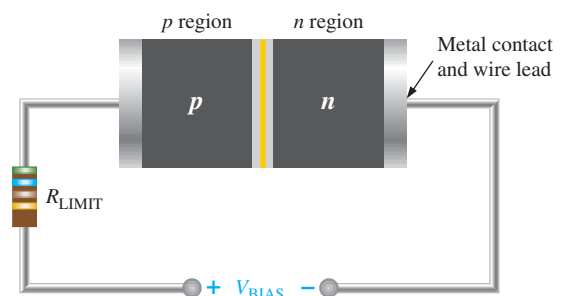
Typical diode packages with terminal identification. The letter K is used for cathode to avoid confusion with certain electrical quantities that are represented by C. Case type numbers are indicated for each diode.

Forward Bias

To **bias** a diode, you apply a dc voltage across it. **Forward bias** is the condition that allows current through the pn junction. Figure 2-3 shows a dc voltage source connected by conductive material (contacts and wire) across a diode in the direction to produce forward bias. This external bias voltage is designated as V_{BIAS} . The resistor limits the forward current to a value that will not damage the diode. Notice that the negative side of V_{BIAS} is connected to the n region of the diode and the positive side is connected to the p region. This is one requirement for forward bias. A second requirement is that the bias voltage, V_{BIAS} , must be greater than the **barrier potential**.

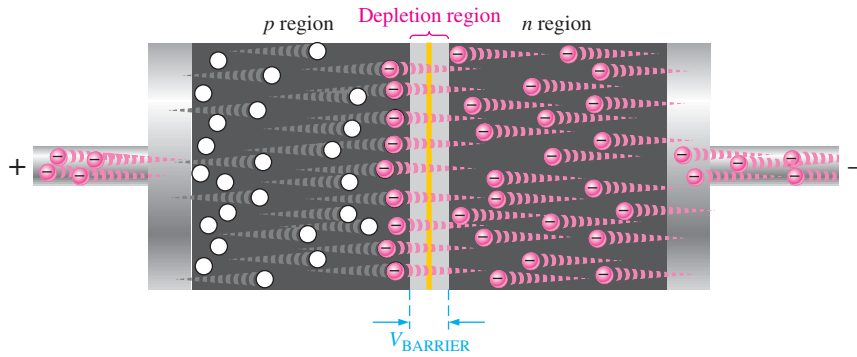
▶ FIGURE 2-3

A diode connected for forward bias.



A fundamental picture of what happens when a diode is forward-biased is shown in Figure 2-4. Because like charges repel, the negative side of the bias-voltage source “pushes” the free electrons, which are the majority carriers in the n region, toward the pn junction. This flow of free electrons is called *electron current*. The negative side of the source also provides a continuous flow of electrons through the external connection (conductor) and into the n region as shown.

The bias-voltage source imparts sufficient energy to the free electrons for them to overcome the barrier potential of the depletion region and move on through into the p region. Once in the p region, these conduction electrons have lost enough energy to immediately combine with holes in the valence band.



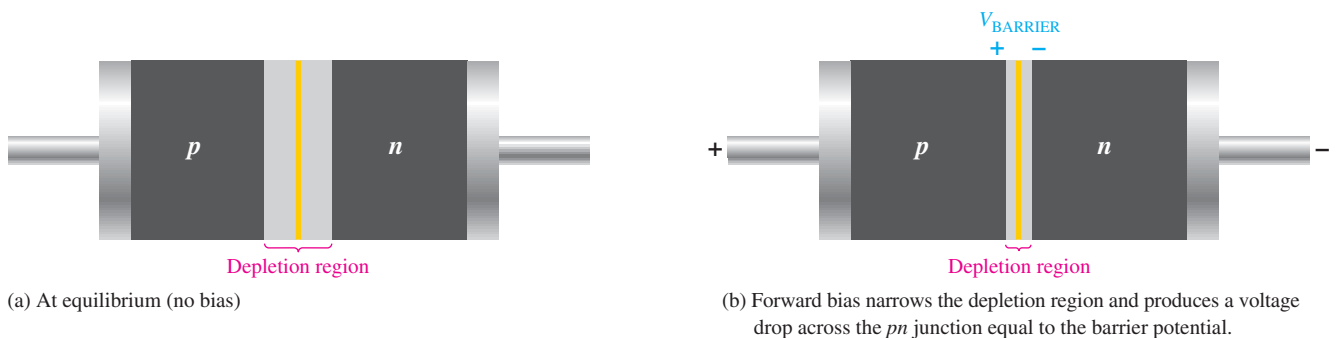
◀ FIGURE 2-4

A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

Now, the electrons are in the valence band in the p region, simply because they have lost too much energy overcoming the barrier potential to remain in the conduction band. Since unlike charges attract, the positive side of the bias-voltage source attracts the valence electrons toward the left end of the p region. The holes in the p region provide the medium or “pathway” for these valence electrons to move through the p region. The valence electrons move from one hole to the next toward the left. The holes, which are the majority carriers in the p region, effectively (not actually) move to the right toward the junction, as you can see in Figure 2-4. This *effective* flow of holes is the hole current. You can also view the hole current as being created by the flow of valence electrons through the p region, with the holes providing the only means for these electrons to flow.

As the electrons flow out of the p region through the external connection (conductor) and to the positive side of the bias-voltage source, they leave holes behind in the p region; at the same time, these electrons become conduction electrons in the metal conductor. Recall that the conduction band in a conductor overlaps the valence band so that it takes much less energy for an electron to be a free electron in a conductor than in a semiconductor and that metallic conductors do not have holes in their structure. There is a continuous availability of holes effectively moving toward the pn junction to combine with the continuous stream of electrons as they come across the junction into the p region.

The Effect of Forward Bias on the Depletion Region As more electrons flow into the depletion region, the number of positive ions is reduced. As more holes effectively flow into the depletion region on the other side of the pn junction, the number of negative ions is reduced. This reduction in positive and negative ions during forward bias causes the depletion region to narrow, as indicated in Figure 2-5.



(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the pn junction equal to the barrier potential.

▲ FIGURE 2-5

The depletion region narrows and a voltage drop is produced across the pn junction when the diode is forward-biased.

The Effect of the Barrier Potential During Forward Bias Recall that the electric field between the positive and negative ions in the depletion region on either side of the junction creates an “energy hill” that prevents free electrons from diffusing across the junction at equilibrium. This is known as the *barrier potential*.

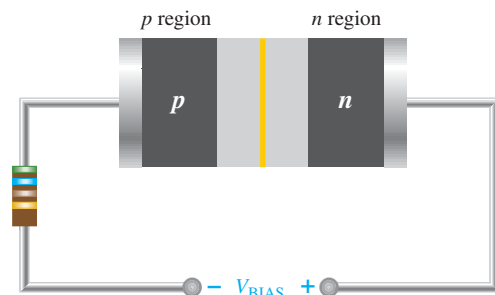
When forward bias is applied, the free electrons are provided with enough energy from the bias-voltage source to overcome the barrier potential and effectively “climb the energy hill” and cross the depletion region. The energy that the electrons require in order to pass through the depletion region is equal to the barrier potential. In other words, the electrons give up an amount of energy equivalent to the barrier potential when they cross the depletion region. This energy loss results in a voltage drop across the *pn* junction equal to the barrier potential (0.7 V), as indicated in Figure 2–5(b). An additional small voltage drop occurs across the *p* and *n* regions due to the internal resistance of the material. For doped semiconductive material, this resistance, called the **dynamic resistance**, is very small and can usually be neglected. This is discussed in more detail in Section 2–2.

Reverse Bias

Reverse bias is the condition that essentially prevents current through the diode. Figure 2–6 shows a dc voltage source connected across a diode in the direction to produce reverse bias. This external bias voltage is designated as V_{BIAS} just as it was for forward bias. Notice that the positive side of V_{BIAS} is connected to the *n* region of the diode and the negative side is connected to the *p* region. Also note that the depletion region is shown much wider than in forward bias or equilibrium.

► **FIGURE 2-6**

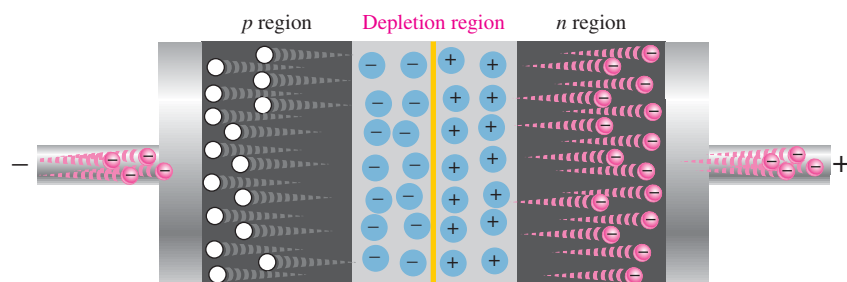
A diode connected for reverse bias. A limiting resistor is shown although it is not important in reverse bias because there is essentially no current.



An illustration of what happens when a diode is reverse-biased is shown in Figure 2–7. Because unlike charges attract, the positive side of the bias-voltage source “pulls” the free electrons, which are the majority carriers in the *n* region, away from the *pn* junction. As the electrons flow toward the positive side of the voltage source, additional positive ions are created. This results in a widening of the depletion region and a depletion of majority carriers.

► **FIGURE 2-7**

The diode during the short transition time immediately after reverse-bias voltage is applied.

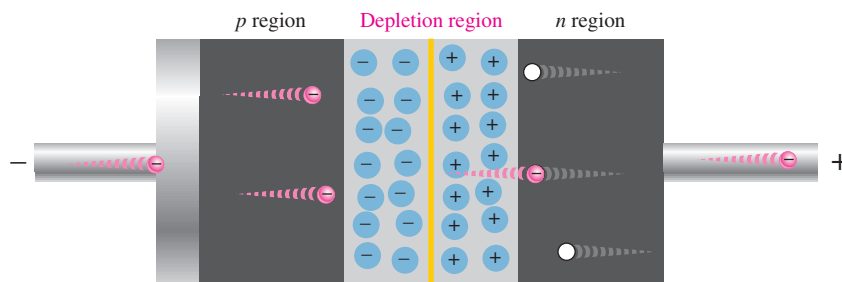


In the p region, electrons from the negative side of the voltage source enter as valence electrons and move from hole to hole toward the depletion region where they create additional negative ions. This results in a widening of the depletion region and a depletion of majority carriers. The flow of valence electrons can be viewed as holes being “pulled” toward the positive side.

The initial flow of charge carriers is transitional and lasts for only a very short time after the reverse-bias voltage is applied. As the depletion region widens, the availability of majority carriers decreases. As more of the n and p regions become depleted of majority carriers, the electric field between the positive and negative ions increases in strength until the potential across the depletion region equals the bias voltage, V_{BIAS} . At this point, the transition current essentially ceases except for a very small reverse current that can usually be neglected.

Reverse Current The extremely small current that exists in reverse bias after the transition current dies out is caused by the minority carriers in the n and p regions that are produced by thermally generated electron-hole pairs. The small number of free minority electrons in the p region are “pushed” toward the pn junction by the negative bias voltage. When these electrons reach the wide depletion region, they “fall down the energy hill” and combine with the minority holes in the n region as valence electrons and flow toward the positive bias voltage, creating a small hole current.

The conduction band in the p region is at a higher energy level than the conduction band in the n region. Therefore, the minority electrons easily pass through the depletion region because they require no additional energy. Reverse current is illustrated in Figure 2–8.



◀ FIGURE 2–8

The extremely small reverse current in a reverse-biased diode is due to the minority carriers from thermally generated electron-hole pairs.

Reverse Breakdown Normally, the reverse current is so small that it can be neglected. However, if the external reverse-bias voltage is increased to a value called the *breakdown voltage*, the reverse current will drastically increase.

This is what happens. The high reverse-bias voltage imparts energy to the free minority electrons so that as they speed through the p region, they collide with atoms with enough energy to knock valence electrons out of orbit and into the conduction band. The newly created conduction electrons are also high in energy and repeat the process. If one electron knocks only two others out of their valence orbit during its travel through the p region, the numbers quickly multiply. As these high-energy electrons go through the depletion region, they have enough energy to go through the n region as conduction electrons, rather than combining with holes.

The multiplication of conduction electrons just discussed is known as the **avalanche effect**, and reverse current can increase dramatically if steps are not taken to limit the current. When the reverse current is not limited, the resulting heating will permanently damage the diode. Most diodes are not operated in reverse breakdown, but if the current is limited (by adding a series-limiting resistor for example), there is no permanent damage to the diode.

SECTION 2-1 CHECKUP

Answers can be found at
www.pearsonhighered.com/
floyd.

1. Describe forward bias of a diode.
2. Explain how to forward-bias a diode.
3. Describe reverse bias of a diode.
4. Explain how to reverse-bias a diode.
5. Compare the depletion regions in forward bias and reverse bias.
6. Which bias condition produces majority carrier current?
7. How is reverse current in a diode produced?
8. When does reverse breakdown occur in a diode?
9. Define *avalanche effect* as applied to diodes.

2-2 VOLTAGE-CURRENT CHARACTERISTIC OF A DIODE

As you have learned, forward bias produces current through a diode and reverse bias essentially prevents current, except for a negligible reverse current. Reverse bias prevents current as long as the reverse-bias voltage does not equal or exceed the breakdown voltage of the junction. In this section, we will examine the relationship between the voltage and the current in a diode on a graphical basis.

After completing this section, you should be able to

- **Analyze the voltage-current (V - I) characteristic of a diode**
- Explain the V - I characteristic for forward bias
 - ♦ Graph the V - I curve for forward bias
 - ♦ Describe how the barrier potential affects the V - I curve
 - ♦ Define *dynamic resistance*
- Explain the V - I characteristic for reverse bias
 - ♦ Graph the V - I curve for reverse bias
- Discuss the complete V - I characteristic curve
 - ♦ Describe the effects of temperature on the diode characteristic

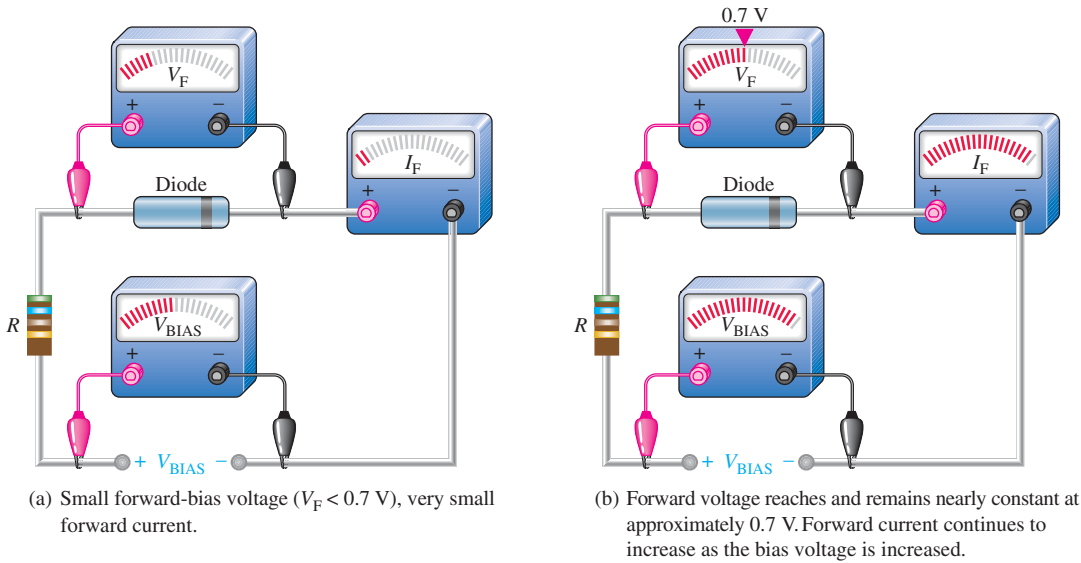
V - I Characteristic for Forward Bias

When a forward-bias voltage is applied across a diode, there is current. This current is called the *forward current* and is designated I_F . Figure 2-9 illustrates what happens as the forward-bias voltage is increased positively from 0 V. The resistor is used to limit the forward current to a value that will not overheat the diode and cause damage.

With 0 V across the diode, there is no forward current. As you gradually increase the forward-bias voltage, the forward current *and* the voltage across the diode gradually increase, as shown in Figure 2-9(a). A portion of the forward-bias voltage is dropped across the limiting resistor. When the forward-bias voltage is increased to a value where the voltage across the diode reaches approximately 0.7 V (barrier potential), the forward current begins to increase rapidly, as illustrated in Figure 2-9(b).

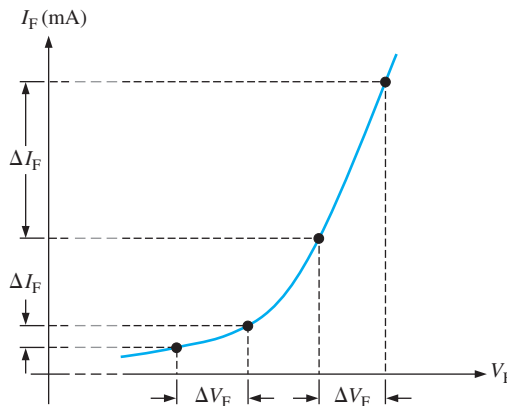
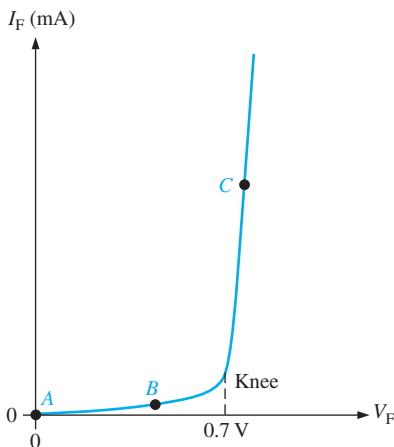
As you continue to increase the forward-bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases only gradually above 0.7 V. This small increase in the diode voltage above the barrier potential is due to the voltage drop across the internal dynamic resistance of the semiconductive material.

Graphing the V - I Curve If you plot the results of the type of measurements shown in Figure 2-9 on a graph, you get the **V - I characteristic** curve for a forward-biased diode, as shown in Figure 2-10(a). The diode forward voltage (V_F) increases to the right along the horizontal axis, and the forward current (I_F) increases upward along the vertical axis.



▲ FIGURE 2-9

Forward-bias measurements show general changes in V_F and I_F as V_{BIAS} is increased.



◀ FIGURE 2-10

Relationship of voltage and current in a forward-biased diode.

As you can see in Figure 2-10(a), the forward current increases very little until the forward voltage across the pn junction reaches approximately 0.7 V at the knee of the curve. After this point, the forward voltage remains nearly constant at approximately 0.7 V , but I_F increases rapidly. As previously mentioned, there is a slight increase in V_F above 0.7 V as the current increases due mainly to the voltage drop across the dynamic resistance. The I_F scale is typically in mA, as indicated.

Three points A, B, and C are shown on the curve in Figure 2-10(a). Point A corresponds to a zero-bias condition. Point B corresponds to Figure 2-10(a) where the forward voltage is less than the barrier potential of 0.7 V . Point C corresponds to Figure 2-10(a) where the forward voltage *approximately* equals the barrier potential. As the external bias voltage and forward current continue to increase above the knee, the forward voltage will increase slightly above 0.7 V . In reality, the forward voltage can be as much as approximately 1 V , depending on the forward current.

Dynamic Resistance Figure 2–10(b) is an expanded view of the V - I characteristic curve in part (a) and illustrates dynamic resistance. Unlike a linear resistance, the resistance of the forward-biased diode is not constant over the entire curve. Because the resistance changes as you move along the V - I curve, it is called *dynamic* or *ac resistance*. Internal resistances of electronic devices are usually designated by lowercase italic r with a prime, instead of the standard R . The dynamic resistance of a diode is designated r'_d .

Below the knee of the curve the resistance is greatest because the current increases very little for a given change in voltage ($r'_d = \Delta V_F / \Delta I_F$). The resistance begins to decrease in the region of the knee of the curve and becomes smallest above the knee where there is a large change in current for a given change in voltage.

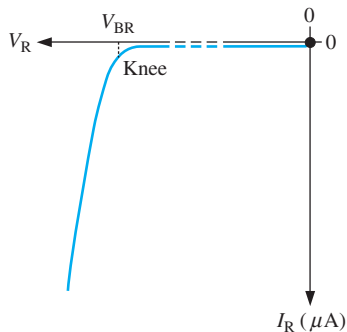
V - I Characteristic for Reverse Bias

When a reverse-bias voltage is applied across a diode, there is only an extremely small reverse current (I_R) through the pn junction. With 0 V across the diode, there is no reverse current. As you gradually increase the reverse-bias voltage, there is a very small reverse current and the voltage across the diode increases. When the applied bias voltage is increased to a value where the reverse voltage across the diode (V_R) reaches the breakdown value (V_{BR}), the reverse current begins to increase rapidly.

As you continue to increase the bias voltage, the current continues to increase very rapidly, but the voltage across the diode increases very little above V_{BR} . Breakdown, with exceptions, is not a normal mode of operation for most pn junction devices.

Graphing the V - I Curve If you plot the results of reverse-bias measurements on a graph, you get the V - I characteristic curve for a reverse-biased diode. A typical curve is shown in Figure 2–11. The diode reverse voltage (V_R) increases to the left along the horizontal axis, and the reverse current (I_R) increases downward along the vertical axis.

There is very little reverse current (usually μA or nA) until the reverse voltage across the diode reaches approximately the breakdown value (V_{BR}) at the knee of the curve. After this point, the reverse voltage remains at approximately V_{BR} , but I_R increases very rapidly, resulting in overheating and possible damage if current is not limited to a safe level. The breakdown voltage for a diode depends on the doping level, which the manufacturer sets, depending on the type of diode. A typical rectifier diode (the most widely used type) has a breakdown voltage of greater than 50 V. Some specialized diodes have a breakdown voltage that is only 5 V.



▲ FIGURE 2–11

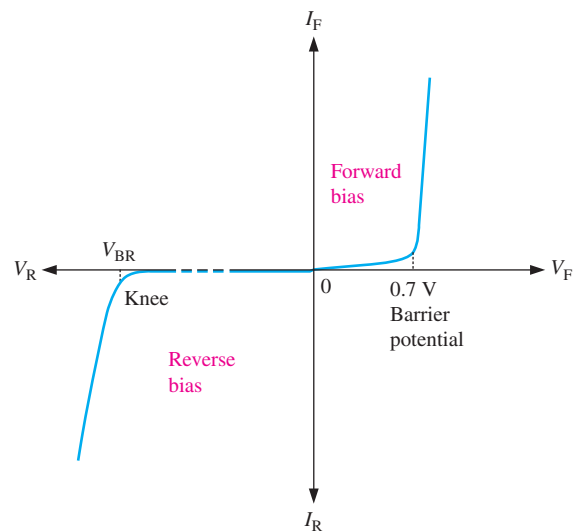
V - I characteristic curve for a reverse-biased diode.

The Complete V - I Characteristic Curve

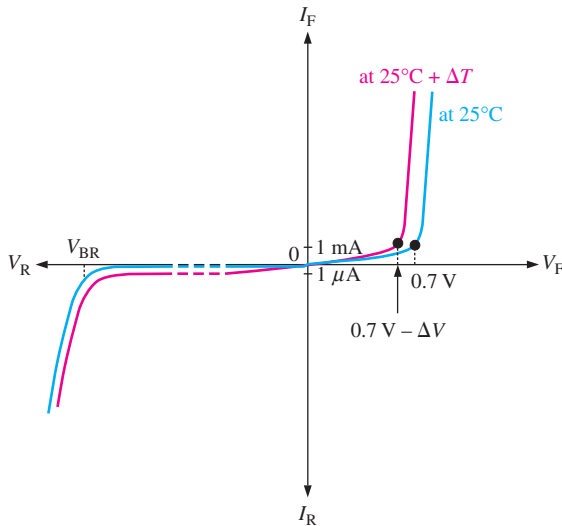
Combine the curves for both forward bias and reverse bias, and you have the complete V - I characteristic curve for a diode, as shown in Figure 2–12.

► FIGURE 2–12

The complete V - I characteristic curve for a diode.



Temperature Effects For a forward-biased diode, as temperature is increased, the forward current increases for a given value of forward voltage. Also, for a given value of forward current, the forward voltage decreases. This is shown with the V - I characteristic curves in Figure 2–13. The blue curve is at room temperature (25°C) and the red curve is at an elevated temperature ($25^{\circ}\text{C} + \Delta T$). The barrier potential decreases by 2 mV for each degree increase in temperature.



◀ **FIGURE 2–13**

Temperature effect on the diode V - I characteristic. The 1 mA and 1 μA marks on the vertical axis are given as a basis for a relative comparison of the current scales.

For a reverse-biased diode, as temperature is increased, the reverse current increases. The difference in the two curves is exaggerated on the graph in Figure 2–13 for illustration. Keep in mind that the reverse current below breakdown remains extremely small and can usually be neglected.

SECTION 2–2 CHECKUP

1. Discuss the significance of the knee of the characteristic curve in forward bias.
2. On what part of the curve is a forward-biased diode normally operated?
3. Which is greater, the breakdown voltage or the barrier potential?
4. On what part of the curve is a reverse-biased diode normally operated?
5. What happens to the barrier potential when the temperature increases?

2–3 DIODE MODELS

You have learned that a diode is a pn junction device. In this section, you will learn the electrical symbol for a diode and how a diode can be modeled for circuit analysis using any one of three levels of complexity. Also, diode packaging and terminal identification are introduced.

After completing this section, you should be able to

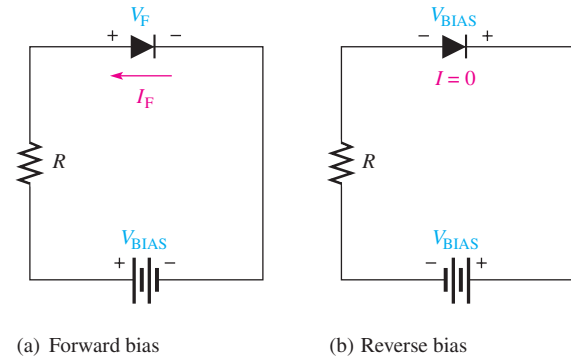
- **Explain how the three diode models differ**
- Discuss bias connections
- Describe the diode approximations
 - ♦ Describe the ideal diode model
 - ♦ Describe the practical diode model
 - ♦ Describe the complete diode model

Bias Connections

Forward-Bias Recall that a diode is forward-biased when a voltage source is connected as shown in Figure 2–14(a). The positive terminal of the source is connected to the anode through a current-limiting resistor. The negative terminal of the source is connected to the cathode. The forward current (I_F) is from cathode to anode as indicated. The forward voltage drop (V_F) due to the barrier potential is from positive at the anode to negative at the cathode.

► **FIGURE 2–14**

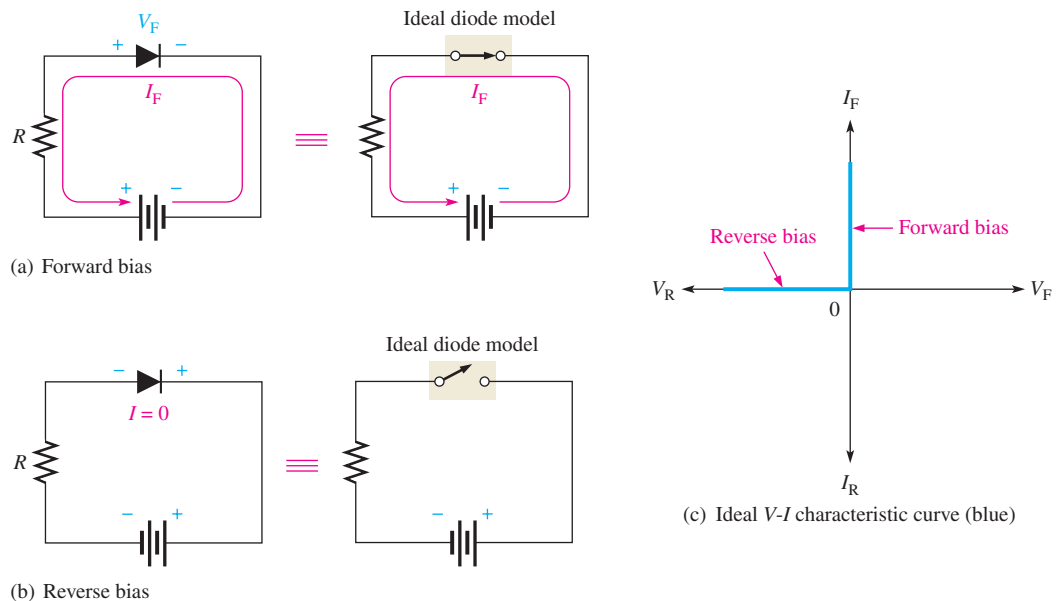
Forward-bias and reverse-bias connections showing the diode symbol.



Reverse-Bias Connection A diode is reverse-biased when a voltage source is connected as shown in Figure 2–14(b). The negative terminal of the source is connected to the anode side of the circuit, and the positive terminal is connected to the cathode side. A resistor is not necessary in reverse bias but it is shown for circuit consistency. The reverse current is extremely small and can be considered to be zero. Notice that the entire bias voltage (V_{BIAS}) appears across the diode.

Diode Approximations

The Ideal Diode Model The ideal model of a diode is the least accurate approximation and can be represented by a simple switch. When the diode is forward-biased, it ideally acts like a closed (on) switch, as shown in Figure 2–15(a). When the diode is reverse-biased, it



▲ **FIGURE 2–15**

The ideal model of a diode.

ideally acts like an open (off) switch, as shown in part (b). Although the barrier potential, the forward dynamic resistance, and the reverse current are all neglected, this model is adequate for most troubleshooting when you are trying to determine if the diode is working properly.

In Figure 2–15(c), the ideal V - I characteristic curve graphically depicts the ideal diode operation. Since the barrier potential and the forward dynamic resistance are neglected, the diode is assumed to have a zero voltage across it when forward-biased, as indicated by the portion of the curve on the positive vertical axis.

$$V_F = 0 \text{ V}$$

The forward current is determined by the bias voltage and the limiting resistor using Ohm's law.

$$I_F = \frac{V_{\text{BIAS}}}{R_{\text{LIMIT}}}$$

Equation 2–1

Since the reverse current is neglected, its value is assumed to be zero, as indicated in Figure 2–15(c) by the portion of the curve on the negative horizontal axis.

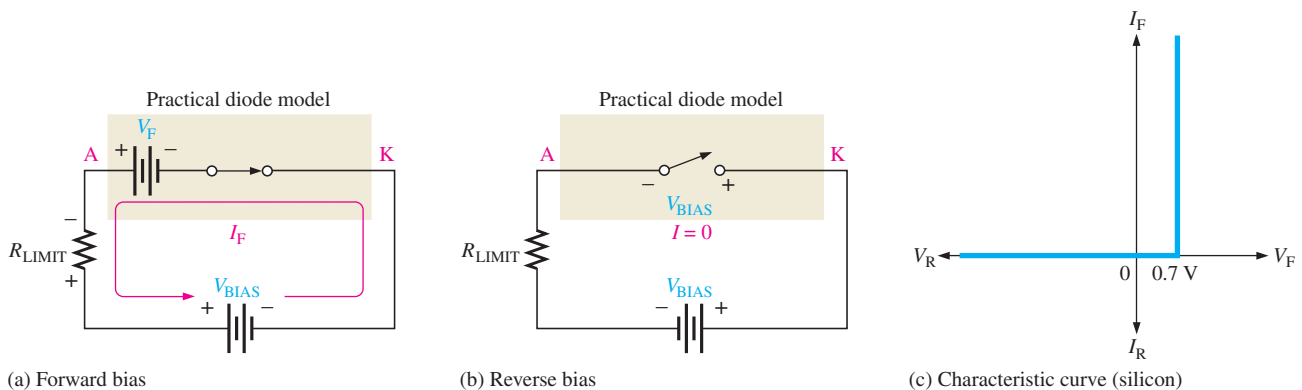
$$I_R = 0 \text{ A}$$

The reverse voltage equals the bias voltage.

$$V_R = V_{\text{BIAS}}$$

You may want to use the ideal model when you are troubleshooting or trying to figure out the operation of a circuit and are not concerned with more exact values of voltage or current.

The Practical Diode Model The practical model includes the barrier potential. When the diode is forward-biased, it is equivalent to a closed switch in series with a small equivalent voltage source (V_F) equal to the barrier potential (0.7 V) with the positive side toward the anode, as indicated in Figure 2–16(a). This equivalent voltage source represents the barrier potential that must be exceeded by the bias voltage before the diode will conduct and is not an active source of voltage. When conducting, a voltage drop of 0.7 V appears across the diode.



▲ FIGURE 2–16

The practical model of a diode.

When the diode is reverse-biased, it is equivalent to an open switch just as in the ideal model, as shown in Figure 2–16(b). The barrier potential does not affect reverse bias, so it is not a factor.

The characteristic curve for the practical diode model is shown in Figure 2–16(c). Since the barrier potential is included and the dynamic resistance is neglected, the diode is assumed to have a voltage across it when forward-biased, as indicated by the portion of the curve to the right of the origin.

$$V_F = 0.7 \text{ V}$$

The forward current is determined as follows by first applying Kirchhoff's voltage law to Figure 2-16(a):

$$\begin{aligned} V_{\text{BIAS}} - V_F - V_{R_{\text{LIMIT}}} &= 0 \\ V_{R_{\text{LIMIT}}} &= I_F R_{\text{LIMIT}} \end{aligned}$$

Substituting and solving for I_F ,

Equation 2-2

$$I_F = \frac{V_{\text{BIAS}} - V_F}{R_{\text{LIMIT}}}$$

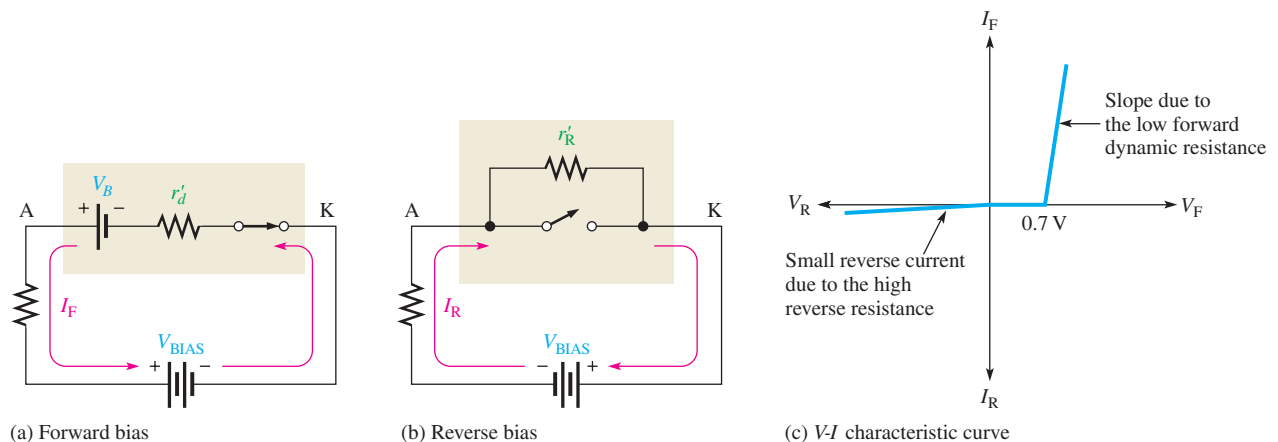
The diode is assumed to have zero reverse current, as indicated by the portion of the curve on the negative horizontal axis.

$$\begin{aligned} I_R &= 0 \text{ A} \\ V_R &= V_{\text{BIAS}} \end{aligned}$$

The practical model is useful when you are troubleshooting in lower-voltage circuits. In these cases, the 0.7 V drop across the diode may be significant and should be taken into account. The practical model is also useful when you are designing basic diode circuits.

The Complete Diode Model The complete model of a diode is the most accurate approximation and includes the barrier potential, the small forward dynamic resistance (r'_d), and the large internal reverse resistance (r'_R). The reverse resistance is taken into account because it provides a path for the reverse current, which is included in this diode model.

When the diode is forward-biased, it acts as a closed switch in series with the equivalent barrier potential voltage (V_B) and the small forward dynamic resistance (r'_d), as indicated in Figure 2-17(a). When the diode is reverse-biased, it acts as an open switch in parallel with the large internal reverse resistance (r'_R), as shown in Figure 2-17(b). The barrier potential does not affect reverse bias, so it is not a factor.



▲ **FIGURE 2-17**

The complete model of a diode.

The characteristic curve for the complete diode model is shown in Figure 2-17(c). Since the barrier potential and the forward dynamic resistance are included, the diode is assumed to have a voltage across it when forward-biased. This voltage (V_F) consists of the barrier potential voltage plus the small voltage drop across the dynamic resistance, as indicated by the portion of the curve to the right of the origin. The curve slopes because the

voltage drop due to dynamic resistance increases as the current increases. For the complete model of a silicon diode, the following formulas apply:

$$V_F = 0.7 \text{ V} + I_F r'_d$$

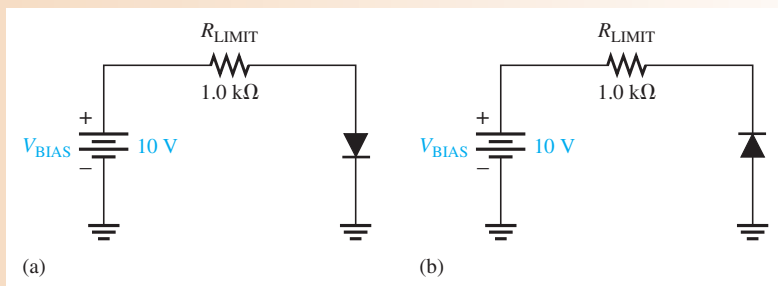
$$I_F = \frac{V_{\text{BIAS}} - 0.7 \text{ V}}{R_{\text{LIMIT}} + r'_d}$$

The reverse current is taken into account with the parallel resistance and is indicated by the portion of the curve to the left of the origin. The breakdown portion of the curve is not shown because breakdown is not a normal mode of operation for most diodes.

For troubleshooting work, it is unnecessary to use the complete model, as it involves complicated calculations. This model is generally suited to design problems using a computer for simulation. The ideal and practical models are used for circuits in this text, except in the following example, which illustrates the differences in the three models.

EXAMPLE 2-1

- (a) Determine the forward voltage and forward current for the diode in Figure 2-18(a) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $r'_d = 10 \Omega$ at the determined value of forward current.
- (b) Determine the reverse voltage and reverse current for the diode in Figure 2-18(b) for each of the diode models. Also find the voltage across the limiting resistor in each case. Assume $I_R = 1 \mu\text{A}$.



▲ FIGURE 2-18

Solution (a) Ideal model:

$$V_F = 0 \text{ V}$$

$$I_F = \frac{V_{\text{BIAS}}}{R_{\text{LIMIT}}} = \frac{10 \text{ V}}{1.0 \text{ k}\Omega} = 10 \text{ mA}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (10 \text{ mA})(1.0 \text{ k}\Omega) = 10 \text{ V}$$

Practical model:

$$V_F = 0.7 \text{ V}$$

$$I_F = \frac{V_{\text{BIAS}} - V_F}{R_{\text{LIMIT}}} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega} = \frac{9.3 \text{ V}}{1.0 \text{ k}\Omega} = 9.3 \text{ mA}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (9.3 \text{ mA})(1.0 \text{ k}\Omega) = 9.3 \text{ V}$$

Complete model:

$$I_F = \frac{V_{\text{BIAS}} - 0.7 \text{ V}}{R_{\text{LIMIT}} + r'_d} = \frac{10 \text{ V} - 0.7 \text{ V}}{1.0 \text{ k}\Omega + 10 \Omega} = \frac{9.3 \text{ V}}{1010 \Omega} = 9.21 \text{ mA}$$

$$V_F = 0.7 \text{ V} + I_F r'_d = 0.7 \text{ V} + (9.21 \text{ mA})(10 \Omega) = 792 \text{ mV}$$

$$V_{R_{\text{LIMIT}}} = I_F R_{\text{LIMIT}} = (9.21 \text{ mA})(1.0 \text{ k}\Omega) = 9.21 \text{ V}$$

(b) Ideal model:

$$\begin{aligned}I_R &= 0 \text{ A} \\V_R &= V_{\text{BIAS}} = 10 \text{ V} \\V_{R_{\text{LIMIT}}} &= 0 \text{ V}\end{aligned}$$

Practical model:

$$\begin{aligned}I_R &= 0 \text{ A} \\V_R &= V_{\text{BIAS}} = 10 \text{ V} \\V_{R_{\text{LIMIT}}} &= 0 \text{ V}\end{aligned}$$

Complete model:

$$\begin{aligned}I_R &= 1 \mu\text{A} \\V_{R_{\text{LIMIT}}} &= I_R R_{\text{LIMIT}} = (1 \mu\text{A})(1.0 \text{ k}\Omega) = 1 \text{ mV} \\V_R &= V_{\text{BIAS}} - V_{R_{\text{LIMIT}}} = 10 \text{ V} - 1 \text{ mV} = 9.999 \text{ V}\end{aligned}$$

Related Problem* Assume that the diode in Figure 2–18(a) fails open. What is the voltage across the diode and the voltage across the limiting resistor?

*Answers can be found at www.pearsonhighered.com/floyd.



Open the Multisim file E02-01 in the Examples folder on the companion website. Measure the voltages across the diode and the resistor in both circuits and compare with the calculated results in this example.

SECTION 2–3 CHECKUP

1. What are the two conditions under which a diode is operated?
2. Under what condition is a diode never intentionally operated?
3. What is the simplest way to visualize a diode?
4. To more accurately represent a diode, what factors must be included?
5. Which diode model represents the most accurate approximation?

2–4 HALF-WAVE RECTIFIERS

Because of their ability to conduct current in one direction and block current in the other direction, diodes are used in circuits called rectifiers that convert ac voltage into dc voltage. Rectifiers are found in all dc power supplies that operate from an ac voltage source. A power supply is an essential part of each electronic system from the simplest to the most complex.

After completing this section, you should be able to

- **Explain and analyze the operation of half-wave rectifiers**
- Describe a basic dc power supply
- Discuss half-wave rectification
 - ♦ Determine the average value of a half-wave voltage
- Explain how the barrier potential affects a half-wave rectifier output
 - ♦ Calculate the output voltage
- Define *peak inverse voltage*
- Explain the operation of a transformer-coupled rectifier

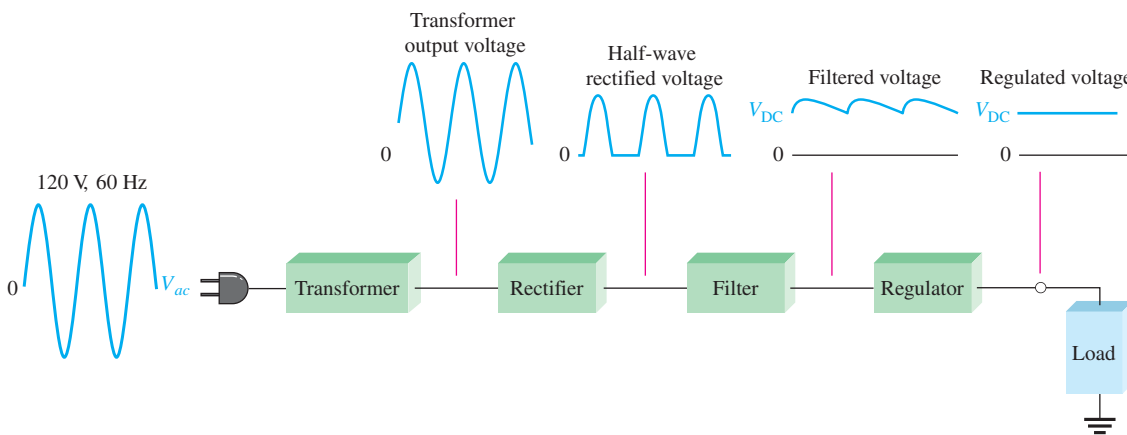
The Basic DC Power Supply

All active electronic devices require a source of constant dc that can be supplied by a battery or a dc power supply. The **dc power supply** converts the standard 120 V, 60 Hz ac voltage available at wall outlets into a constant dc voltage. The dc power supply is one of the most common circuits you will find, so it is important to understand how it works. The voltage produced is used to power all types of electronic circuits including consumer electronics (televisions, DVDs, etc.), computers, industrial controllers, and most laboratory instrumentation systems and equipment. The dc voltage level required depends on the application, but most applications require relatively low voltages.

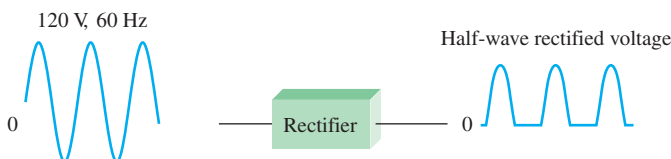
A basic block diagram of the complete power supply is shown in Figure 2–19(a). Generally the ac input line voltage is stepped down to a lower ac voltage with a transformer (although it may be stepped up when higher voltages are needed or there may be no transformer at all in rare instances). As you learned in your dc/ac course, a **transformer** changes ac voltages based on the turns ratio between the primary and secondary. If the secondary has more turns than the primary, the output voltage across the secondary will be higher and the current will be smaller. If the secondary has fewer turns than the primary, the output voltage across the secondary will be lower and the current will be higher. The rectifier can be either a half-wave rectifier or a full-wave rectifier (covered in Section 2–5). The **rectifier** converts the ac input voltage to a pulsating dc voltage, called a half-wave rectified voltage, as shown in Figure 2–19(b). The **filter** eliminates the fluctuations in the rectified voltage and produces a relatively smooth dc voltage. The power supply filter is covered in Section 2–6. The **regulator** is a circuit that maintains a constant dc voltage for variations in the input line voltage or in the load. Regulators vary from a single semiconductor device to more complex integrated circuits. The load is a circuit or device connected to the output of the power supply and operates from the power supply voltage and current.

F Y I

The standard line voltage in North America is 120 V/240 V at 60 Hz. Most small appliances operate on 120 V and larger appliances such as dryers, ranges, and heaters operate on 240 V. Occasionally, you will see references to 110 V or 115 V, but the standard is 120 V. Some foreign countries do use 110 V or 115 V at either 60 Hz or 50 Hz.



(a) Complete power supply with transformer, rectifier, filter, and regulator



(b) Half-wave rectifier

▲ FIGURE 2–19

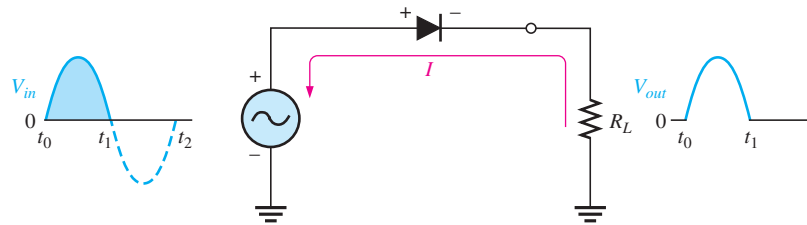
Block diagram of a dc power supply with a load and a rectifier.

GREENTECH NOTE

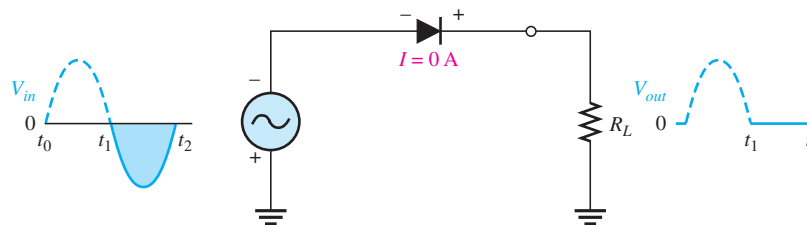
The *Energy Star* program was originally established by the EPA as a voluntary labeling program designed to indicate energy-efficient products. In order for power supplies to comply with the Energy Star requirements, they must have a minimum 80% efficiency rating for all rated power output. Try to choose a power supply that carries as 80 PLUS logo on it. This means that the power supply efficiency has been tested and approved to meet the Energy Star guidelines. Not all power supplies that claim to be high efficiency meet the Energy Star requirements.

Half-Wave Rectifier Operation

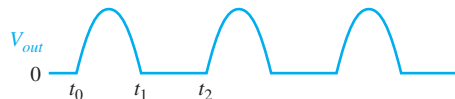
Figure 2–20 illustrates the process called *half-wave rectification*. A diode is connected to an ac source and to a load resistor, R_L , forming a **half-wave rectifier**. Keep in mind that all ground symbols represent the same point electrically. Let's examine what happens during one cycle of the input voltage using the ideal model for the diode. When the sinusoidal input voltage (V_{in}) goes positive, the diode is forward-biased and conducts current through the load resistor, as shown in part (a). The current produces an output voltage across the load R_L , which has the same shape as the positive half-cycle of the input voltage.



(a) During the positive alternation of the 60 Hz input voltage, the output voltage looks like the positive half of the input voltage. The current path is through ground back to the source.



(b) During the negative alternation of the input voltage, the current is 0, so the output voltage is also 0.



(c) 60 Hz half-wave output voltage for three input cycles

▲ FIGURE 2–20

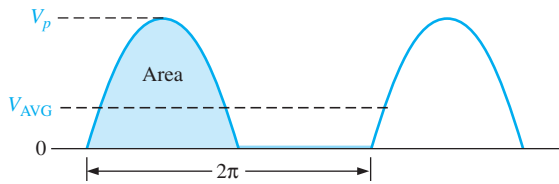
Half-wave rectifier operation. The diode is considered to be ideal.

When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased. There is no current, so the voltage across the load resistor is 0 V, as shown in Figure 2–20(b). The net result is that only the positive half-cycles of the ac input voltage appear across the load. Since the output does not change polarity, it is a pulsating dc voltage with a frequency of 60 Hz, as shown in part (c).

Average Value of the Half-Wave Output Voltage The average value of the half-wave rectified output voltage is the value you would measure on a dc voltmeter. Mathematically, it is determined by finding the area under the curve over a full cycle, as illustrated in Figure 2–21, and then dividing by 2π , the number of radians in a full cycle. The result of this is expressed in Equation 2–3, where V_p is the peak value of the voltage. This equation shows that V_{AVG} is approximately 31.8% of V_p for a half-wave rectified voltage. The derivation for this equation can be found in “Derivations of Selected Equations” at www.pearsonhighered.com/floyd.

Equation 2–3

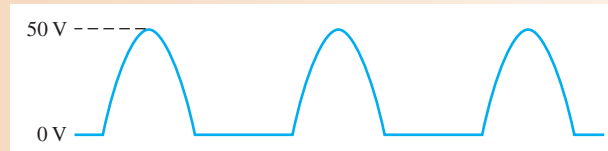
$$V_{AVG} = \frac{V_p}{\pi}$$


FIGURE 2-21

Average value of the half-wave rectified signal.

EXAMPLE 2-2

What is the average value of the half-wave rectified voltage in Figure 2-22?

FIGURE 2-22


Solution

$$V_{\text{AVG}} = \frac{V_p}{\pi} = \frac{50 \text{ V}}{\pi} = 15.9 \text{ V}$$

Notice that V_{AVG} is 31.8% of V_p .

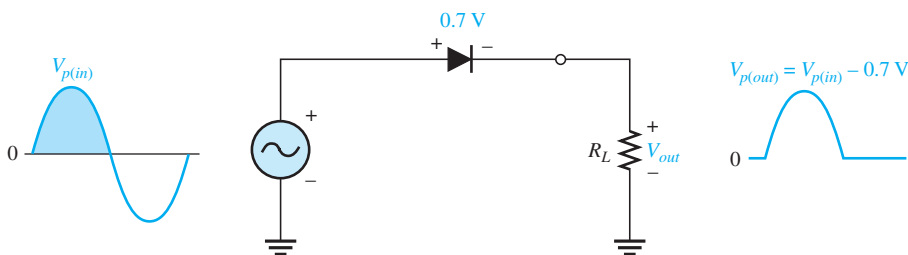
Related Problem Determine the average value of the half-wave voltage if its peak amplitude is 12 V.

Effect of the Barrier Potential on the Half-Wave Rectifier Output

In the previous discussion, the diode was considered ideal. When the practical diode model is used with the barrier potential of 0.7 V taken into account, this is what happens. During the positive half-cycle, the input voltage must overcome the barrier potential before the diode becomes forward-biased. This results in a half-wave output with a peak value that is 0.7 V less than the peak value of the input, as shown in Figure 2-23. The expression for the peak output voltage is

$$V_{p(\text{out})} = V_{p(\text{in})} - 0.7 \text{ V}$$

Equation 2-4

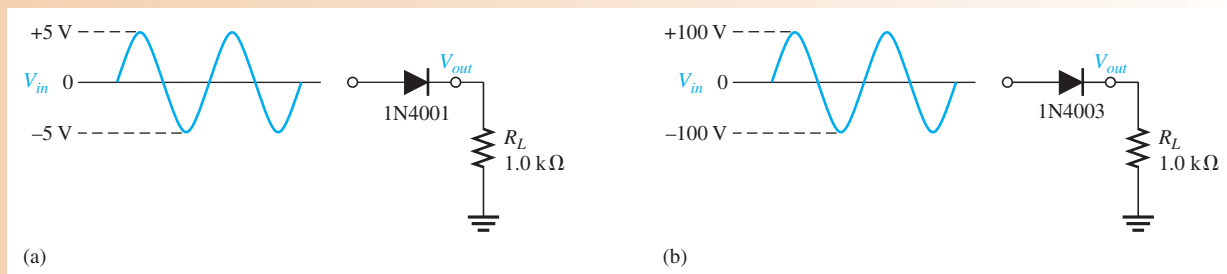

FIGURE 2-23

The effect of the barrier potential on the half-wave rectified output voltage is to reduce the peak value of the input by about 0.7 V.

It is usually acceptable to use the ideal diode model, which neglects the effect of the barrier potential, when the peak value of the applied voltage is much greater than the barrier potential (at least 10 V, as a rule of thumb). However, we will use the practical model of a diode, taking the 0.7 V barrier potential into account unless stated otherwise.

EXAMPLE 2-3

Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2-24. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ **FIGURE 2-24**

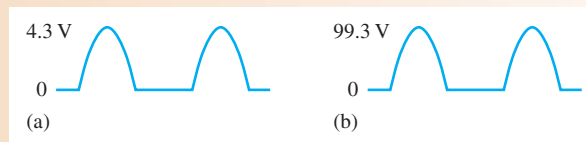
Solution The peak output voltage for circuit (a) is

$$V_{p(out)} = V_{p(in)} - 0.7 \text{ V} = 5 \text{ V} - 0.7 \text{ V} = \mathbf{4.30 \text{ V}}$$

The peak output voltage for circuit (b) is

$$V_{p(out)} = V_{p(in)} - 0.7 \text{ V} = 100 \text{ V} - 0.7 \text{ V} = \mathbf{99.3 \text{ V}}$$

The output voltage waveforms are shown in Figure 2-25. Note that the barrier potential could have been neglected in circuit (b) with very little error (0.7 percent); but, if it is neglected in circuit (a), a significant error results (14 percent).



▲ **FIGURE 2-25**

Output voltages for the circuits in Figure 2-24. They are not shown on the same scale.

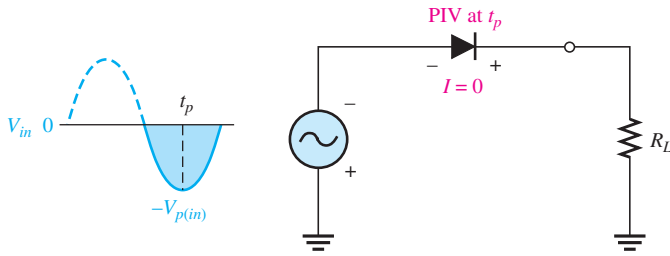
Related Problem Determine the peak output voltages for the rectifiers in Figure 2-24 if the peak input in part (a) is 3 V and the peak input in part (b) is 50 V.



Open the Multisim file E02-03 in the Examples folder on the companion website. For the inputs specified in the example, measure the resulting output voltage waveforms. Compare your measured results with those shown in the example.

Peak Inverse Voltage (PIV)

The **peak inverse voltage (PIV)** equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage. For the diode in Figure 2-26, the maximum value of reverse voltage, designated as PIV, occurs at the peak of each negative alternation of the input voltage when the diode is reverse-biased. A diode should be rated at least 20% higher than the PIV.

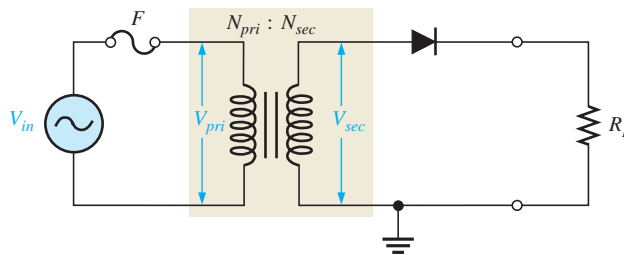


▲ FIGURE 2-26

The PIV occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. In this circuit, the PIV occurs at the peak of each negative half-cycle.

Transformer Coupling

As you have seen, a transformer is often used to couple the ac input voltage from the source to the rectifier, as shown in Figure 2-27. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped down as needed. Second, the ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.



◀ FIGURE 2-27

Half-wave rectifier with transformer-coupled input voltage.

The amount that the voltage is stepped down is determined by the **turns ratio** of the transformer. Unfortunately, the definition of turns ratio for transformers is not consistent between various sources and disciplines. In this text, we use the definition given by the IEEE for electronic power transformers, which is “the number of turns in the secondary (N_{sec}) divided by the number of turns in the primary (N_{pri}).” Thus, a transformer with a turns ratio less than 1 is a step-down type and one with a turns ratio greater than 1 is a step-up type. To show the turns ratio on a schematic, it is common practice to show the numerical ratio directly above the windings.

The secondary voltage of a transformer equals the turns ratio, n , times the primary voltage.

$$V_{sec} = nV_{pri}$$

If $n > 1$, the secondary voltage is greater than the primary voltage. If $n < 1$, the secondary voltage is less than the primary voltage. If $n = 1$, then $V_{sec} = V_{pri}$.

The peak secondary voltage, $V_{p(sec)}$, in a transformer-coupled half-wave rectifier is the same as $V_{p(in)}$ in Equation 2-4. Therefore, Equation 2-4 written in terms of $V_{p(sec)}$ is

$$V_{p(out)} = V_{p(sec)} - 0.7 \text{ V}$$

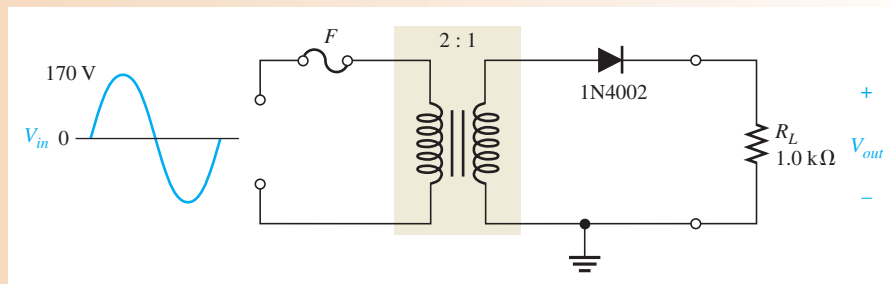
and Equation 2-5 in terms of $V_{p(sec)}$ is

$$\text{PIV} = V_{p(sec)}$$

Turns ratio is useful for understanding the voltage transfer from primary to secondary. However, transformer datasheets rarely show the turns ratio. A transformer is generally specified based on the secondary voltage rather than the turns ratio.

EXAMPLE 2–4

Determine the peak value of the output voltage for Figure 2–28 if the turns ratio is 0.5.

▶ **FIGURE 2–28****Solution**

$$V_{p(\text{pri})} = V_{p(\text{in})} = 170 \text{ V}$$

The peak secondary voltage is

$$V_{p(\text{sec})} = nV_{p(\text{pri})} = 0.5(170 \text{ V}) = 85 \text{ V}$$

The rectified peak output voltage is

$$V_{p(\text{out})} = V_{p(\text{sec})} - 0.7 \text{ V} = 85 \text{ V} - 0.7 \text{ V} = \mathbf{84.3 \text{ V}}$$

where $V_{p(\text{sec})}$ is the input to the rectifier.

- Related Problem**
- Determine the peak value of the output voltage for Figure 2–28 if $n = 2$ and $V_{p(\text{in})} = 312 \text{ V}$.
 - What is the PIV across the diode?
 - Describe the output voltage if the diode is turned around.



Open the Multisim file E02-04 in the Examples folder on the companion website. For the specified input, measure the peak output voltage. Compare your measured result with the calculated value.

**SECTION 2–4
CHECKUP**

- At what point on the input cycle does the PIV occur?
- For a half-wave rectifier, there is current through the load for approximately what percentage of the input cycle?
- What is the average of a half-wave rectified voltage with a peak value of 10 V?
- What is the peak value of the output voltage of a half-wave rectifier with a peak sine wave input of 25 V?
- What PIV rating must a diode have to be used in a rectifier with a peak output voltage of 50 V?

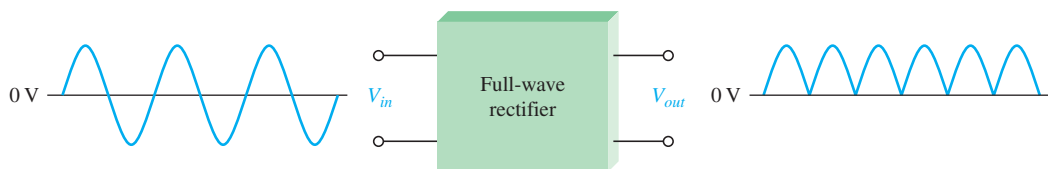
2–5 FULL-WAVE RECTIFIERS

Although half-wave rectifiers have some applications, the full-wave rectifier is the most commonly used type in dc power supplies. In this section, you will use what you learned about half-wave rectification and expand it to full-wave rectifiers. You will learn about two types of full-wave rectifiers: center-tapped and bridge.

After completing this section, you should be able to

- **Explain and analyze the operation of full-wave rectifiers**
- Describe how a center-tapped full-wave rectifier works
 - ♦ Discuss the effect of the turns ratio on the rectifier output
 - ♦ Calculate the peak inverse voltage
- Describe how a bridge full-wave rectifier works
 - ♦ Determine the bridge output voltage
 - ♦ Calculate the peak inverse voltage

A **full-wave rectifier** allows unidirectional (one-way) current through the load during the entire 360° of the input cycle, whereas a half-wave rectifier allows current through the load only during one-half of the cycle. The result of full-wave rectification is an output voltage with a frequency twice the input frequency and that pulsates every half-cycle of the input, as shown in Figure 2–29.



▲ **FIGURE 2–29**

Full-wave rectification.

The number of positive alternations that make up the full-wave rectified voltage is twice that of the half-wave voltage for the same time interval. The average value, which is the value measured on a dc voltmeter, for a full-wave rectified sinusoidal voltage is twice that of the half-wave, as shown in the following formula:

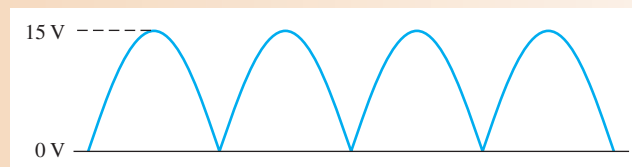
$$V_{\text{AVG}} = \frac{2V_p}{\pi} \quad \text{Equation 2–6}$$

V_{AVG} is approximately 63.7% of V_p for a full-wave rectified voltage.

EXAMPLE 2–5

Find the average value of the full-wave rectified voltage in Figure 2–30.

► **FIGURE 2–30**



Solution

$$V_{\text{AVG}} = \frac{2V_p}{\pi} = \frac{2(15 \text{ V})}{\pi} = 9.55 \text{ V}$$

V_{AVG} is 63.7% of V_p .

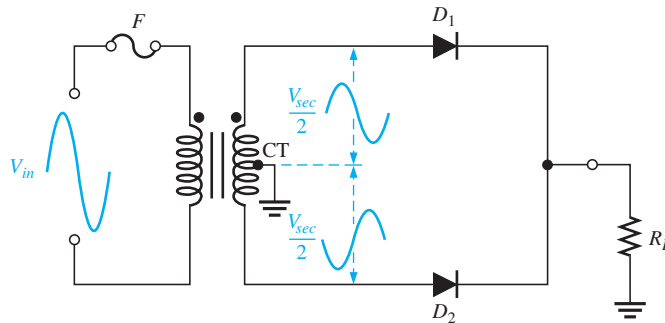
Related Problem Find the average value of the full-wave rectified voltage if its peak is 155 V.

Center-Tapped Full-Wave Rectifier Operation

A **center-tapped rectifier** is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer, as shown in Figure 2–31. The input voltage is coupled through the transformer to the center-tapped secondary. Half of the total secondary voltage appears between the center tap and each end of the secondary winding as shown.

► **FIGURE 2–31**

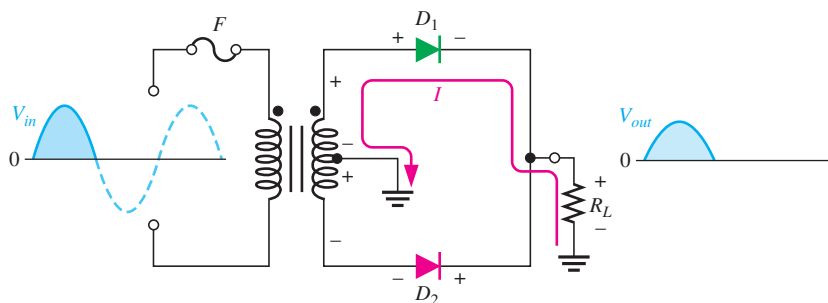
A center-tapped full-wave rectifier.



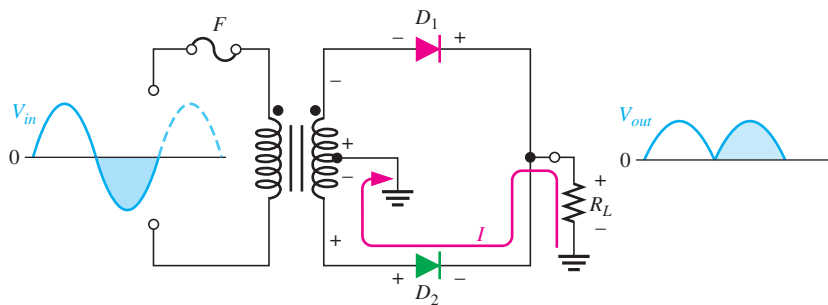
For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown in Figure 2–32(a). This condition forward-biases diode D_1 and reverse-biases diode D_2 . The current path is through D_1 and the load resistor R_L , as indicated. For a negative half-cycle of the input voltage, the voltage polarities on the secondary are as shown in Figure 2–32(b). This condition reverse-biases D_1 and forward-biases D_2 . The current path is through D_2 and R_L , as indicated. Because the output current during both the positive and negative portions of the input cycle is in the same direction through the load, the output voltage developed across the load resistor is a full-wave rectified dc voltage, as shown.

► **FIGURE 2–32**

Basic operation of a center-tapped full-wave rectifier. Note that the current through the load resistor is in the same direction during the entire input cycle, so the output voltage always has the same polarity.

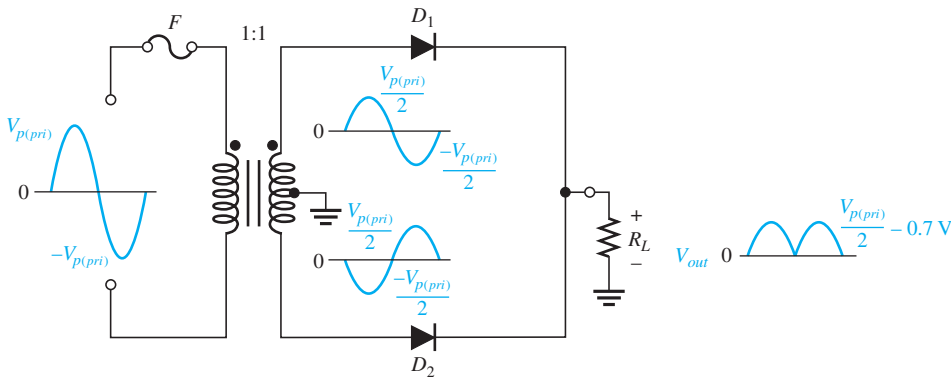


(a) During positive half-cycles, D_1 is forward-biased and D_2 is reverse-biased.



(b) During negative half-cycles, D_2 is forward-biased and D_1 is reverse-biased.

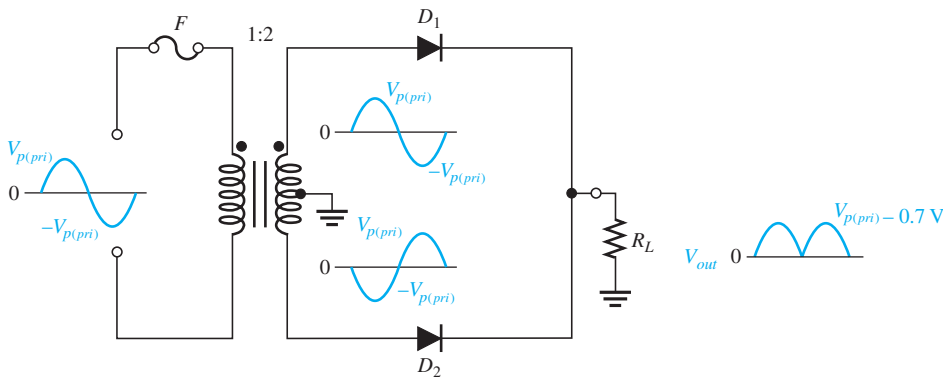
Effect of the Turns Ratio on the Output Voltage If the transformer's turns ratio is 1, the peak value of the rectified output voltage equals half the peak value of the primary input voltage less the barrier potential, as illustrated in Figure 2–33. Half of the primary



◀ **FIGURE 2-33**
Center-tapped full-wave rectifier with a transformer turns ratio of 1. $V_{p(prim)}$ is the peak value of the primary voltage.

voltage appears across each half of the secondary winding ($V_{p(sec)} = V_{p(prim)}$). We will begin referring to the forward voltage due to the barrier potential as the **diode drop**.

In order to obtain an output voltage with a peak equal to the input peak (less the diode drop), a step-up transformer with a turns ratio of $n = 2$ must be used, as shown in Figure 2-34. In this case, the total secondary voltage (V_{sec}) is twice the primary voltage ($2V_{pri}$), so the voltage across each half of the secondary is equal to V_{pri} .

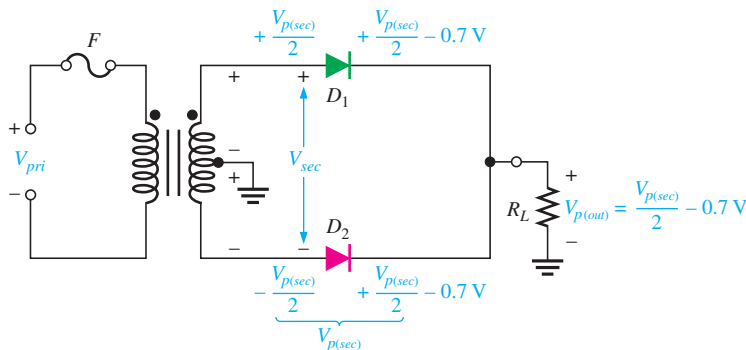


◀ **FIGURE 2-34**
Center-tapped full-wave rectifier with a transformer turns ratio of 2.

In any case, the output voltage of a center-tapped full-wave rectifier is always one-half of the total secondary voltage less the diode drop, no matter what the turns ratio.

$$V_{out} = \frac{V_{sec}}{2} - 0.7 \text{ V} \tag{Equation 2-7}$$

Peak Inverse Voltage Each diode in the full-wave rectifier is alternately forward-biased and then reverse-biased. The maximum reverse voltage that each diode must withstand is the peak secondary voltage $V_{p(sec)}$. This is shown in Figure 2-35 where D_2 is assumed to be reverse-biased (red) and D_1 is assumed to be forward-biased (green) to illustrate the concept.



◀ **FIGURE 2-35**
Diode reverse voltage (D_2 shown reverse-biased and D_1 shown forward-biased).

When the total secondary voltage V_{sec} has the polarity shown, the maximum anode voltage of D_1 is $+V_{p(sec)}/2$ and the maximum anode voltage of D_2 is $-V_{p(sec)}/2$. Since D_1 is assumed to be forward-biased, its cathode is at the same voltage as its anode minus the diode drop; this is also the voltage on the cathode of D_2 .

The peak inverse voltage across D_2 is

$$\begin{aligned} \text{PIV} &= \left(\frac{V_{p(sec)}}{2} - 0.7 \text{ V} \right) - \left(-\frac{V_{p(sec)}}{2} \right) = \frac{V_{p(sec)}}{2} + \frac{V_{p(sec)}}{2} - 0.7 \text{ V} \\ &= V_{p(sec)} - 0.7 \text{ V} \end{aligned}$$

Since $V_{p(out)} = V_{p(sec)}/2 - 0.7 \text{ V}$, then by multiplying each term by 2 and transposing,

$$V_{p(sec)} = 2V_{p(out)} + 1.4 \text{ V}$$

Therefore, by substitution, the peak inverse voltage across either diode in a full-wave center-tapped rectifier is

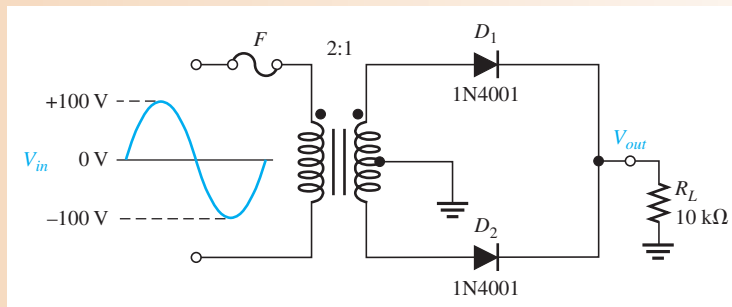
Equation 2-8

$$\text{PIV} = 2V_{p(out)} + 0.7 \text{ V}$$

EXAMPLE 2-6

- (a) Show the voltage waveforms across each half of the secondary winding and across R_L when a 100 V peak sine wave is applied to the primary winding in Figure 2-36.
 (b) What minimum PIV rating must the diodes have?

► FIGURE 2-36



Solution (a) The transformer turns ratio $n = 0.5$. The total peak secondary voltage is

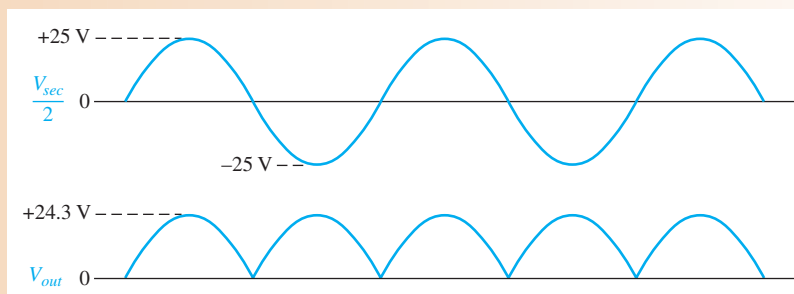
$$V_{p(sec)} = nV_{p(prim)} = 0.5(100 \text{ V}) = 50 \text{ V}$$

There is a 25 V peak across each half of the secondary with respect to ground. The output load voltage has a peak value of 25 V, less the 0.7 V drop across the diode. The waveforms are shown in Figure 2-37.

- (b) Each diode must have a minimum PIV rating of

$$\text{PIV} = 2V_{p(out)} + 0.7 \text{ V} = 2(24.3 \text{ V}) + 0.7 \text{ V} = \mathbf{49.3 \text{ V}}$$

► FIGURE 2-37



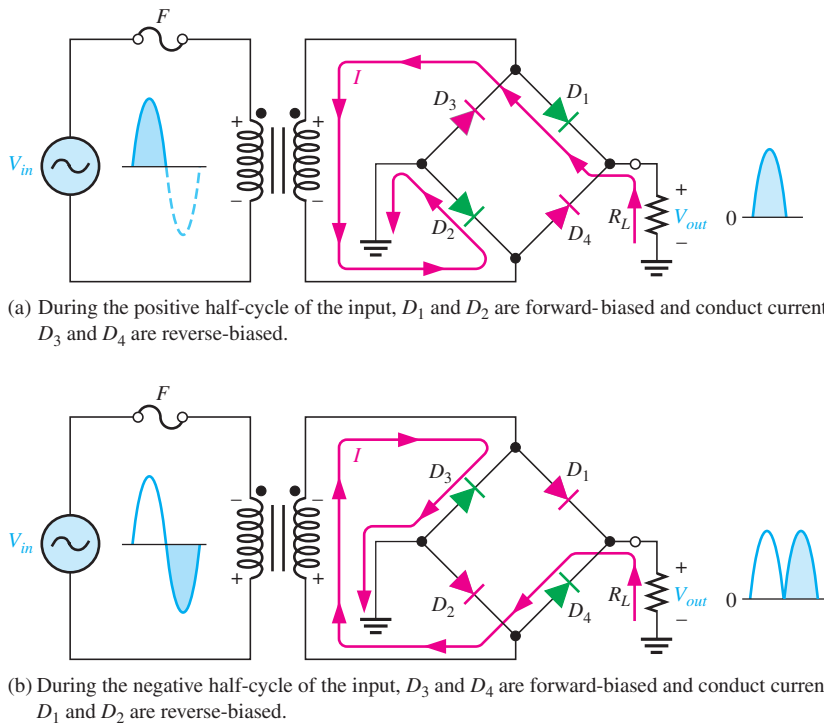
Related Problem What diode PIV rating is required to handle a peak input of 160 V in Figure 2–36?



Open the Multisim file E02-06 in the Examples folder on the companion website. For the specified input voltage, measure the voltage waveforms across each half of the secondary and across the load resistor. Compare with the results shown in the example.

Bridge Full-Wave Rectifier Operation

The **bridge rectifier** uses four diodes connected as shown in Figure 2–38. When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L that looks like the positive half of the input cycle. During this time, diodes D_3 and D_4 are reverse-biased.



◀ **FIGURE 2–38**

Operation of a bridge rectifier.

When the input cycle is negative as in Figure 2–38(b), diodes D_3 and D_4 are forward-biased and conduct current in the same direction through R_L as during the positive half-cycle. During the negative half-cycle, D_1 and D_2 are reverse-biased. A full-wave rectified output voltage appears across R_L as a result of this action.

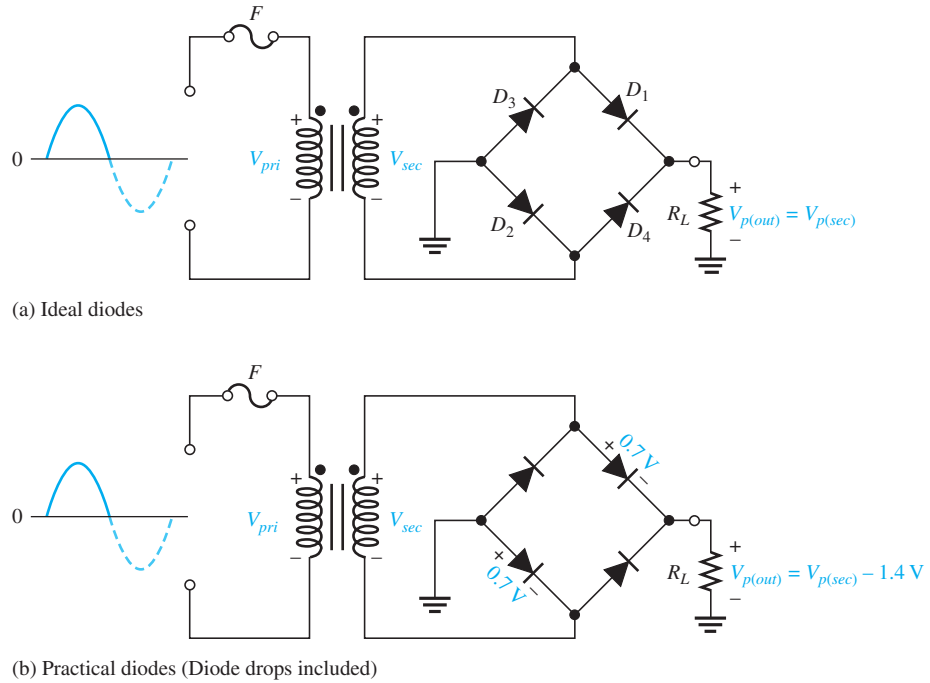
Bridge Output Voltage A bridge rectifier with a transformer-coupled input is shown in Figure 2–39(a). During the positive half-cycle of the total secondary voltage, diodes D_1 and D_2 are forward-biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true when D_3 and D_4 are forward-biased during the negative half-cycle.

$$V_{p(out)} = V_{p(sec)}$$

As you can see in Figure 2–39(b), two diodes are always in series with the load resistor during both the positive and negative half-cycles. If these diode drops are taken into account, the output voltage is

$$V_{p(out)} = V_{p(sec)} - 1.4 \text{ V}$$

Equation 2–9



▲ FIGURE 2-39

Bridge operation during a positive half-cycle of the primary and secondary voltages.

Peak Inverse Voltage Let's assume that D_1 and D_2 are forward-biased and examine the reverse voltage across D_3 and D_4 . Visualizing D_1 and D_2 as shorts (ideal model), as in Figure 2-40(a), you can see that D_3 and D_4 have a peak inverse voltage equal to the peak secondary voltage. Since the output voltage is *ideally* equal to the secondary voltage,

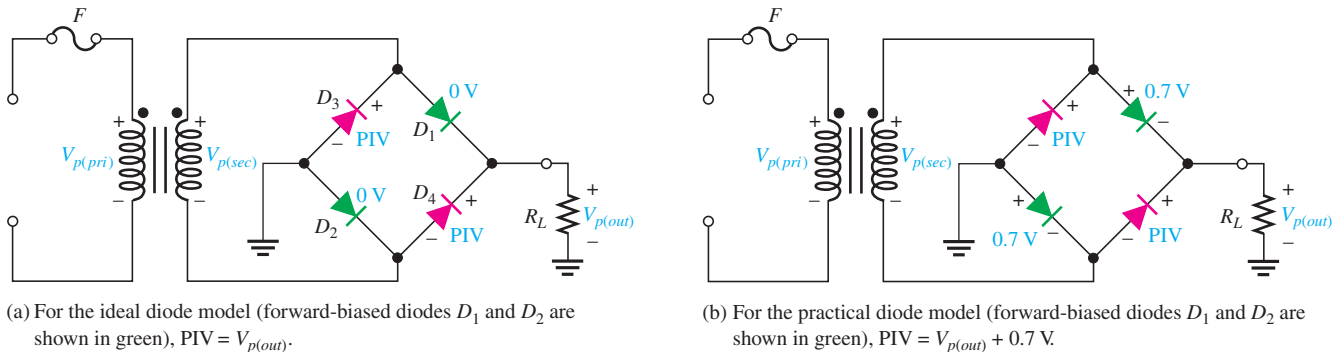
$$PIV = V_{p(out)}$$

If the diode drops of the forward-biased diodes are included as shown in Figure 2-40(b), the peak inverse voltage across each reverse-biased diode in terms of $V_{p(out)}$ is

Equation 2-10

$$PIV = V_{p(out)} + 0.7 \text{ V}$$

The PIV rating of the bridge diodes is less than that required for the center-tapped configuration. If the diode drop is neglected, the bridge rectifier requires diodes with half the PIV rating of those in a center-tapped rectifier for the same output voltage.

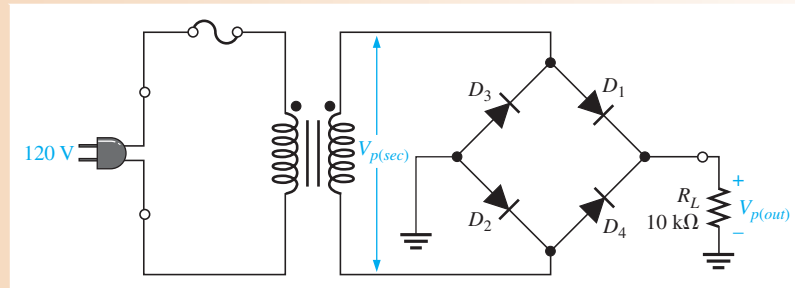


▲ FIGURE 2-40

Peak inverse voltages across diodes D_3 and D_4 in a bridge rectifier during the positive half-cycle of the secondary voltage.

EXAMPLE 2-7

Determine the peak output voltage for the bridge rectifier in Figure 2-41. Assuming the practical model, what PIV rating is required for the diodes? The transformer is specified to have a 12 V rms secondary voltage for the standard 120 V across the primary.

▶ **FIGURE 2-41**

Solution The peak output voltage (taking into account the two diode drops) is

$$V_{p(sec)} = 1.414V_{rms} = 1.414(12 \text{ V}) \cong 17 \text{ V}$$

$$V_{p(out)} = V_{p(sec)} - 1.4 \text{ V} = 17 \text{ V} - 1.4 \text{ V} = \mathbf{15.6 \text{ V}}$$

The PIV rating for each diode is

$$\text{PIV} = V_{p(out)} + 0.7 \text{ V} = 15.6 \text{ V} + 0.7 \text{ V} = \mathbf{16.3 \text{ V}}$$

Related Problem Determine the peak output voltage for the bridge rectifier in Figure 2-41 if the transformer produces an rms secondary voltage of 30 V. What is the PIV rating for the diodes?



Open the Multisim file E02-07 in the Examples folder on the companion website. Measure the output voltage and compare to the calculated value.

**SECTION 2-5
CHECKUP**

1. How does a full-wave voltage differ from a half-wave voltage?
2. What is the average value of a full-wave rectified voltage with a peak value of 60 V?
3. Which type of full-wave rectifier has the greater output voltage for the same input voltage and transformer turns ratio?
4. For a peak output voltage of 45 V, in which type of rectifier would you use diodes with a PIV rating of 50 V?
5. What PIV rating is required for diodes used in the type of rectifier that was not selected in Question 4?

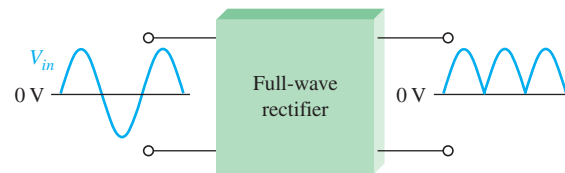
2-6 POWER SUPPLY FILTERS AND REGULATORS

A power supply filter ideally eliminates the fluctuations in the output voltage of a half-wave or full-wave rectifier and produces a constant-level dc voltage. Filtering is necessary because electronic circuits require a constant source of dc voltage and current to provide power and biasing for proper operation. Filters are implemented with capacitors, as you will see in this section. Voltage regulation in power supplies is usually done with integrated circuit voltage regulators. A voltage regulator prevents changes in the filtered dc voltage due to variations in input voltage or load.

After completing this section, you should be able to

- **Explain and analyze power supply filters and regulators**
- Describe the operation of a capacitor-input filter
 - ♦ Define *ripple voltage*
 - ♦ Calculate the ripple factor
 - ♦ Calculate the output voltage of a filtered full-wave rectifier
 - ♦ Discuss surge current
- Discuss voltage regulators
 - ♦ Calculate the line regulation
 - ♦ Calculate the load regulation

In most power supply applications, the standard 60 Hz ac power line voltage must be converted to an approximately constant dc voltage. The 60 Hz pulsating dc output of a half-wave rectifier or the 120 Hz pulsating output of a full-wave rectifier must be filtered to reduce the large voltage variations. Figure 2–42 illustrates the filtering concept showing a nearly smooth dc output voltage from the filter. The small amount of fluctuation in the filter output voltage is called *ripple*.



(a) Rectifier without a filter



(b) Rectifier with a filter (output ripple is exaggerated)

▲ **FIGURE 2–42**

Power supply filtering.

Capacitor-Input Filter

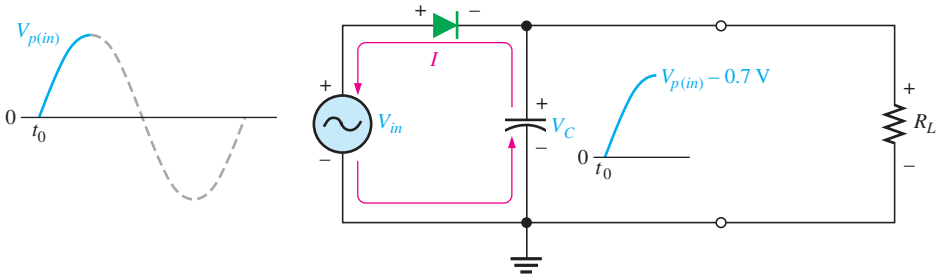
A half-wave rectifier with a capacitor-input filter is shown in Figure 2–43. The filter is simply a capacitor connected from the rectifier output to ground. R_L represents the equivalent resistance of a load. We will use the half-wave rectifier to illustrate the basic principle and then expand the concept to full-wave rectification.

During the positive first quarter-cycle of the input, the diode is forward-biased, allowing the capacitor to charge to within 0.7 V of the input peak, as illustrated in Figure 2–43(a). When the input begins to decrease below its peak, as shown in part (b), the capacitor retains its charge and the diode becomes reverse-biased because the cathode is more positive than the anode. During the remaining part of the cycle, the capacitor can discharge only through the load resistance at a rate determined by the $R_L C$ time constant, which is normally long compared to the period of the input. The larger the time constant, the less the capacitor will discharge. During the first quarter of the next cycle, as illustrated in part (c), the diode will again become forward-biased when the input voltage exceeds the capacitor voltage by approximately 0.7 V.

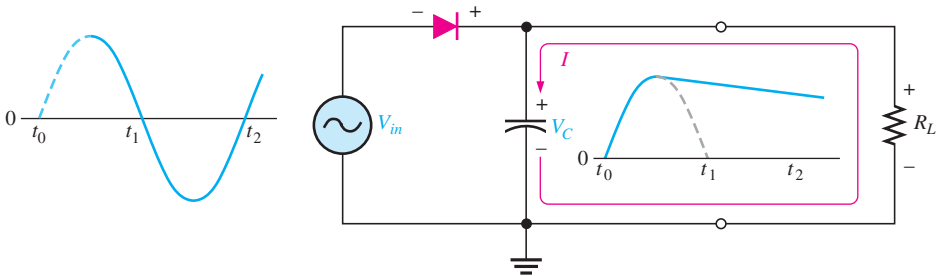


SAFETY NOTE

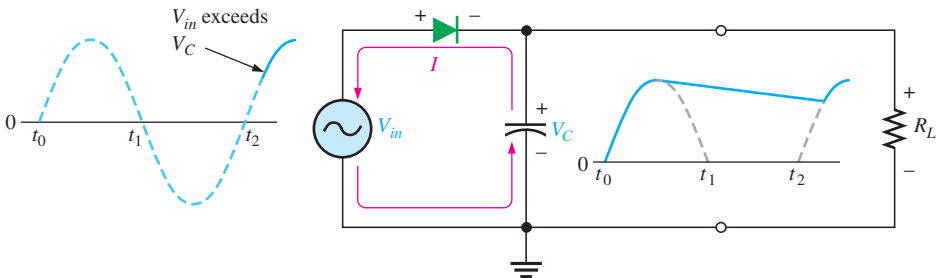
When installing polarized capacitors in a circuit, be sure to observe the proper polarity. The positive lead always connects to the more positive side of the circuit. An incorrectly connected polarized capacitor can explode.



(a) Initial charging of the capacitor (diode is forward-biased) happens only once when power is turned on.



(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid dark blue curve.

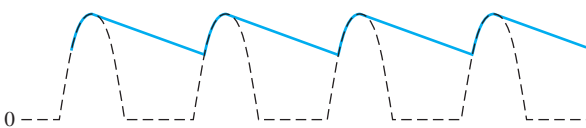


(c) The capacitor charges back to peak of input when the diode becomes forward-biased. This charging occurs during the portion of the input voltage indicated by the solid dark blue curve.

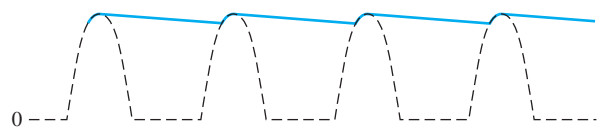
▲ FIGURE 2-43

Operation of a half-wave rectifier with a capacitor-input filter. The current indicates charging or discharging of the capacitor.

Ripple Voltage As you have seen, the capacitor quickly charges at the beginning of a cycle and slowly discharges through R_L after the positive peak of the input voltage (when the diode is reverse-biased). The variation in the capacitor voltage due to the charging and discharging is called the **ripple voltage**. Generally, ripple is undesirable; thus, the smaller the ripple, the better the filtering action, as illustrated in Figure 2-44.



(a) Larger ripple (blue) means less effective filtering.



(b) Smaller ripple means more effective filtering. Generally, the larger the capacitor value, the smaller the ripple for the same input and load.

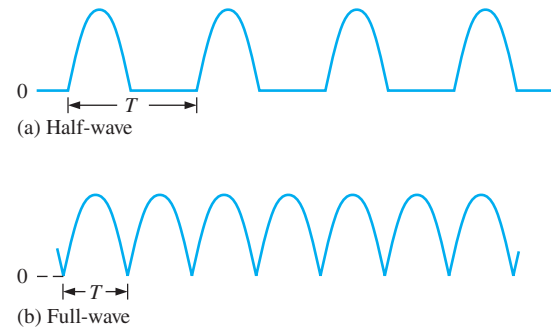
▲ FIGURE 2-44

Half-wave ripple voltage (blue line).

For a given input frequency, the output frequency of a full-wave rectifier is twice that of a half-wave rectifier, as illustrated in Figure 2–45. This makes a full-wave rectifier easier to filter because of the shorter time between peaks. When filtered, the full-wave rectified voltage has a smaller ripple than does a half-wave voltage for the same load resistance and capacitor values. The capacitor discharges less during the shorter interval between full-wave pulses, as shown in Figure 2–46.

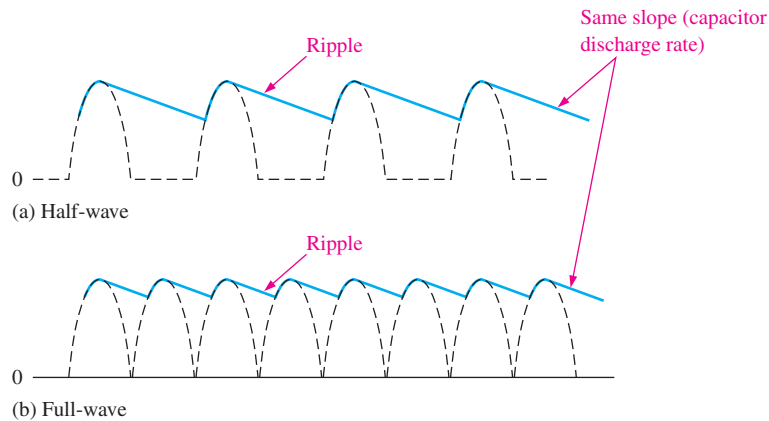
► **FIGURE 2–45**

The period of a full-wave rectified voltage is half that of a half-wave rectified voltage. The output frequency of a full-wave rectifier is twice that of a half-wave rectifier.



► **FIGURE 2–46**

Comparison of ripple voltages for half-wave and full-wave rectified voltages with the same filter capacitor and load and derived from the same sinusoidal input voltage.



Ripple Factor The **ripple factor (r)** is an indication of the effectiveness of the filter and is defined as

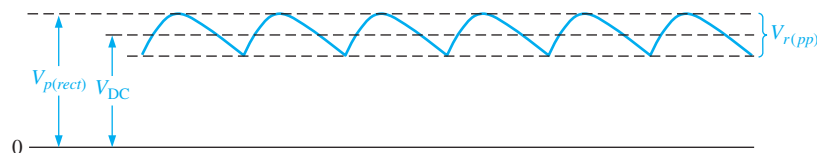
Equation 2–11

$$r = \frac{V_{r(pp)}}{V_{DC}}$$

where $V_{r(pp)}$ is the peak-to-peak ripple voltage and V_{DC} is the dc (average) value of the filter's output voltage, as illustrated in Figure 2–47. The lower the ripple factor, the better the filter. The ripple factor can be lowered by increasing the value of the filter capacitor or increasing the load resistance.

► **FIGURE 2–47**

V_r and V_{DC} determine the ripple factor.



For a full-wave rectifier with a capacitor-input filter, approximations for the peak-to-peak ripple voltage, $V_{r(pp)}$, and the dc value of the filter output voltage, V_{DC} , are given in the following equations. The variable $V_{p(rect)}$ is the unfiltered peak rectified voltage. Notice that if R_L or C increases, the ripple voltage decreases and the dc voltage increases.

$$V_{r(pp)} \cong \left(\frac{1}{fR_L C} \right) V_{p(rect)} \quad \text{Equation 2-12}$$

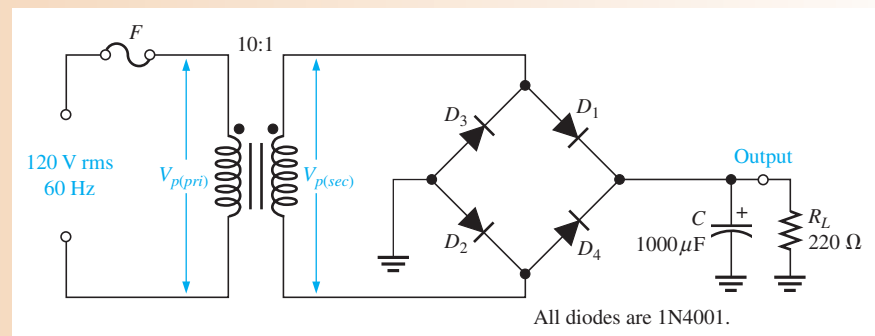
$$V_{DC} \cong \left(1 - \frac{1}{2fR_L C} \right) V_{p(rect)} \quad \text{Equation 2-13}$$

The derivations for these equations can be found in “Derivations of Selected Equations” at www.pearsonhighered.com/floyd.

EXAMPLE 2-8

Determine the ripple factor for the filtered bridge rectifier with a load as indicated in Figure 2-48.

► FIGURE 2-48



Solution The transformer turns ratio is $n = 0.1$. The peak primary voltage is

$$V_{p(pri)} = 1.414V_{rms} = 1.414(120 \text{ V}) = 170 \text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.1(170 \text{ V}) = 17.0 \text{ V}$$

The unfiltered peak full-wave rectified voltage is

$$V_{p(rect)} = V_{p(sec)} - 1.4 \text{ V} = 17.0 \text{ V} - 1.4 \text{ V} = 15.6 \text{ V}$$

The frequency of a full-wave rectified voltage is 120 Hz. The approximate peak-to-peak ripple voltage at the output is

$$V_{r(pp)} \cong \left(\frac{1}{fR_L C} \right) V_{p(rect)} = \left(\frac{1}{(120 \text{ Hz})(220 \Omega)(1000 \mu\text{F})} \right) 15.6 \text{ V} = 0.591 \text{ V}$$

The approximate dc value of the output voltage is determined as follows:

$$V_{DC} = \left(1 - \frac{1}{2fR_L C} \right) V_{p(rect)} = \left(1 - \frac{1}{(240 \text{ Hz})(220 \Omega)(1000 \mu\text{F})} \right) 15.6 \text{ V} = 15.3 \text{ V}$$

The resulting ripple factor is

$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{0.591 \text{ V}}{15.3 \text{ V}} = \mathbf{0.039}$$

The percent ripple is 3.9%.

Related Problem Determine the peak-to-peak ripple voltage if the filter capacitor in Figure 2-48 is increased to 2200 μF and the load resistance changes to 2.2 k Ω .

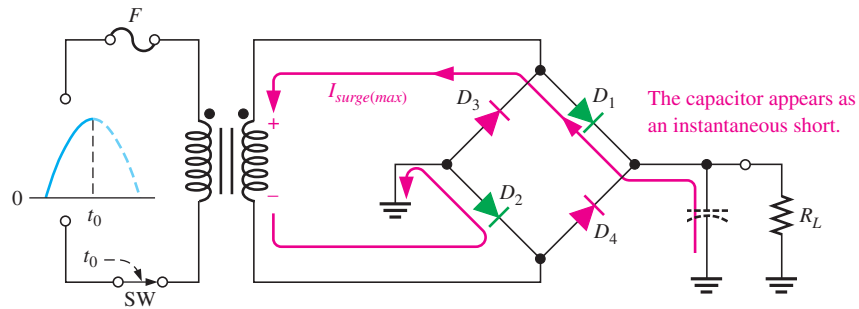


Open the Multisim file E02-08 in the Examples folder on the companion website. For the specified input voltage, measure the peak-to-peak ripple voltage and the dc value at the output. Do the results agree closely with the calculated values? If not, can you explain why?

Surge Current in the Capacitor-Input Filter Before the switch in Figure 2–49 is closed, the filter capacitor is uncharged. At the instant the switch is closed, voltage is connected to the bridge and the uncharged capacitor appears as a short, as shown. This produces an initial surge of current, I_{surge} , through the two forward-biased diodes D_1 and D_2 . The worst-case situation occurs when the switch is closed at a peak of the secondary voltage and a maximum surge current, $I_{surge(max)}$, is produced, as illustrated in the figure.

► FIGURE 2–49

Surge current in a capacitor-input filter.



In dc power supplies, a **fuse** is always placed in the primary circuit of the transformer, as shown in Figure 2–49. A slow-blow type fuse is generally used because of the surge current that initially occurs when power is first turned on. The fuse rating is determined by calculating the power in the power supply load, which is the output power. Since $P_{in} = P_{out}$ in an ideal transformer, the primary current can be calculated as

$$I_{pri} = \frac{P_{in}}{120 \text{ V}}$$

The fuse rating should be at least 20% larger than the calculated value of I_{pri} .

Voltage Regulators

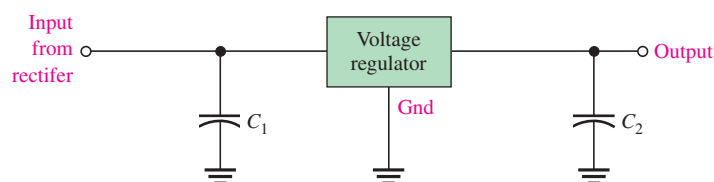
While filters can reduce the ripple from power supplies to a low value, the most effective approach is a combination of a capacitor-input filter used with a voltage regulator. A voltage regulator is connected to the output of a filtered rectifier and maintains a constant output voltage (or current) despite changes in the input, the load current, or the temperature. The capacitor-input filter reduces the input ripple to the regulator to an acceptable level. The combination of a large capacitor and a voltage regulator helps produce an excellent power supply.

Most regulators are integrated circuits and have three terminals—an input terminal, an output terminal, and a reference (or adjust) terminal. The input to the regulator is first filtered with a capacitor to reduce the ripple to <10%. The regulator reduces the ripple to a negligible amount. In addition, most regulators have an internal voltage reference, short-circuit protection, and thermal shutdown circuitry. They are available in a variety of voltages, including positive and negative outputs, and can be designed for variable outputs with a minimum of external components. Typically, voltage regulators can furnish a constant output of one or more amps of current with high ripple rejection.

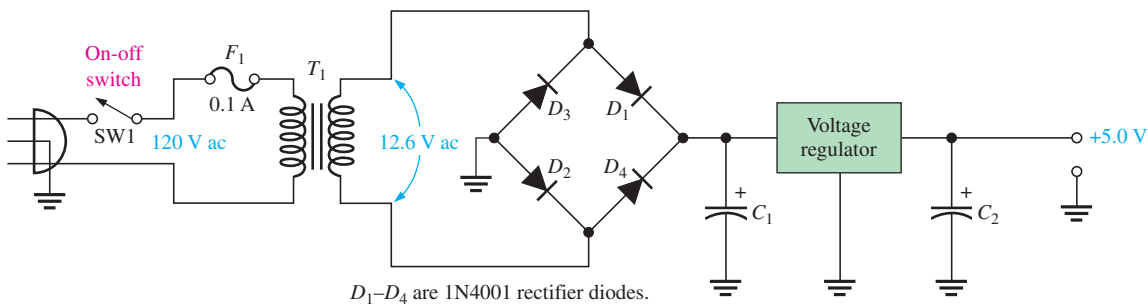
Three-terminal regulators designed for fixed output voltages require only external capacitors to complete the regulation portion of the power supply, as shown in Figure 2–50. Filtering is accomplished by a large-value capacitor between the input voltage and ground. An output capacitor (typically 0.1 μF to 1.0 μF) is connected from the output to ground to improve the transient response.

► FIGURE 2–50

A voltage regulator with input and output capacitors.



A basic fixed power supply with a +5 V voltage regulator is shown in Figure 2–51. Specific integrated circuit three-terminal regulators with fixed output voltages are covered in Chapter 17.



▲ FIGURE 2–51

A basic +5.0 V regulated power supply.

Percent Regulation

The regulation expressed as a percentage is a figure of merit used to specify the performance of a voltage regulator. It can be in terms of input (line) regulation or load regulation.

Line Regulation The **line regulation** specifies how much change occurs in the output voltage for a given change in the input voltage. It is typically defined as a ratio of a change in output voltage for a corresponding change in the input voltage expressed as a percentage.

$$\text{Line regulation} = \left(\frac{\Delta V_{\text{OUT}}}{\Delta V_{\text{IN}}} \right) 100\% \quad \text{Equation 2–14}$$

Load Regulation The **load regulation** specifies how much change occurs in the output voltage over a certain range of load current values, usually from minimum current (no load, NL) to maximum current (full load, FL). It is normally expressed as a percentage and can be calculated with the following formula:

$$\text{Load regulation} = \left(\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \right) 100\% \quad \text{Equation 2–15}$$

where V_{NL} is the output voltage with no load and V_{FL} is the output voltage with full (maximum) load.

EXAMPLE 2–9

A certain 7805 regulator has a measured no-load output voltage of 5.18 V and a full-load output of 5.15 V. What is the load regulation expressed as a percentage?

Solution Load regulation = $\left(\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \right) 100\% = \left(\frac{5.18 \text{ V} - 5.15 \text{ V}}{5.15 \text{ V}} \right) 100\% = \mathbf{0.58\%}$

Related Problem If the no-load output voltage of a regulator is 24.8 V and the full-load output is 23.9 V, what is the load regulation expressed as a percentage?

SECTION 2–6 CHECKUP

1. When a 60 Hz sinusoidal voltage is applied to the input of a half-wave rectifier, what is the output frequency?
2. When a 60 Hz sinusoidal voltage is applied to the input of a full-wave rectifier, what is the output frequency?

3. What causes the ripple voltage on the output of a capacitor-input filter?
4. If the load resistance connected to a filtered power supply is decreased, what happens to the ripple voltage?
5. Define *ripple factor*.
6. What is the difference between input (line) regulation and load regulation?

2-7 DIODE LIMITERS AND CLAMPERS

Diode circuits, called limiters or clippers, are sometimes used to clip off portions of signal voltages above or below certain levels. Another type of diode circuit, called a clamper, is used to add or restore a dc level to an electrical signal. Both limiter and clamper diode circuits will be examined in this section.

After completing this section, you should be able to

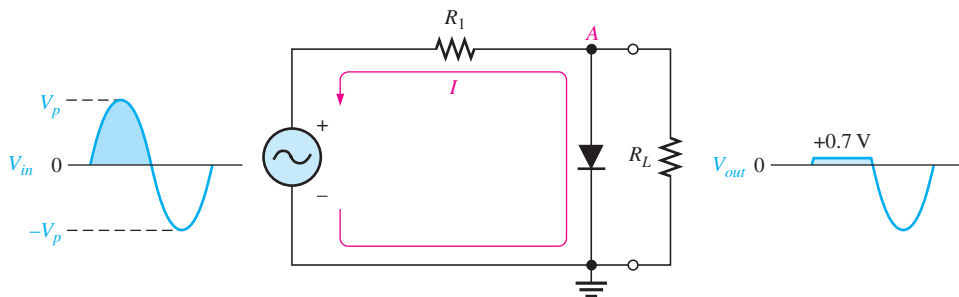
- **Explain and analyze the operation of diode limiters and clippers**
- Describe the operation of a diode limiter
 - ♦ Discuss biased limiters
 - ♦ Discuss voltage-divider bias
 - ♦ Describe an application
- Describe the operation of a diode clamper

Diode Limiters

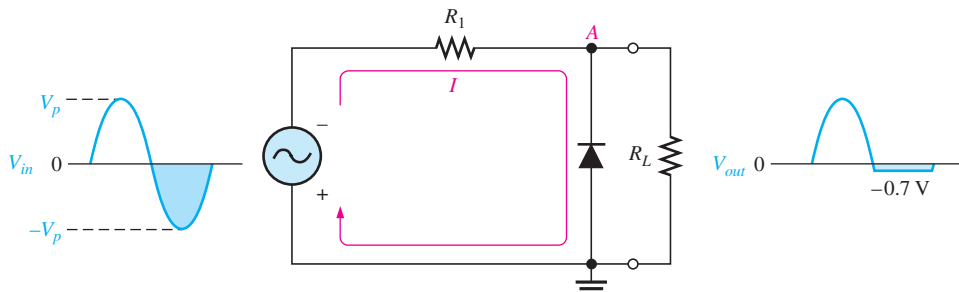
Figure 2-52(a) shows a diode positive **limiter** (also called **clipper**) that limits or clips the positive part of the input voltage. As the input voltage goes positive, the diode becomes forward-biased and conducts current. Point A is limited to +0.7 V when the input voltage exceeds this

► **FIGURE 2-52**

Examples of diode limiters (clippers).



(a) Limiting of the positive alternation. The diode is forward-biased during the positive alternation (above 0.7 V) and reverse-biased during the negative alternation.



(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below -0.7 V) and reverse-biased during the positive alternation.

value. When the input voltage goes back below 0.7 V, the diode is reverse-biased and appears as an open. The output voltage looks like the negative part of the input voltage, but with a magnitude determined by the voltage divider formed by R_1 and the load resistor, R_L , as follows:

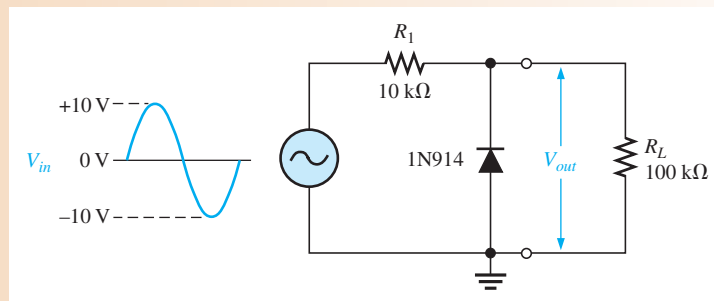
$$V_{out} = \left(\frac{R_L}{R_1 + R_L} \right) V_{in}$$

If R_1 is small compared to R_L , then $V_{out} \cong V_{in}$.

If the diode is turned around, as in Figure 2–52(b), the negative part of the input voltage is clipped off. When the diode is forward-biased during the negative part of the input voltage, point A is held at -0.7 V by the diode drop. When the input voltage goes above -0.7 V, the diode is no longer forward-biased; and a voltage appears across R_L proportional to the input voltage.

EXAMPLE 2–10

What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in Figure 2–53?

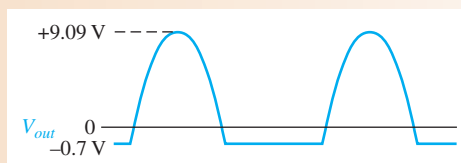


► FIGURE 2–53

Solution The diode is forward-biased and conducts when the input voltage goes below -0.7 V. So, for the negative limiter, determine the peak output voltage across R_L by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L} \right) V_{p(in)} = \left(\frac{100 \text{ k}\Omega}{110 \text{ k}\Omega} \right) 10 \text{ V} = 9.09 \text{ V}$$

The scope will display an output waveform as shown in Figure 2–54.



► FIGURE 2–54

Output voltage waveform for Figure 2–53.

Related Problem Describe the output waveform for Figure 2–53 if R_1 is changed to $1 \text{ k}\Omega$.

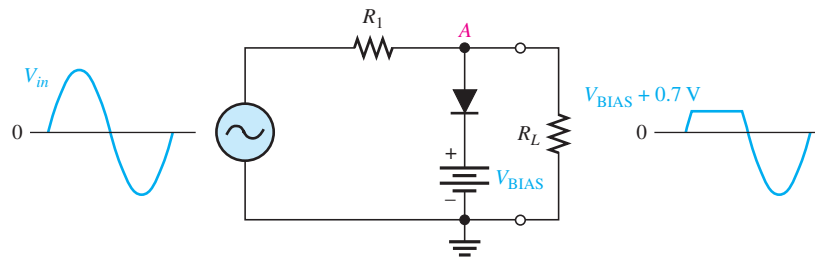


Open the Multisim file E02-10 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

Biased Limiters The level to which an ac voltage is limited can be adjusted by adding a bias voltage, V_{BIAS} , in series with the diode, as shown in Figure 2–55. The voltage at point A must equal $V_{\text{BIAS}} + 0.7 \text{ V}$ before the diode will become forward-biased and conduct. Once the diode begins to conduct, the voltage at point A is limited to $V_{\text{BIAS}} + 0.7 \text{ V}$ so that all input voltage above this level is clipped off.

► **FIGURE 2–55**

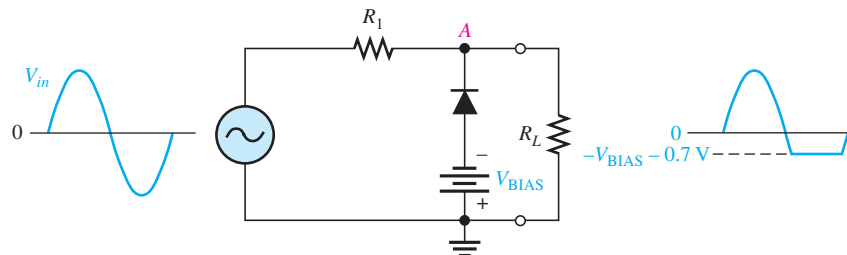
A positive limiter.



To limit a voltage to a specified negative level, the diode and bias voltage must be connected as in Figure 2–56. In this case, the voltage at point A must go below $-V_{\text{BIAS}} - 0.7 \text{ V}$ to forward-bias the diode and initiate limiting action as shown.

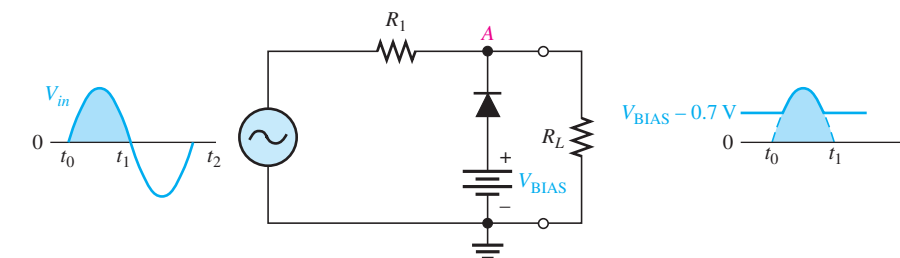
► **FIGURE 2–56**

A negative limiter.

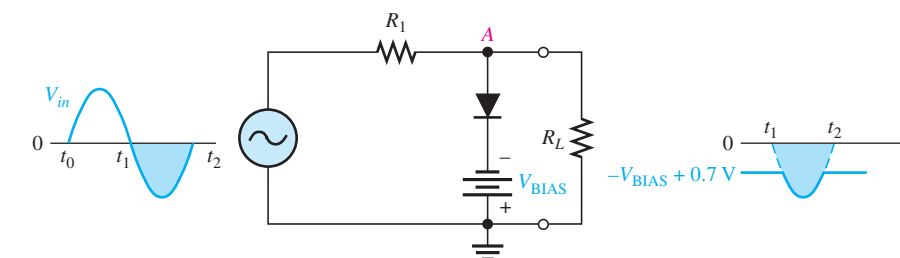


By turning the diode around, the positive limiter can be modified to limit the output voltage to the portion of the input voltage waveform above $V_{\text{BIAS}} - 0.7 \text{ V}$, as shown by the output waveform in Figure 2–57(a). Similarly, the negative limiter can be modified to limit the output voltage to the portion of the input voltage waveform below $-V_{\text{BIAS}} + 0.7 \text{ V}$, as shown by the output waveform in part (b).

► **FIGURE 2–57**



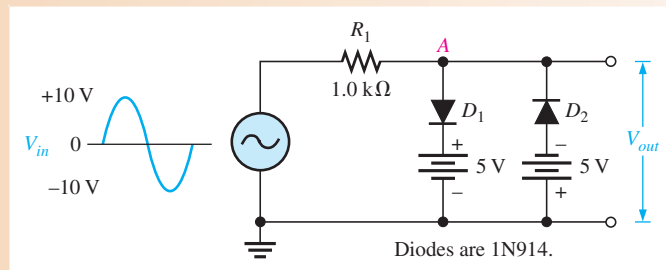
(a)



(b)

EXAMPLE 2–11

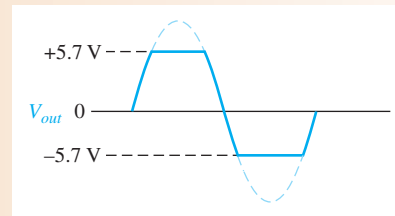
Figure 2–58 shows a circuit combining a positive limiter with a negative limiter. Determine the output voltage waveform.

▶ **FIGURE 2–58**

Solution When the voltage at point A reaches +5.7 V, diode D_1 conducts and limits the waveform to +5.7 V. Diode D_2 does not conduct until the voltage reaches -5.7 V. Therefore, positive voltages above +5.7 V and negative voltages below -5.7 V are clipped off. The resulting output voltage waveform is shown in Figure 2–59.

▶ **FIGURE 2–59**

Output voltage waveform for Figure 2–58.



Related Problem Determine the output voltage waveform in Figure 2–58 if both dc sources are 10 V and the input voltage has a peak value of 20 V.



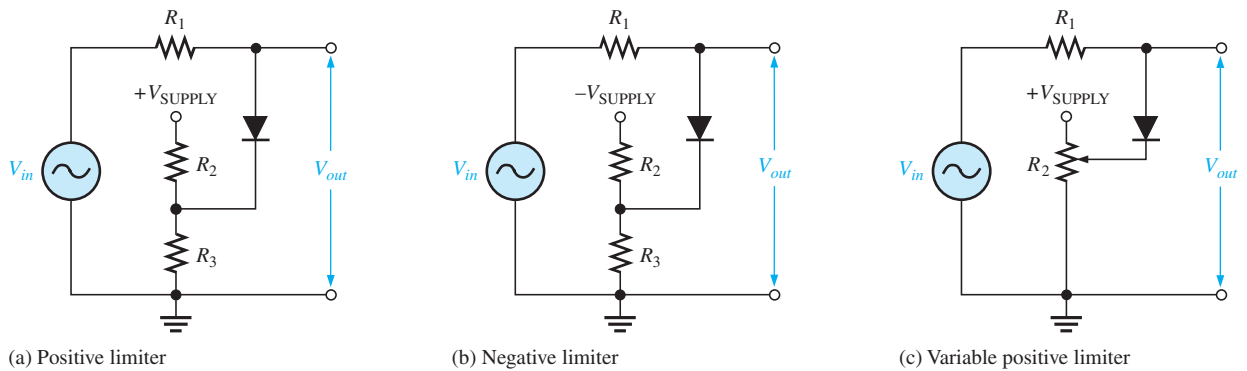
Open the Multisim file E02-11 in the Examples folder on the companion website. For the specified input, measure the resulting output waveform. Compare with the waveform shown in the example.

Voltage-Divider Bias The bias voltage sources that have been used to illustrate the basic operation of diode limiters can be replaced by a resistive voltage divider that derives the desired bias voltage from the dc supply voltage, as shown in Figure 2–60. The bias voltage is set by the resistor values according to the voltage-divider formula.

$$V_{\text{BIAS}} = \left(\frac{R_3}{R_2 + R_3} \right) V_{\text{SUPPLY}}$$

A positively biased limiter is shown in Figure 2–60(a), a negatively biased limiter is shown in part (b), and a variable positive bias circuit using a potentiometer voltage divider is shown in part (c). The bias resistors must be small compared to R_1 so that the forward current through the diode will not affect the bias voltage.

A Limiter Application Many circuits have certain restrictions on the input level to avoid damaging the circuit. For example, almost all digital circuits should not have an input level that exceeds the power supply voltage. An input of a few volts more than this could damage the circuit. To prevent the input from exceeding a specific level, you may see a diode limiter across the input signal path in many digital circuits.



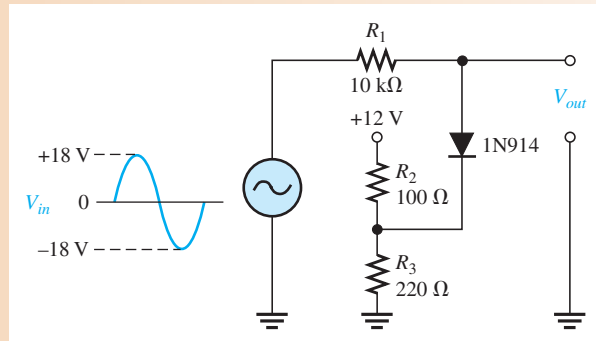
▲ FIGURE 2-60

Diode limiters implemented with voltage-divider bias.

EXAMPLE 2-12

Describe the output voltage waveform for the diode limiter in Figure 2-61.

► FIGURE 2-61

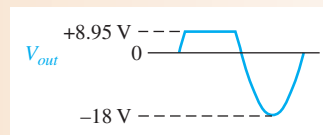


Solution The circuit is a positive limiter. Use the voltage-divider formula to determine the bias voltage.

$$V_{\text{BIAS}} = \left(\frac{R_3}{R_2 + R_3} \right) V_{\text{SUPPLY}} = \left(\frac{220 \, \Omega}{100 \, \Omega + 220 \, \Omega} \right) 12 \, \text{V} = 8.25 \, \text{V}$$

The output voltage waveform is shown in Figure 2-62. The positive part of the output voltage waveform is limited to $V_{\text{BIAS}} + 0.7 \, \text{V}$.

► FIGURE 2-62



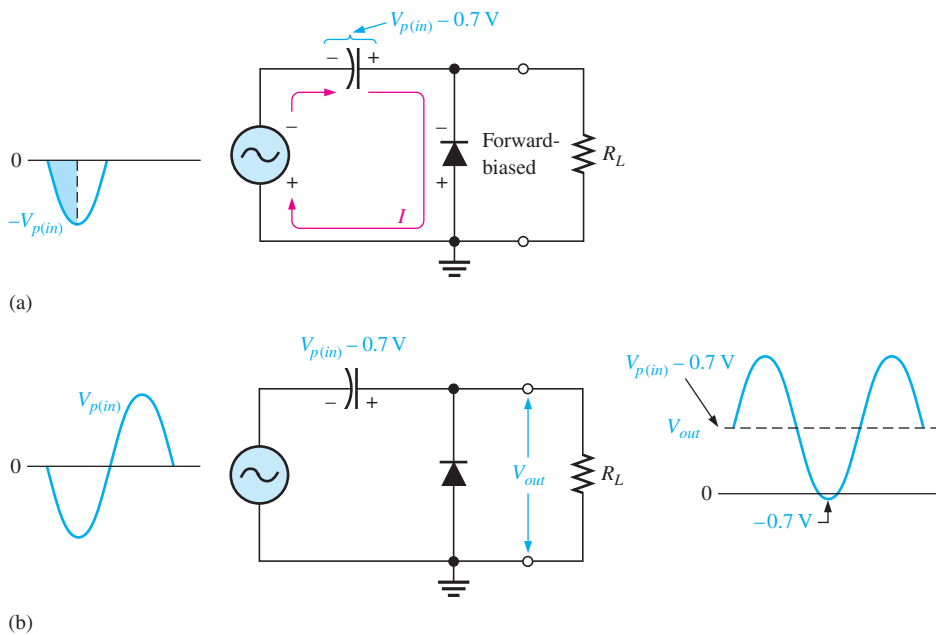
Related Problem How would you change the voltage divider in Figure 2-61 to limit the output voltage to +6.7 V?



Open the Multisim file E02-12 in the Examples folder on the companion website. Observe the output voltage on the oscilloscope and compare to the calculated result.

Diode Clampers

A clamper adds a dc level to an ac voltage. **Clampers** are sometimes known as *dc restorers*. Figure 2–63 shows a diode clamper that inserts a positive dc level in the output waveform. The operation of this circuit can be seen by considering the first negative half-cycle of the input voltage. When the input voltage initially goes negative, the diode is forward-biased, allowing the capacitor to charge to near the peak of the input ($V_{p(in)} - 0.7\text{ V}$), as shown in Figure 2–63(a). Just after the negative peak, the diode is reverse-biased. This is because the cathode is held near $V_{p(in)} - 0.7\text{ V}$ by the charge on the capacitor. The capacitor can only discharge through the high resistance of R_L . So, from the peak of one negative half-cycle to the next, the capacitor discharges very little. The amount that is discharged, of course, depends on the value of R_L .



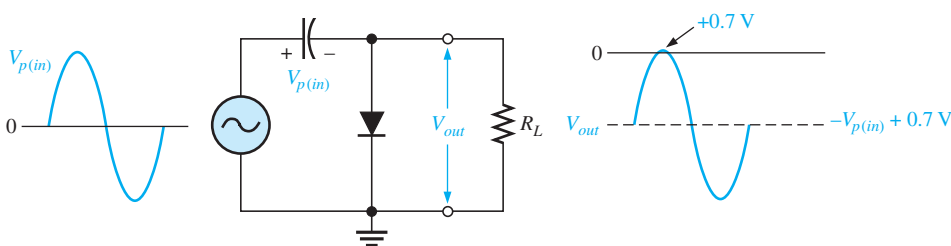
◀ FIGURE 2–63

Positive clamper operation.

If the capacitor discharges during the period of the input wave, clamping action is affected. If the RC time constant is 100 times the period, the clamping action is excellent. An RC time constant of ten times the period will have a small amount of distortion at the ground level due to the charging current.

The net effect of the clamping action is that the capacitor retains a charge approximately equal to the peak value of the input less the diode drop. The capacitor voltage acts essentially as a battery in series with the input voltage. The dc voltage of the capacitor adds to the input voltage by superposition, as in Figure 2–63(b).

If the diode is turned around, a negative dc voltage is added to the input voltage to produce the output voltage as shown in Figure 2–64.

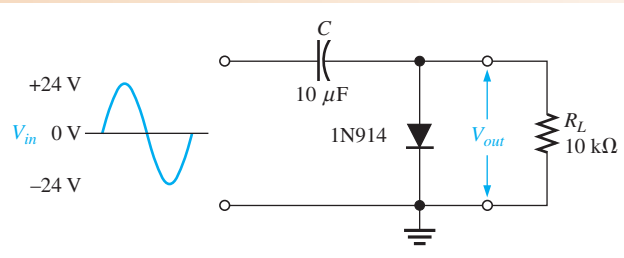


◀ FIGURE 2–64

Negative clamper.

EXAMPLE 2-13

What is the output voltage that you would expect to observe across R_L in the clamping circuit of Figure 2-65? Assume that RC is large enough to prevent significant capacitor discharge.

▶ **FIGURE 2-65**

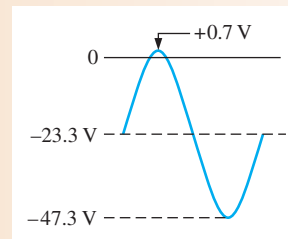
Solution Ideally, a negative dc value equal to the input peak less the diode drop is inserted by the clamping circuit.

$$V_{DC} \cong -(V_{p(in)} - 0.7 \text{ V}) = -(24 \text{ V} - 0.7 \text{ V}) = -23.3 \text{ V}$$

Actually, the capacitor will discharge slightly between peaks, and, as a result, the output voltage will have an average value of slightly less than that calculated above. The output waveform goes to approximately $+0.7 \text{ V}$, as shown in Figure 2-66.

▶ **FIGURE 2-66**

Output waveform across R_L for Figure 2-65.



Related Problem What is the output voltage that you would observe across R_L in Figure 2-65 for $C = 22 \mu\text{F}$ and $R_L = 18 \text{ k}\Omega$?



Open the Multisim file E02-13 in the Examples folder on the companion website. For the specified input, measure the output waveform. Compare with the waveform shown in the example.

**SECTION 2-7
CHECKUP**

1. Discuss how diode limiters and diode clippers differ in terms of their function.
2. What is the difference between a positive limiter and a negative limiter?
3. What is the maximum voltage across an unbiased positive silicon diode limiter during the positive alternation of the input voltage?
4. To limit the output voltage of a positive limiter to 5 V when a 10 V peak input is applied, what value must the bias voltage be?
5. What component in a clamping circuit effectively acts as a battery?

2-8 VOLTAGE MULTIPLIERS

Voltage multipliers use clamping action to increase peak rectified voltages without the necessity of increasing the transformer's voltage rating. Multiplication factors of two, three, and four are common. Voltage multipliers are used in high-voltage, low-current applications such as cathode-ray tubes (CRTs) and particle accelerators.

After completing this section, you should be able to

- **Explain and analyze the operation of diode voltage multipliers**
- Discuss voltage doublers
 - ♦ Explain the half-wave voltage doubler
 - ♦ Explain the full-wave voltage doubler
- Discuss voltage triplers
- Discuss voltage quadruplers

Voltage Doubler

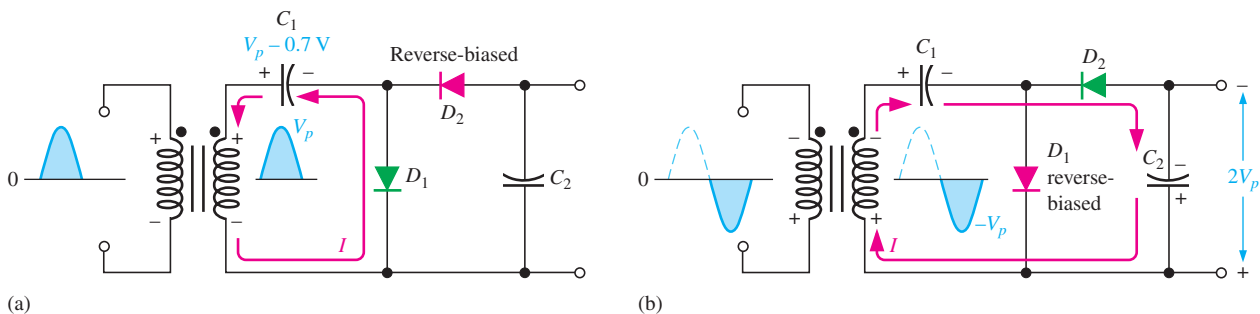
Half-Wave Voltage Doubler A voltage doubler is a **voltage multiplier** with a multiplication factor of two. A half-wave voltage doubler is shown in Figure 2-67. During the positive half-cycle of the secondary voltage, diode D_1 is forward-biased and D_2 is reverse-biased. Capacitor C_1 is charged to the peak of the secondary voltage (V_p) less the diode drop with the polarity shown in part (a). During the negative half-cycle, diode D_2 is forward-biased and D_1 is reverse-biased, as shown in part (b). Since C_1 can't discharge, the peak voltage on C_1 adds to the secondary voltage to charge C_2 to approximately $2V_p$. Applying Kirchhoff's law around the loop as shown in part (b), the voltage across C_2 is

$$V_{C1} - V_{C2} + V_p = 0$$

$$V_{C2} = V_p + V_{C1}$$

Neglecting the diode drop of D_2 , $V_{C1} = V_p$. Therefore,

$$V_{C2} = V_p + V_p = 2V_p$$

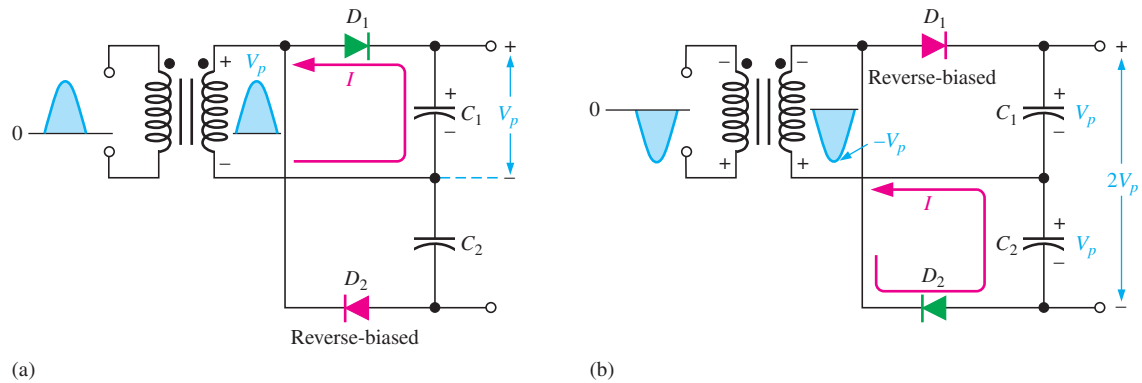


▲ FIGURE 2-67

Half-wave voltage doubler operation. V_p is the peak secondary voltage.

Under a no-load condition, C_2 remains charged to approximately $2V_p$. If a load resistance is connected across the output, C_2 discharges slightly through the load on the next positive half-cycle and is again recharged to $2V_p$ on the following negative half-cycle. The resulting output is a half-wave, capacitor-filtered voltage. The peak inverse voltage across each diode is $2V_p$. If the diode were reversed, the output voltage across C_2 would have the opposite polarity.

Full-Wave Voltage Doubler A full-wave doubler is shown in Figure 2–68. When the secondary voltage is positive, D_1 is forward-biased and C_1 charges to approximately V_p , as shown in part (a). During the negative half-cycle, D_2 is forward-biased and C_2 charges to approximately V_p , as shown in part (b). The output voltage, $2V_p$, is taken across the two capacitors in series.



▲ FIGURE 2–68

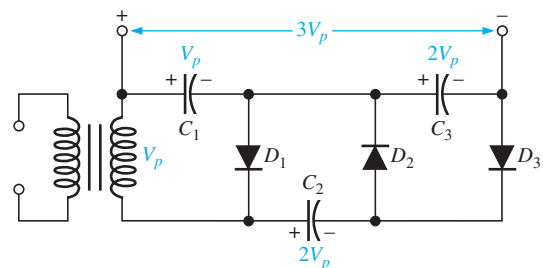
Full-wave voltage doubler operation.

Voltage Tripler

The addition of another diode-capacitor section to the half-wave voltage doubler creates a voltage tripler, as shown in Figure 2–69. The operation is as follows: On the positive half-cycle of the secondary voltage, C_1 charges to V_p through D_1 . During the negative half-cycle, C_2 charges to $2V_p$ through D_2 , as described for the doubler. During the next positive half-cycle, C_3 charges to $2V_p$ through D_3 . The tripler output is taken across C_1 and C_3 , as shown in the figure.

▶ FIGURE 2–69

Voltage tripler.

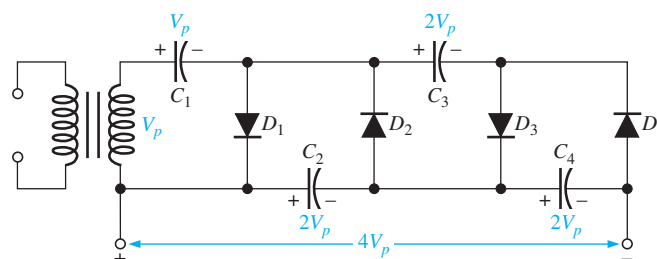


Voltage Quadrupler

The addition of still another diode-capacitor section, as shown in Figure 2–70, produces an output four times the peak secondary voltage. C_4 charges to $2V_p$ through D_4 on a negative half-cycle. The $4V_p$ output is taken across C_2 and C_4 , as shown. In both the tripler and quadrupler circuits, the PIV of each diode is $2V_p$.

▶ FIGURE 2–70

Voltage quadrupler.



SECTION 2–8
CHECKUP

1. What must be the peak voltage rating of the transformer secondary for a voltage doubler that produces an output of 200 V?
2. The output voltage of a quadrupler is 620 V. What minimum PIV rating must each diode have?

2–9 THE DIODE DATASHEET

A manufacturer's datasheet gives detailed information on a device so that it can be used properly in a given application. A typical datasheet provides maximum ratings, electrical characteristics, mechanical data, and graphs of various parameters.

After completing this section, you should be able to

□ **Interpret and use diode datasheets**

- ◆ Define several absolute maximum ratings
- ◆ Define diode thermal characteristics
- ◆ Define several electrical characteristics
- ◆ Interpret the forward current derating curve
- ◆ Interpret the forward characteristic curve
- ◆ Discuss nonrepetitive surge current
- ◆ Discuss the reverse characteristics

Figure 2–71 shows a typical rectifier diode datasheet. The presentation of information on datasheets may vary from one manufacturer to another, but they basically all convey the same information. The mechanical information, such as package dimensions, are not shown on this particular datasheet but are generally available from the manufacturer. Notice on this datasheet that there are three categories of data given in table form and four types of characteristics shown in graphical form.

Data Categories

Absolute Maximum Ratings The absolute maximum ratings indicate the maximum values of the several parameters under which the diode can be operated without damage or degradation. For greatest reliability and longer life, the diode should be operated well under these maximums. Generally, the maximum ratings are specified for an operating ambient temperature (T_A) of 25°C unless otherwise stated. Ambient temperature is the temperature of the air surrounding the device. The parameters given in Figure 2–71 are as follows:

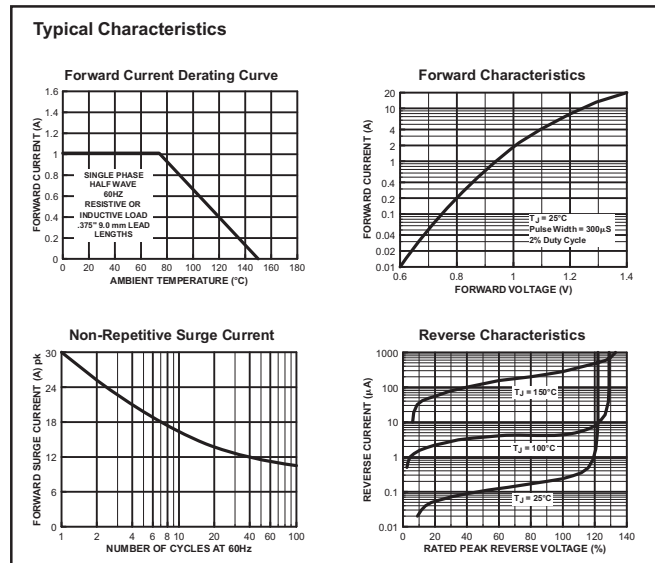
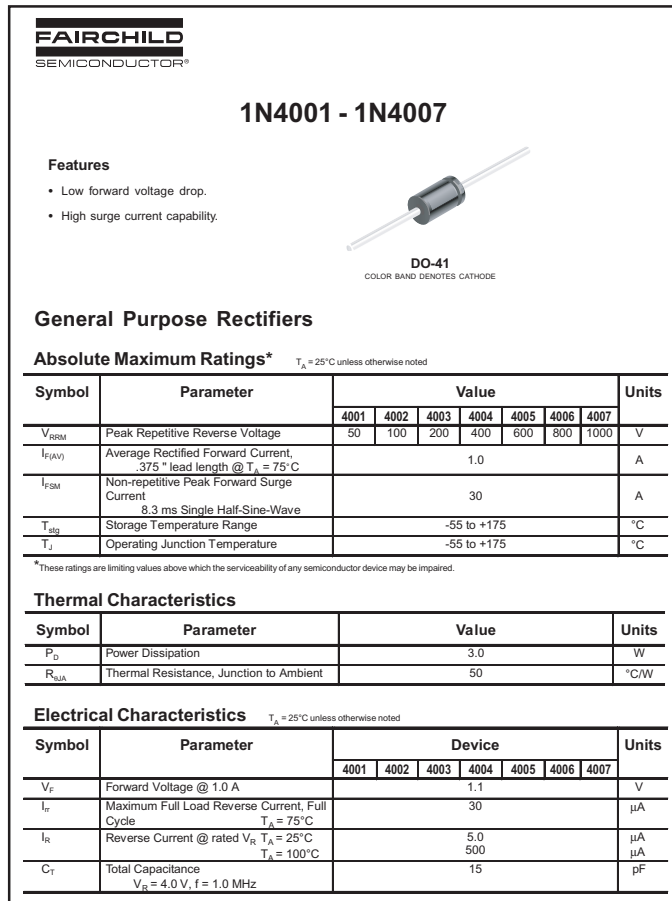
V_{RRM} The peak reverse voltage that can be applied repetitively across the diode. Notice that it is 50 V for the 1N4001 and 1000 V for the 1N4007. This rating is the same as the PIV.

$I_{F(AV)}$ The maximum average value of a 60 Hz half-wave rectified forward current. This current parameter is 1.0 A for all of the diode types and is specified for an ambient temperature of 75°C.

I_{FSM} The maximum peak value of nonrepetitive single half-sine-wave forward surge current with a duration of 8.3 ms. This current parameter is 30 A for all of the diode types.

T_{stg} The allowable range of temperatures at which the device can be kept when not operating or connected to a circuit.

T_J The allowable range of temperatures for the pn junction when the diode is operated in a circuit.



▲ FIGURE 2-71

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Thermal Characteristics All devices have a limit on the amount of heat that they can tolerate without failing in some way.

P_D Average power dissipation is the amount of power that the diode can dissipate under any condition. A diode should never be operated at maximum power, except for brief periods, to assure reliability and longer life.

$R_{\theta JA}$ Thermal resistance from the diode junction to the surrounding air. This indicates the ability of the device material to resist the flow of heat and specifies the number of degrees difference between the junction and the surrounding air for each watt transferred from the junction to the air.

Electrical Characteristics The electrical characteristics are specified under certain conditions and are the same for each type of diode. These values are typical and can be more or less for a given diode. Some datasheets provide a minimum and a maximum value in addition to a typical value for a parameter.

V_F The forward voltage drop across the diode when there is 1 A of forward current. To determine the forward voltage for other values of forward current, you must examine the forward characteristics graph.

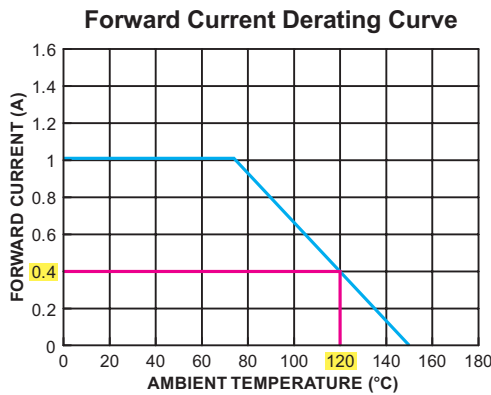
I_{TR} Maximum full load reverse current averaged over a full ac cycle at 75°C .

I_R The reverse current at the rated reverse voltage (V_{RRM}). Values are specified at two different ambient temperatures.

C_T This is the total diode capacitance including the junction capacitance in reverse bias at a frequency of 1 MHz. Most of the time this parameter is not important in low-frequency applications, such as power supply rectifiers.

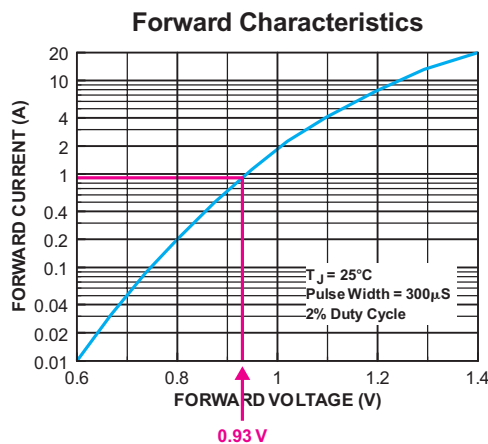
Graphical Characteristics

The Forward Current Derating Curve This curve on the datasheet in Figure 2–71 shows maximum forward diode current $I_{F(AV)}$ in amps versus the ambient temperature. Up to about 75°C, the diode can handle a maximum of 1 A. Above 75°C, the diode cannot handle 1 A, so the maximum current must be derated as shown by the curve. For example, if a diode is operating in an ambient temperature of 120°C, it can handle only a maximum of 0.4 A, as shown in Figure 2–72.



◀ FIGURE 2–72

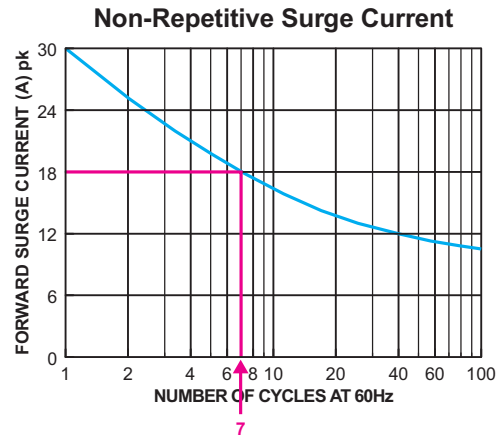
Forward Characteristics Curve Another graph from the datasheet shows instantaneous forward current as a function of instantaneous forward voltage. As indicated, data for this curve is derived by applying 300 μs pulses with a duty cycle of 2%. Notice that this graph is for $T_J = 25^\circ\text{C}$. For example, a forward current of 1 A corresponds to a forward voltage of about 0.93 V, as shown in Figure 2–73.



◀ FIGURE 2–73

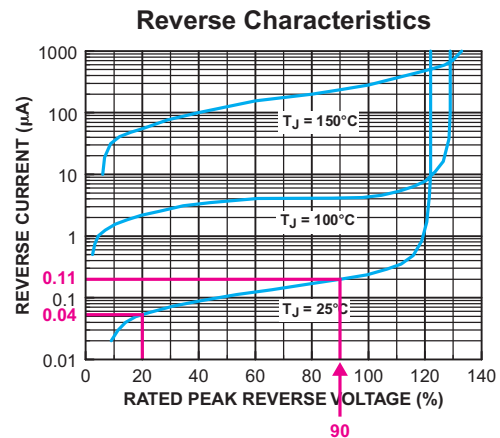
Nonrepetitive Surge Current This graph from the datasheet shows I_{FSM} as a function of the number of cycles at 60 Hz. For a one-time surge, the diode can withstand 30 A. However, if the surges are repeated at a frequency of 60 Hz, the maximum surge current decreases. For example, if the surge is repeated 7 times, the maximum current is 18 A, as shown in Figure 2–74.

▶ FIGURE 2-74



Reverse Characteristics This graph from the datasheet shows how the reverse current varies with the reverse voltage for three different junction temperatures. The horizontal axis is the percentage of maximum reverse voltage, V_{RRM} . For example, at 25°C, a 1N4001 has a reverse current of approximately 0.04 μA at 20% of its maximum V_{RRM} or 10 V. If the V_{RRM} is increased to 90%, the reverse current increases to approximately 0.11 μA , as shown in Figure 2-75.

▶ FIGURE 2-75



SECTION 2-9 CHECKUP

1. Determine the peak repetitive reverse voltage for each of the following diodes: 1N4002, 1N4003, 1N4004, 1N4005, 1N4006.
2. If the forward current is 800 mA and the forward voltage is 0.75 V in a 1N4005, is the power rating exceeded?
3. What is $I_{F(AV)}$ for a 1N4001 at an ambient temperature of 100°C?
4. What is I_{FSM} for a 1N4003 if the surge is repeated 40 times at 60 Hz?

2-10 TROUBLESHOOTING

This section provides a general overview and application of an approach to troubleshooting. Specific troubleshooting examples of the power supply and diode circuits are covered.

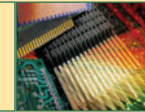
After completing this section, you should be able to

- **Troubleshoot diodes and power supply circuits**
- Test a diode with a DMM
 - ◆ Use the diode test position
 - ◆ Determine if the diode is good or bad
 - ◆ Use the Ohms function to check a diode
- Troubleshoot a dc power supply by analysis, planning, and measurement
 - ◆ Use the half-splitting method
- Perform fault analysis
 - ◆ Isolate fault to a single component



Chapter 18: Basic Programming Concepts for Automated Testing

Selected sections from Chapter 18 may be introduced as part of this troubleshooting coverage or, optionally, the entire Chapter 18 may be covered later or not at all.



Testing a Diode

A multimeter can be used as a fast and simple way to check a diode out of the circuit. A good diode will show an extremely high resistance (ideally an open) with reverse bias and a very low resistance with forward bias. A defective open diode will show an extremely high resistance (or open) for both forward and reverse bias. A defective shorted or resistive diode will show zero or a low resistance for both forward and reverse bias. An open diode is the most common type of failure.

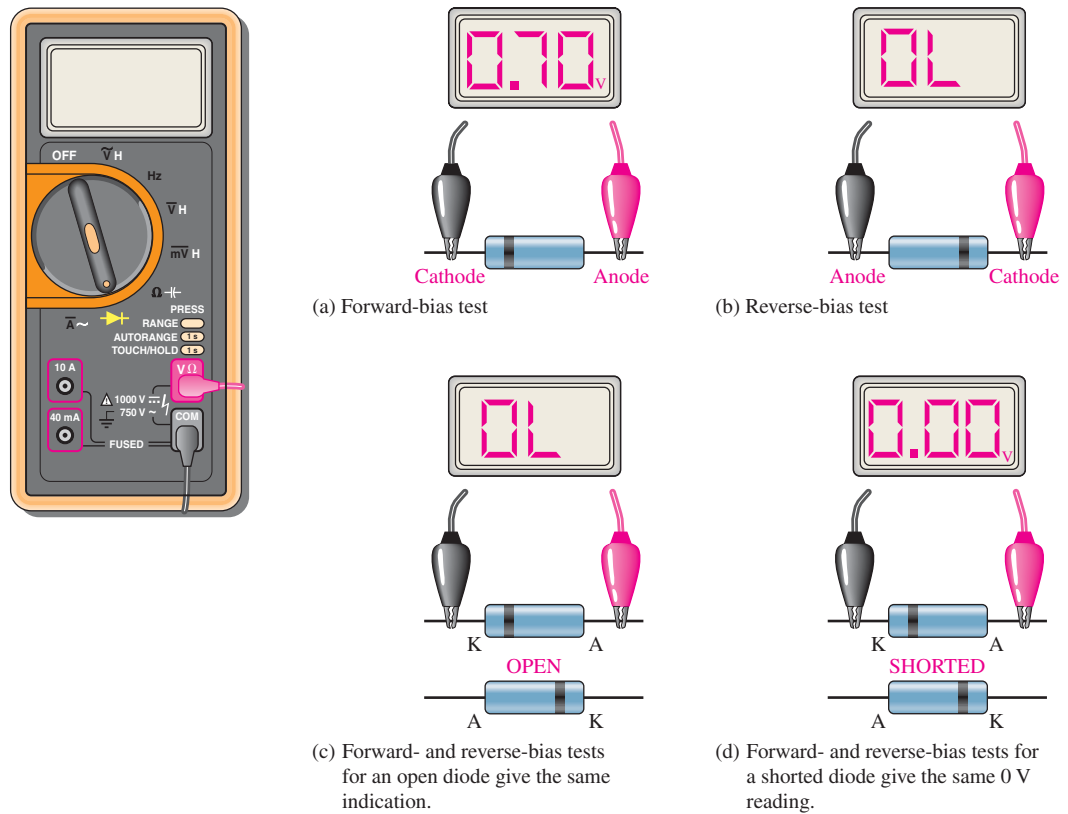
The DMM Diode Test Position Many digital multimeters (DMMs) have a diode test function that provides a convenient way to test a diode. A typical DMM, as shown in Figure 2–76, has a small diode symbol to mark the position of the function switch. When set to *diode test*, the meter provides an internal voltage sufficient to forward-bias and reverse-bias a diode. This internal voltage may vary among different makes of DMM, but 2.5 V to 3.5 V is a typical range of values. The meter provides a voltage reading or other indication to show the condition of the diode under test.

When the Diode Is Working In Figure 2–76(a), the red (positive) lead of the meter is connected to the anode and the black (negative) lead is connected to the cathode to forward-bias the diode. If the diode is good, you will get a reading of between approximately 0.5 V and 0.9 V, with 0.7 V being typical for forward bias.

In Figure 2–76(b), the diode is turned around for reverse bias as shown. If the diode is working properly, you will typically get a reading of “OL”. Some DMMs may display the internal voltage for a reverse-bias condition.

When the Diode Is Defective When a diode has failed open, you get an out-of-range “OL” indication for both the forward-bias and the reverse-bias conditions, as illustrated in Figure 2–76(c). If a diode is shorted, the meter reads 0 V in both forward- and reverse-bias tests, as indicated in part (d).

Checking a Diode with the OHMs Function DMMs that do not have a diode test position can be used to check a diode by setting the function switch on an OHMs range. For a forward-bias check of a good diode, you will get a resistance reading that can vary depending on the meter’s internal battery. Many meters do not have sufficient voltage on the OHMs setting to fully forward-bias a diode and you may get a reading of from several hundred to several thousand ohms. For the reverse-bias check of a good diode, you will get an



▲ FIGURE 2-76

Testing a diode out-of-circuit with a DMM.

out-of-range indication such as “OL” on most DMMs because the reverse resistance is too high for the meter to measure.

Even though you may not get accurate forward- and reverse-resistance readings on a DMM, the relative readings indicate that a diode is functioning properly, and that is usually all you need to know. The out-of-range indication shows that the reverse resistance is extremely high, as you expect. The reading of a few hundred to a few thousand ohms for forward bias is relatively small compared to the reverse resistance, indicating that the diode is working properly. The actual resistance of a forward-biased diode is typically much less than 100 Ω .

Troubleshooting a Power Supply

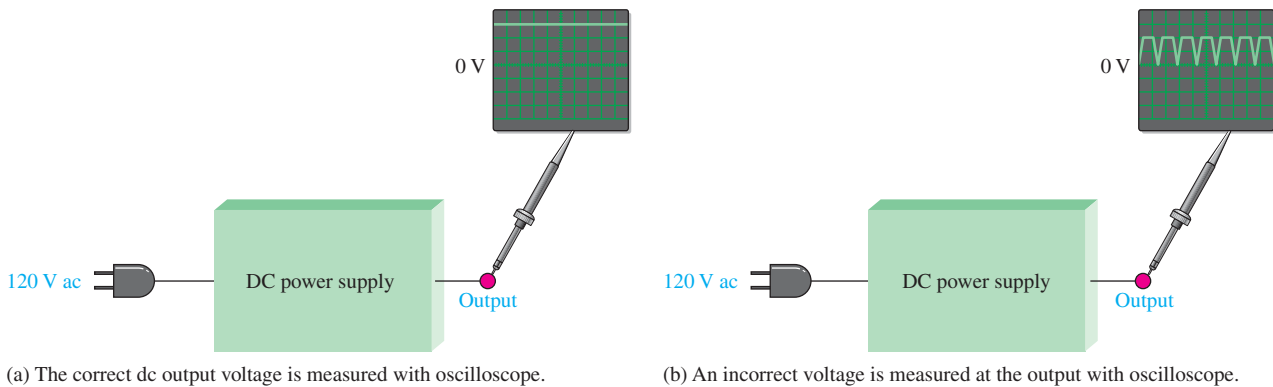
Troubleshooting is the application of logical thinking combined with a thorough knowledge of circuit or system operation to identify and correct a malfunction. A systematic approach to troubleshooting consists of three steps: *analysis*, *planning*, and *measuring*.

A defective circuit or system is one with a known good input but with no output or an incorrect output. For example, in Figure 2-77(a), a properly functioning dc power supply is represented by a single block with a known input voltage and a correct output voltage. A defective dc power supply is represented in part (b) as a block with an input voltage and an incorrect output voltage.

Analysis The first step in troubleshooting a defective circuit or system is to analyze the problem, which includes identifying the symptom and eliminating as many causes as possible. In the case of the power supply example illustrated in Figure 2-77(b), the symptom is that the output voltage is not a constant regulated dc voltage. This symptom does not tell you much about what the specific cause may be. In other situations, however, a particular symptom may point to a given area where a fault is most likely.

SAFETY NOTE

When working with low-voltage power supplies, be careful not to come in contact with the 120 V ac line. Severe shock or worse could result. To verify input voltage to a rectifier, it is always better to check at the transformer secondary instead of trying to measure the line voltage directly. If it becomes necessary to measure the line voltage, use a multimeter and be careful.



▲ FIGURE 2-77

Block representations of functioning and nonfunctioning power supplies.

The first thing you should do in analyzing the problem is to try to eliminate any obvious causes. In general, you should start by making sure the power cord is plugged into an active outlet and that the fuse is not blown. In the case of a battery-powered system, make sure the battery is good. Something as simple as this is sometimes the cause of a problem. However, in this case, there must be power because there is an output voltage.

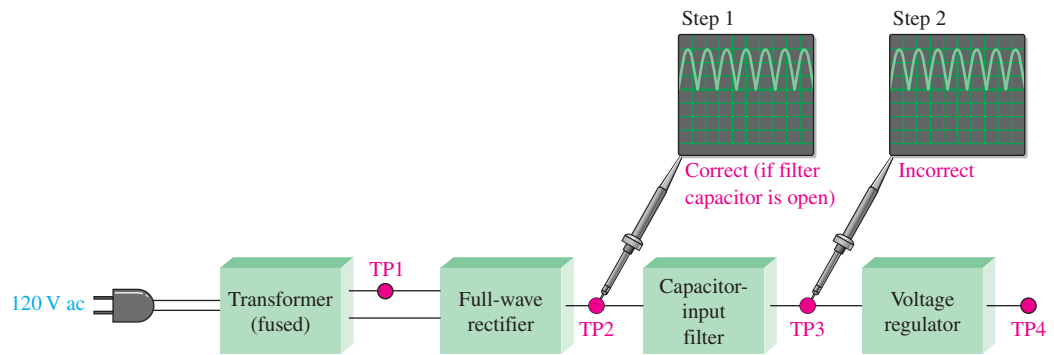
Beyond the power check, use your senses to detect obvious defects, such as a burned resistor, broken wire, loose connection, or an open fuse. Since some failures are temperature dependent, you can sometimes find an overheated component by touch. However, be very cautious in a live circuit to avoid possible burn or shock. For intermittent failures, the circuit may work properly for awhile and then fail due to heat buildup. As a rule, you should always do a sensory check as part of the analysis phase before proceeding.

Planning In this phase, you must consider how you will attack the problem. There are three possible approaches to troubleshooting most circuits or systems.

1. Start at the input (the transformer secondary in the case of a dc power supply) where there is a known input voltage and work toward the output until you get an incorrect measurement. When you find no voltage or an incorrect voltage, you have narrowed the problem to the part of the circuit between the last test point where the voltage was good and the present test point. In all troubleshooting approaches, you must know what the voltage is supposed to be at each point in order to recognize an incorrect measurement when you see it.
2. Start at the output of a circuit and work toward the input. Check for voltage at each test point until you get a correct measurement. At this point, you have isolated the problem to the part of the circuit between the last test point and the current test point where the voltage is correct.
3. Use the half-splitting method and start in the middle of the circuit. If this measurement shows a correct voltage, you know that the circuit is working properly from the input to that test point. This means that the fault is between the current test point and the output point, so begin tracing the voltage from that point toward the output. If the measurement in the middle of the circuit shows no voltage or an incorrect voltage, you know that the fault is between the input and that test point. Therefore, begin tracing the voltage from the test point toward the input.

For illustration, let's say that you decide to apply the half-splitting method using an oscilloscope.

Measurement The half-splitting method is illustrated in Figure 2-78 with the measurements indicating a particular fault (open filter capacitor in this case). At test point 2 (TP2) you observe a full-wave rectified voltage that indicates that the transformer and rectifier

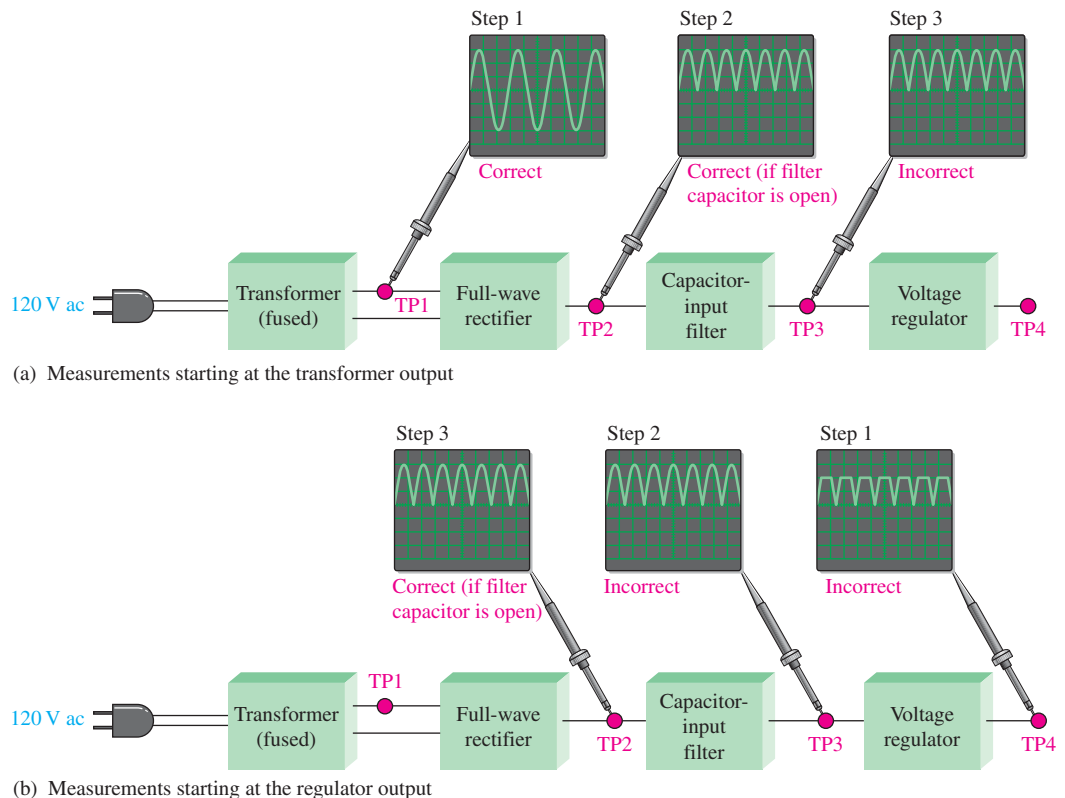


▲ FIGURE 2-78

Example of the half-splitting approach. An open filter capacitor is indicated.

are working properly. This measurement also indicates that the filter capacitor is open, which is verified by the full-wave voltage at TP3. If the filter were working properly, you would measure a dc voltage at both TP2 and TP3. If the filter capacitor were shorted, you would observe no voltage at all of the test points because the fuse would most likely be blown. A short anywhere in the system is very difficult to isolate because, if the system is properly fused, the fuse will blow immediately when a short to ground develops.

For the case illustrated in Figure 2-78, the half-splitting method took two measurements to isolate the fault to the open filter capacitor. If you had started from the transformer output, it would have taken three measurements; and if you had started at the final output, it would have also taken three measurements, as illustrated in Figure 2-79.



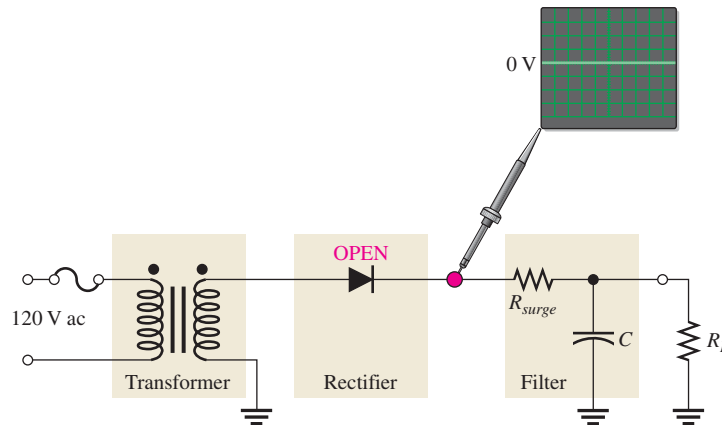
▲ FIGURE 2-79

In this particular case, the two other approaches require more oscilloscope measurements than the half-splitting approach in Figure 2-78.

Fault Analysis

In some cases, after isolating a fault to a particular circuit, it may be necessary to isolate the problem to a single component in the circuit. In this event, you have to apply logical thinking and your knowledge of the symptoms caused by certain component failures. Some typical component failures and the symptoms they produce are now discussed.

Effect of an Open Diode in a Half-Wave Rectifier A half-wave filtered rectifier with an open diode is shown in Figure 2–80. The resulting symptom is zero output voltage as indicated. This is obvious because the open diode breaks the current path from the transformer secondary winding to the filter and load resistor and there is no load current.

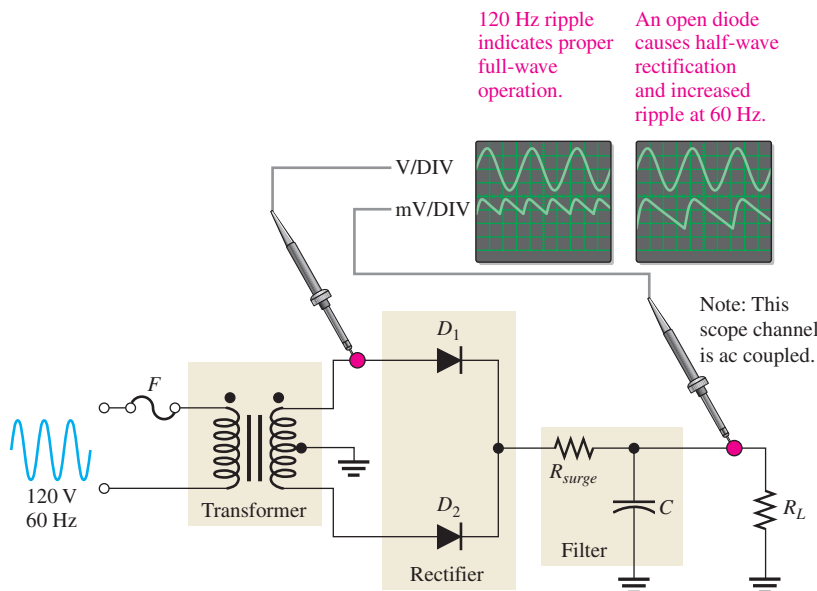


◀ **FIGURE 2–80**

The effect of an open diode in a half-wave rectifier is an output of 0 V.

Other faults that will cause the same symptom in this circuit are an open transformer winding, an open fuse, or no input voltage.

Effect of an Open Diode in a Full-Wave Rectifier A full-wave center-tapped filtered rectifier is shown in Figure 2–81. If either of the two diodes is open, the output voltage will have twice the normal ripple voltage at 60 Hz rather than at 120 Hz, as indicated.



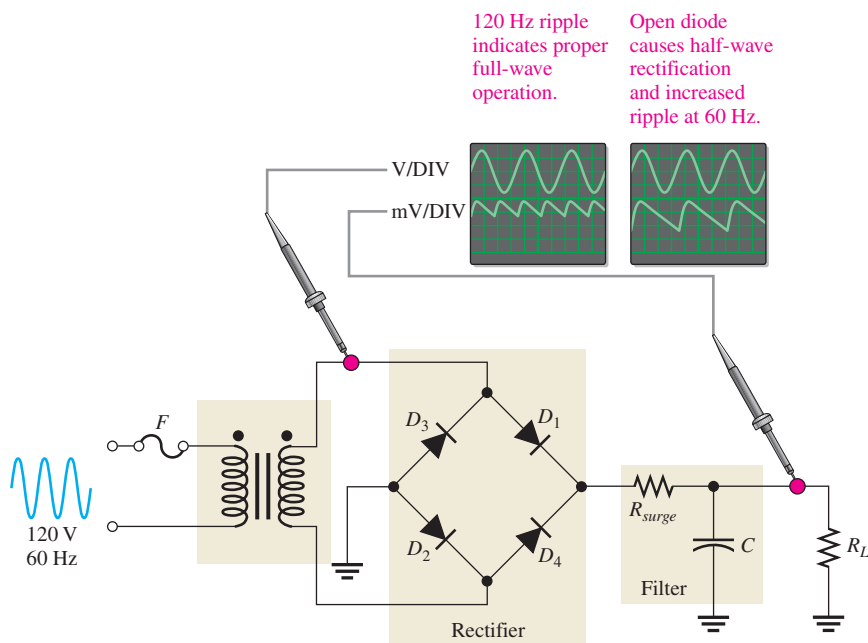
▲ **FIGURE 2–81**

The effect of an open diode in a center-tapped rectifier is half-wave rectification and twice the ripple voltage at 60 Hz.

Another fault that will cause the same symptom is an open in the transformer secondary winding.

The reason for the increased ripple at 60 Hz rather than at 120 Hz is as follows. If one of the diodes in Figure 2–81 is open, there is current through R_L only during one half-cycle of the input voltage. During the other half-cycle of the input, the open path caused by the open diode prevents current through R_L . The result is half-wave rectification, as shown in Figure 2–81, which produces the larger ripple voltage with a frequency of 60 Hz.

An open diode in a full-wave bridge rectifier will produce the same symptom as in the center-tapped circuit, as shown in Figure 2–82. The open diode prevents current through R_L during half of the input voltage cycle. The result is half-wave rectification, which produces double the ripple voltage at 60 Hz.



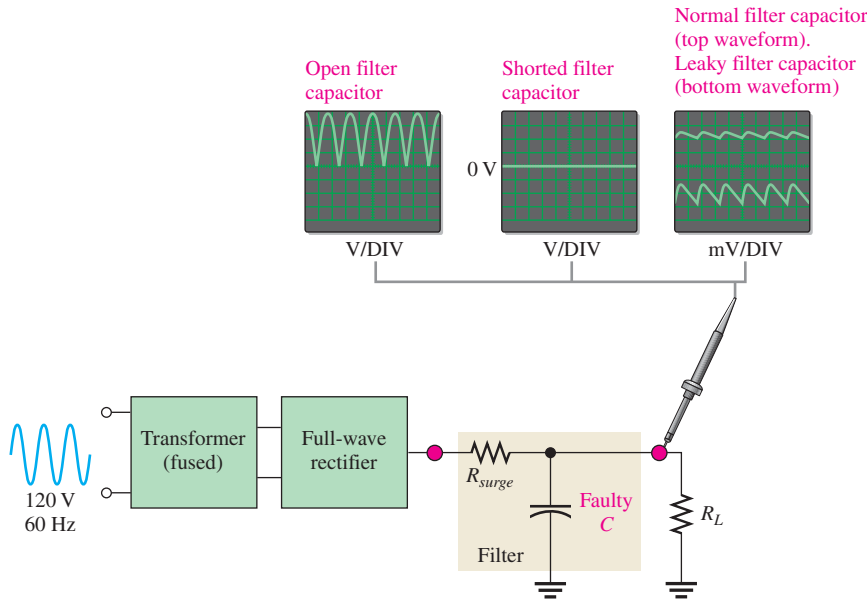
▲ FIGURE 2–82

Effect of an open diode in a bridge rectifier.

Effects of a Faulty Filter Capacitor Three types of defects of a filter capacitor are illustrated in Figure 2–83.

- ♦ *Open* If the filter capacitor for a full-wave rectifier opens, the output is a full-wave rectified voltage.
- ♦ *Shorted* If the filter capacitor shorts, the output is 0 V. A shorted capacitor should cause the fuse to blow open. If not properly fused, a shorted capacitor may cause some or all of the diodes in the rectifier to burn open due to excessive current. In any event, the output is 0 V.
- ♦ *Leaky* A leaky filter capacitor is equivalent to a capacitor with a parallel leakage resistance. The effect of the leakage resistance is to reduce the time constant and allow the capacitor to discharge more rapidly than normal. This results in an increase in the ripple voltage on the output. This fault is rare.

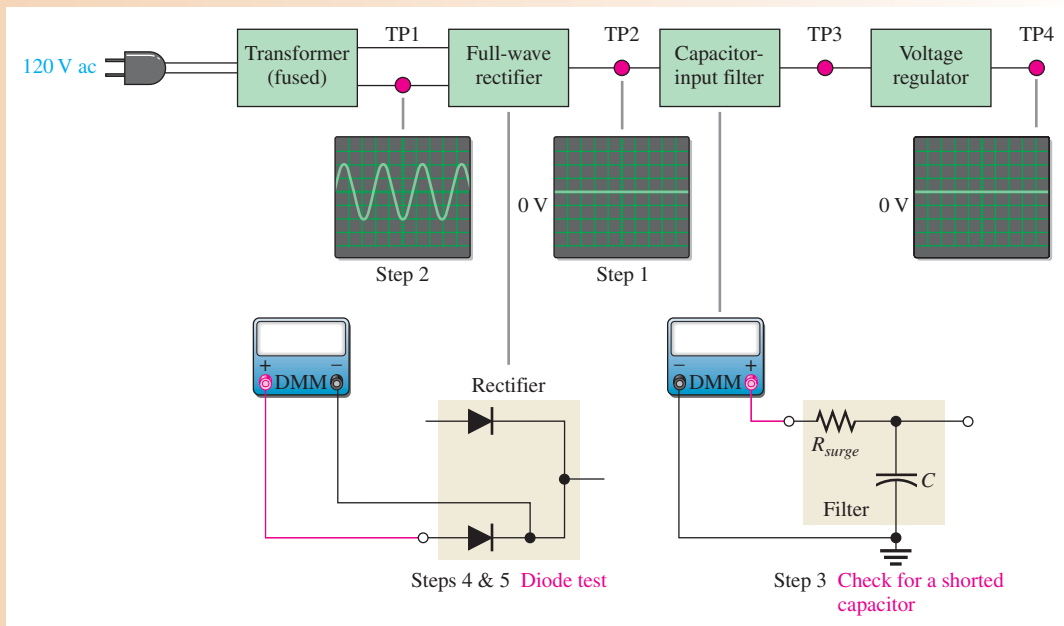
Effects of a Faulty Transformer An open primary or secondary winding of a power supply transformer results in an output of 0 V, as mentioned before.



◀ **FIGURE 2-83**
Effects of a faulty filter capacitor.

EXAMPLE 2-14

You are troubleshooting the power supply shown in the block diagram of Figure 2-84. You have found in the analysis phase that there is no output voltage from the regulator, as indicated. Also, you have found that the unit is plugged into the outlet and have verified the input to the transformer with a DMM. You decide to use the half-splitting method using the scope. What is the problem?



▲ **FIGURE 2-84**

Solution The step-by-step measurement procedure is illustrated in the figure and described as follows.

Step 1: There is no voltage at test point 2 (TP2). This indicates that the fault is between the input to the transformer and the output of the rectifier. Most

likely, the problem is in the transformer or in the rectifier, but there may be a short from the filter input to ground.

- Step 2:** The voltage at test point 1 (TP1) is correct, indicating that the transformer is working. So, the problem must be in the rectifier or a shorted filter input.
- Step 3:** With the power turned off, use a DMM to check for a short from the filter input to ground. Assume that the DMM indicates no short. The fault is now isolated to the rectifier.
- Step 4:** Apply fault analysis to the rectifier circuit. Determine the component failure in the rectifier that will produce a 0 V input. If only one of the diodes in the rectifier is open, there should be a half-wave rectified output voltage, so this is not the problem. In order to have a 0 V output, there must be an open in the rectifier circuit.
- Step 5:** With the power off, use the DMM in the diode test mode to check each diode. Replace the defective diodes, turn the power on, and check for proper operation. Assume this corrects the problem.

Related Problem Suppose you had found a short in Step 3, what would have been the logical next step?



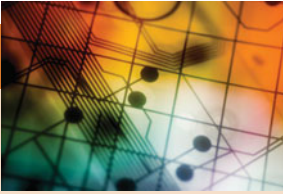
Multisim Troubleshooting Exercises

These file circuits are in the Troubleshooting Exercises folder on the companion website. Open each file and determine if the circuit is working properly. If it is not working properly, determine the fault.

1. Multisim file TSE02-01
2. Multisim file TSE02-02
3. Multisim file TSE02-03
4. Multisim file TSE02-04

SECTION 2-10 CHECKUP

1. A properly functioning diode will produce a reading in what range when forward-biased?
2. What reading might a DMM produce when a diode is reverse-biased?
3. What effect does an open diode have on the output voltage of a half-wave rectifier?
4. What effect does an open diode have on the output voltage of a full-wave rectifier?
5. If one of the diodes in a bridge rectifier shorts, what are some possible consequences?
6. What happens to the output voltage of a rectifier if the filter capacitor becomes very leaky?
7. The primary winding of the transformer in a power supply opens. What will you observe on the rectifier output?
8. The dc output voltage of a filtered rectifier is less than it should be. What may be the problem?



Application Activity: DC Power Supply

Assume that you are working for a company that designs, tests, manufactures, and markets various electronic instruments including dc power supplies. Your first assignment is to develop and test a basic unregulated power supply using the knowledge that you have acquired so far. Later modifications will include the addition of a regulator. The power supply must meet or exceed the following specifications:

- ♦ Input voltage: 120 V rms @60 Hz
- ♦ Output voltage: 16 V dc $\pm 10\%$
- ♦ Ripple factor (max): 3.00%
- ♦ Load current (max): 250 mA

Design of the Power Supply

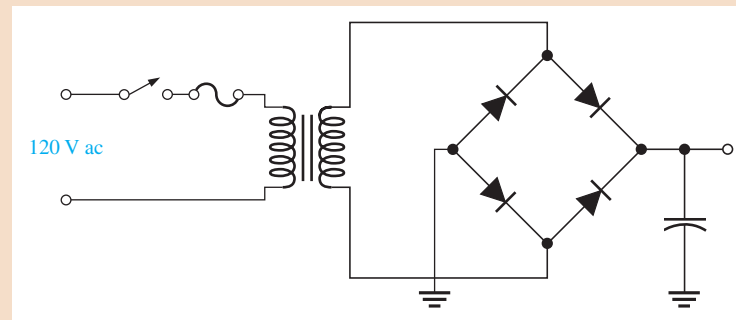
The Rectifier Circuit A full-wave rectifier has less ripple for a given filter capacitor than a half-wave rectifier. A full-wave bridge rectifier is probably the best choice because it provides the most output voltage for a given input voltage and the PIV is less than for a center-tapped rectifier. Also, the full-wave bridge does not require a center-tapped transformer.

1. Compare Equations 2-7 and 2-9 for output voltages.
2. Compare Equations 2-8 and 2-10 for PIV.

The full-wave bridge rectifier circuit is shown in Figure 2-85.

► FIGURE 2-85

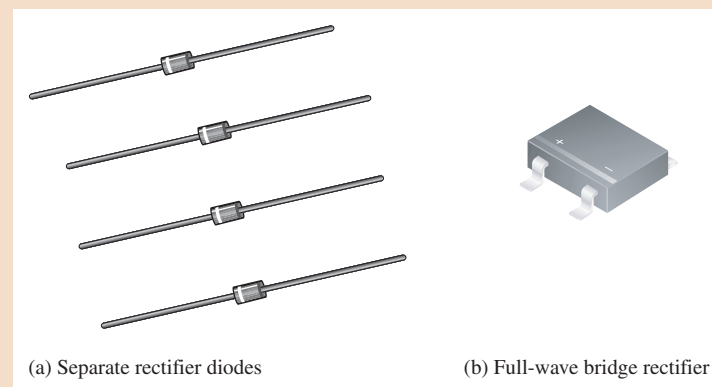
Power supply with full-wave bridge rectifier and capacitor filter.



The Rectifier Diodes There are two approaches for implementing the full-wave bridge: Four individual diodes, as shown in Figure 2-86(a) or a single IC package containing four diodes connected as a bridge rectifier, as shown in part (b).

► FIGURE 2-86

Rectifier components.



Because the rectifier in the single IC package exceeds the specifications and requires less wiring on a board, takes up less space, and requires stocking and handling of only one component versus four, it is the best choice. Another factor to consider is the cost. Requirements for the diodes in the bridge are

- ◆ Forward current rating must be equal or greater than 250 mA (maximum load current).
- ◆ PIV must be greater than the minimum calculated value of 16.7 V ($PIV = V_{p(out)} + 0.7 V$).

By reviewing manufacturer's datasheets on-line, a specific device can be chosen. Figure 2–87 shows a partial datasheet for the rectifier to be used for this power supply. Notice that it exceeds the specified requirements. Four possible websites for rectifiers and diodes are *fairchildsemiconductor.com*; *onsemi.com*; *semiconductor.phillips.com*; and *rectron.com*.

► FIGURE 2–87

Rectifier datasheet. You can view the entire datasheet at www.fairchildsemiconductor.com. Copyright Fairchild Semiconductor Corporation. Used by permission.

Symbol		Parameter	Value					Units
			1S	2S	4S	6S	8S	
V_{RRM}		Maximum Repetitive Reverse Voltage	100	200	400	600	800	V
V_{RMS}		Maximum RMS Bridge Input Voltage	70	140	280	420	560	V
V_R		DC Reverse Voltage (Rated V_R)	100	200	400	600	800	V
$I_{F(AV)}$		Average Rectified Forward Current, @ $T_A = 50^\circ\text{C}$	0.5					A
I_{FSM}		Non-repetitive Peak Forward Surge Current 8.3 ms Single Half-Sine-Wave	35					A
T_{STG}		Storage Temperature Range	-55 to +150					$^\circ\text{C}$
T_J		Operating Junction Temperature	-55 to +150					$^\circ\text{C}$

*These ratings are limiting values above which the serviceability of any semiconductor device may be impaired.

Symbol	Parameter	Value	Units
P_D	Power Dissipation	1.4	W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient,* per leg	85	$^\circ\text{C}/\text{W}$
$R_{\theta JL}$	Thermal Resistance, Junction to Lead,* per leg	20	$^\circ\text{C}/\text{W}$

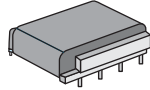
*Device mounted on PCB with 0.5-0.5" (13x13 mm) lead length.

Symbol	Parameter	Device	Units
V_F	Forward Voltage, per bridge @ 0.5 A	1.0	V
I_R	Reverse Current, per leg @ rated V_R	5.0 0.5	A mA
	t rating for fusing t < 8.3 ms	5.0	A's
C_T	Total Capacitance, per leg $V_R = 4.0 V, f = 1.0 \text{ MHz}$	13	pF

The Transformer The transformer must convert the 120 V line voltage to an ac voltage that will result in a rectified voltage that will produce $16 V \pm 10\%$ when filtered. A typical power transformer for mounting on a printed circuit board and a portion of a datasheet for

the series are shown in Figure 2–88. Notice that transformer power is measured in VA (volt-amperes), not watts.

3. Use Equation 2–9 to calculate the required transformer secondary rms voltage.
4. From the partial datasheet in Figure 2–88, select an appropriate transformer based on its secondary voltage (series) and a VA specification that meets the requirement.
5. Determine the required fuse rating.



VA	Secondary		Dimensions					Wt. Oz.
	Series	Parallel	H	W	L	A	B	
2.5	10.0V CT @ 0.25A	5.0V @ 0.5A	0.650	1.562	1.875	1.600	0.375	5
2.5	12.6V CT @ 0.2A	6.3V @ 0.4A	0.650	1.562	1.875	1.600	0.375	5
2.5	16.0V CT @ 0.15A	8.0V @ 0.3A	0.650	1.562	1.875	1.600	0.375	5
2.5	20.0V CT @ 0.125A	10.0V @ 0.25A	0.650	1.562	1.875	1.600	0.375	5
2.5	24.0V CT @ 0.1A	12.0V @ 0.2A	0.650	1.562	1.875	1.600	0.375	5
2.5	30.0V CT @ 0.08A	15.0V @ 0.16A	0.650	1.562	1.875	1.600	0.375	5
2.5	34.0V CT @ 0.076A	17.0V @ 0.15A	0.650	1.562	1.875	1.600	0.375	5
2.5	40.0V CT @ 0.06A	20.0V @ 0.12A	0.650	1.562	1.875	1.600	0.375	5
2.5	56.0V CT @ 0.045A	28.0V @ 0.09A	0.650	1.562	1.875	1.600	0.375	5
2.5	88.0V CT @ 0.028A	44.0V @ 0.056A	0.650	1.562	1.875	1.600	0.375	5
2.5	120.0V CT @ 0.02A	60.0V @ 0.04A	0.650	1.562	1.875	1.600	0.375	5
2.5	230.0V CT @ 0.01A	115.0V @ 0.02A	0.650	1.562	1.875	1.600	0.375	5
6.0	10.0V CT @ 0.6A	5.0V @ 1.2A	0.875	1.562	1.875	1.600	0.375	7
6.0	12.0V CT @ 0.475A	6.3V @ 0.95A	0.875	1.562	1.875	1.600	0.375	7
6.0	16.0V CT @ 0.375A	8.0V @ 0.75A	0.875	1.562	1.875	1.600	0.375	7
6.0	20.0V CT @ 0.3A	10.0V @ 0.6A	0.875	1.562	1.875	1.600	0.375	7
6.0	24.0V CT @ 0.25A	12.0V @ 0.5A	0.875	1.562	1.875	1.600	0.375	7

▲ FIGURE 2–88

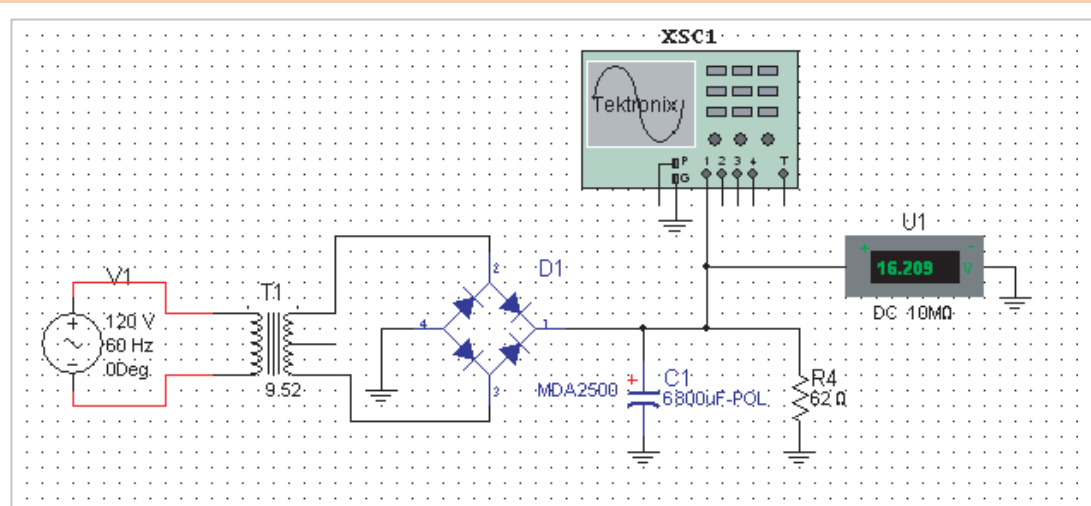
Typical pc-mounted power transformer and data. Volts are rms.

The Filter Capacitor The capacitance of the filter capacitor must be sufficiently large to provide the specified ripple.

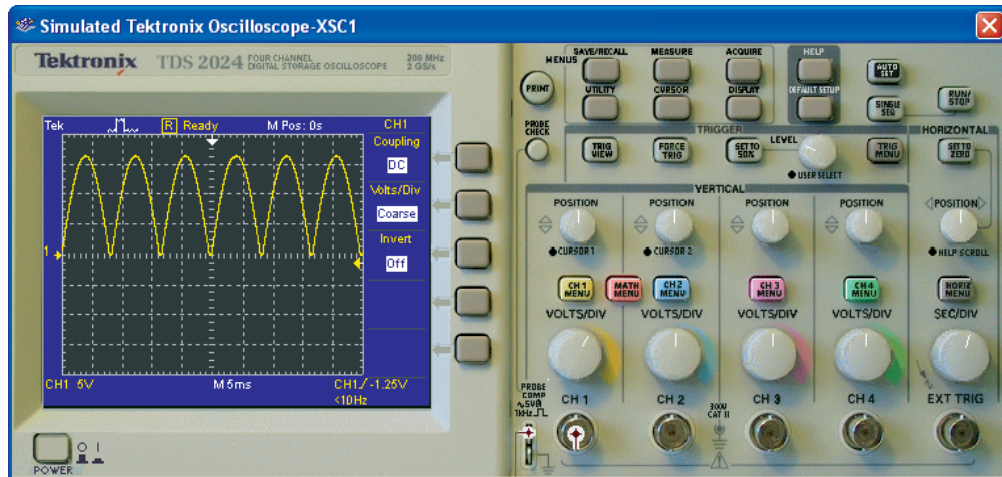
6. Use Equation 2–11 to calculate the peak-to-peak ripple voltage, assuming $V_{DC} = 16\text{ V}$.
7. Use Equation 2–12 to calculate the minimum capacitance value. Use $R_L = 64\ \Omega$, calculated on page 89.

Simulation

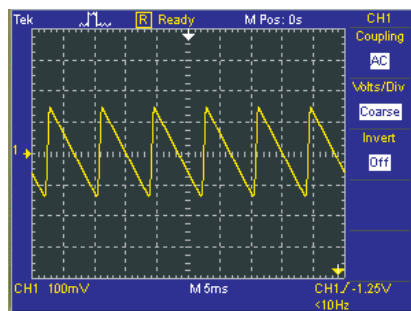
In the development of a new circuit, it is sometimes helpful to simulate the circuit using a software program before actually building it and committing it to hardware. We will use Multisim to simulate this power supply circuit. Figure 2–89 shows the simulated power



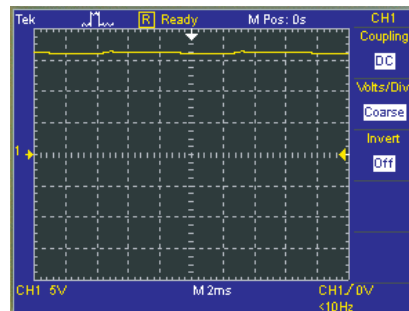
(a) Multisim circuit screen



(b) Output voltage without the filter capacitor



(c) Ripple voltage is less than 300 mV pp



(d) DC output voltage with filter capacitor (near top of screen)

▲ **FIGURE 2-89**
Power supply simulation.

supply circuit with a load connected and scope displays of the output voltage with and without the filter capacitor connected. The filter capacitor value of $6800\ \mu\text{F}$ is the next highest standard value closest to the minimum calculated value required. A load resistor value was chosen to draw a current equal to or greater than the specified maximum load current.

$$R_L = \frac{16\ \text{V}}{250\ \text{mA}} = 64\ \Omega$$

The closest standard value is $62\ \Omega$, which draws $258\ \text{mA}$ at $16\ \text{V}$ and which meets and exceeds the load current specification.

8. Determine the power rating for the load resistor.

To produce a dc output of $16\ \text{V}$, a peak secondary voltage of $16\ \text{V} + 1.4\ \text{V} = 17.4\ \text{V}$ is required. The rms secondary voltage must be

$$V_{\text{rms}(\text{sec})} = 0.707V_{\text{p}(\text{sec})} = 0.707(16\ \text{V} + 1.4\ \text{V}) = 12.3\ \text{V}$$

A standard transformer rms output voltage is $12.6\ \text{V}$. The transformer specification required by Multisim is

$$120\ \text{V}:12.6\ \text{V} = 9.52:1$$

The dc voltmeter in Figure 2–89(a) indicates an output voltage of $16.209\ \text{V}$, which is well within the $16\ \text{V} \pm 10\%$ requirement. In part (c), the scope is AC coupled and set at $100\ \text{mV/division}$. You can see that the peak-to-peak ripple voltage is less than $300\ \text{mV}$, which is less than $480\ \text{mV}$, corresponding to the specified maximum ripple factor of 3% .



SAFETY NOTE

Be very careful to not touch the line voltage connections to the transformer primary. In normal practice, the board is housed in a protective box to prevent the possibility of contact with the $120\ \text{V}$ ac line.



Build and simulate the circuit using your Multisim software. Observe the operation with the virtual oscilloscope and voltmeter.

Prototyping and Testing

Now that all the components have been selected, the prototype circuit is constructed and tested. After the circuit is successfully tested, it is ready to be finalized on a printed circuit board.

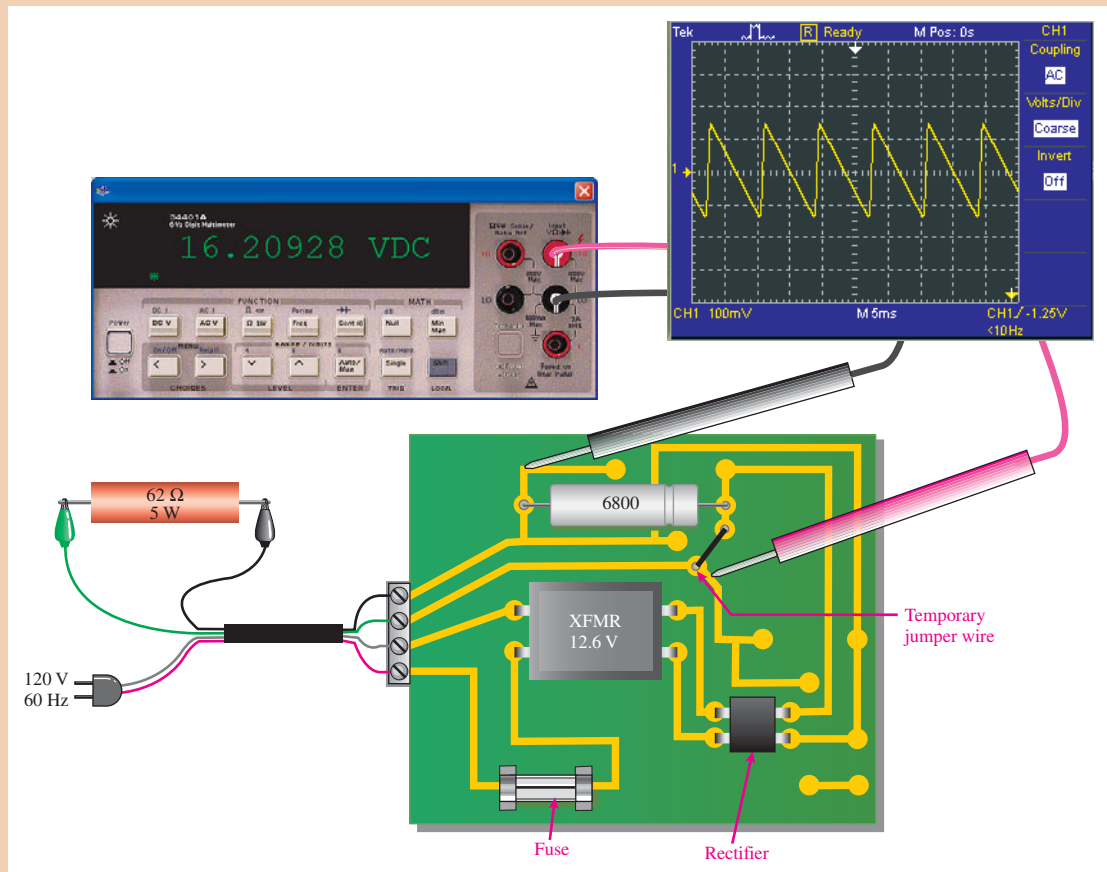
Lab Experiment



To build and test a similar circuit, go to Experiment 2 in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

The Printed Circuit Board

The circuit board is shown in Figure 2–90. There are additional traces and connection points on the board for expansion to a regulated power supply, which will be done in Chapter 3. The circuit board is connected to the ac voltage and to a power load resistor via a cable. The power switch shown in the original schematic will be on the PC board housing and is not shown for the test setup. A DMM measurement of the output voltage indicates a correct value. Oscilloscope measurement of the ripple shows that it is within specifications.

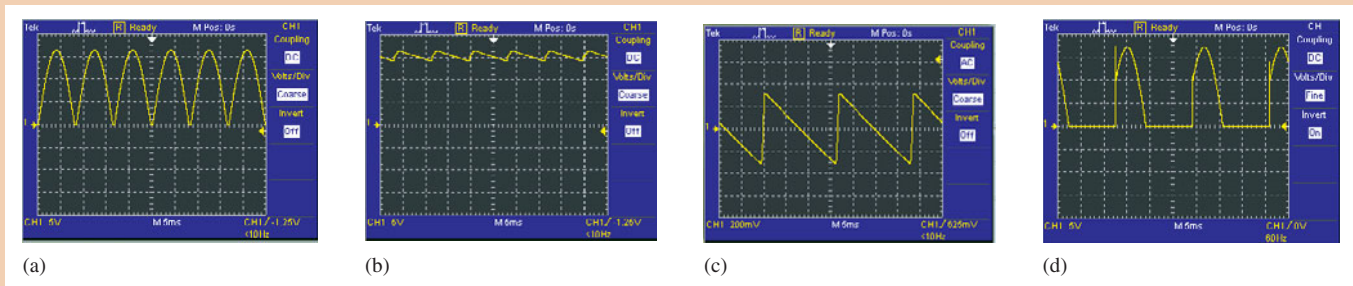


▲ FIGURE 2-90

Testing the power supply printed circuit board. The 62 Ω load is a temporary test load to check ripple when the power supply is used at its maximum rated current.

Troubleshooting

For each of the scope output voltage measurements in Figure 2-91, determine the likely fault or faults, if any.

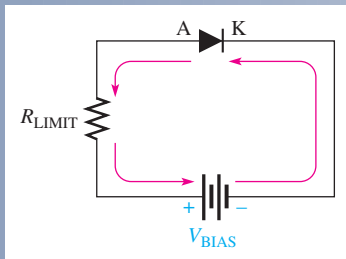


▲ FIGURE 2-91

Output voltage measurements on the power supply circuit.

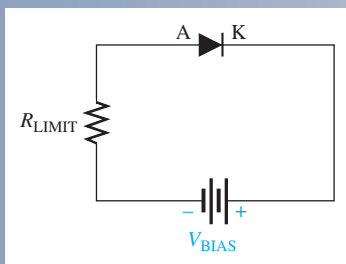
SUMMARY OF DIODE BIAS

FORWARD BIAS: PERMITS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to anode (A); negative to cathode (K).
- The bias voltage must be greater than the barrier potential.
- Barrier potential: 0.7 V for silicon.
- Majority carriers provide the forward current.
- The depletion region narrows.

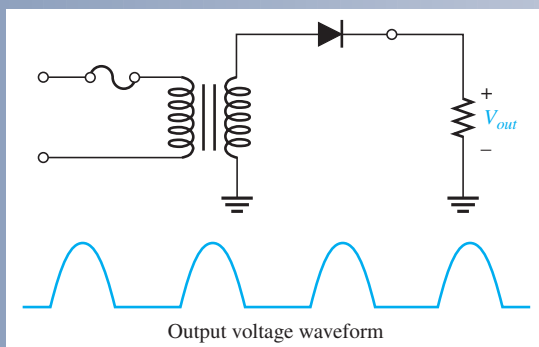
REVERSE BIAS: PREVENTS MAJORITY-CARRIER CURRENT



- Bias voltage connections: positive to cathode (K); negative to anode (A).
- The bias voltage must be less than the breakdown voltage.
- There is no majority carrier current after transition time.
- Minority carriers provide a negligibly small reverse current.
- The depletion region widens.

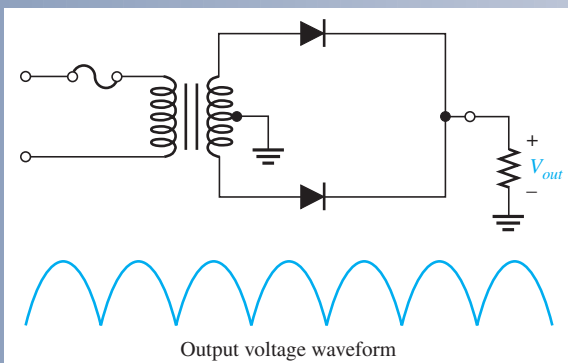
SUMMARY OF POWER SUPPLY RECTIFIERS

HALF-WAVE RECTIFIER



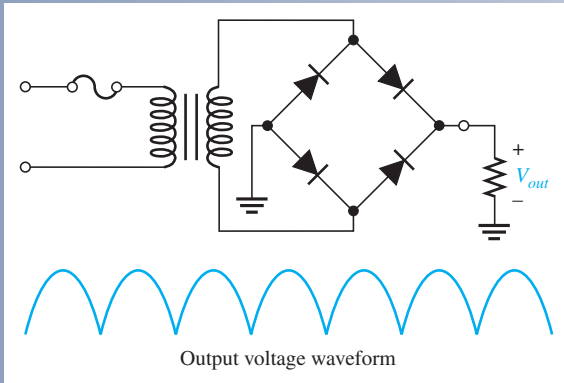
- Peak value of output:
 $V_{p(out)} = V_{p(sec)} - 0.7 \text{ V}$
- Average value of output:
 $V_{AVG} = \frac{V_{p(out)}}{\pi}$
- Diode peak inverse voltage:
 $PIV = V_{p(sec)}$

CENTER-TAPPED FULL-WAVE RECTIFIER



- Peak value of output:
 $V_{p(out)} = \frac{V_{p(sec)}}{2} - 0.7 \text{ V}$
- Average value of output:
 $V_{AVG} = \frac{2V_{p(out)}}{\pi}$
- Diode peak inverse voltage:
 $PIV = 2V_{p(out)} + 0.7 \text{ V}$

BRIDGE FULL-WAVE RECTIFIER



- Peak value of output:

$$V_{p(out)} = V_{p(sec)} - 1.4 \text{ V}$$

- Average value of output:

$$V_{AVG} = \frac{2V_{p(out)}}{\pi}$$

- Diode peak inverse voltage:

$$PIV = V_{p(out)} + 0.7 \text{ V}$$

SUMMARY

- Section 2-1**
- ◆ There is current through a diode only when it is forward-biased. Ideally, there is no current when there is no bias nor when there is reverse bias. Actually, there is a very small current in reverse bias due to the thermally generated minority carriers, but this can usually be neglected.
 - ◆ Avalanche occurs in a reverse-biased diode if the bias voltage equals or exceeds the breakdown voltage.
 - ◆ A diode conducts current when forward-biased and blocks current when reversed-biased.
 - ◆ Reverse breakdown voltage for a diode is typically greater than 50 V.
- Section 2-2**
- ◆ The V - I characteristic curve shows the diode current as a function of voltage across the diode.
 - ◆ The resistance of a forward-biased diode is called the *dynamic* or *ac resistance*.
 - ◆ Reverse current increases rapidly at the reverse breakdown voltage.
 - ◆ Reverse breakdown should be avoided in most diodes.
- Section 2-3**
- ◆ The ideal model represents the diode as a closed switch in forward bias and as an open switch in reverse bias.
 - ◆ The practical model represents the diode as a switch in series with the barrier potential.
 - ◆ The complete model includes the dynamic forward resistance in series with the practical model in forward bias and the reverse resistance in parallel with the open switch in reverse bias.
- Section 2-4**
- ◆ A dc power supply typically consists of a transformer, a diode rectifier, a filter, and a regulator.
 - ◆ The single diode in a half-wave rectifier is forward-biased and conducts for 180° of the input cycle.
 - ◆ The output frequency of a half-wave rectifier equals the input frequency.
 - ◆ PIV (peak inverse voltage) is the maximum voltage appearing across the diode in reverse bias.
- Section 2-5**
- ◆ Each diode in a full-wave rectifier is forward-biased and conducts for 180° of the input cycle.
 - ◆ The output frequency of a full-wave rectifier is twice the input frequency.
 - ◆ The two basic types of full-wave rectifier are center-tapped and bridge.
 - ◆ The peak output voltage of a center-tapped full-wave rectifier is approximately one-half of the total peak secondary voltage less one diode drop.
 - ◆ The PIV for each diode in a center-tapped full-wave rectifier is twice the peak output voltage plus one diode drop.
 - ◆ The peak output voltage of a bridge rectifier equals the total peak secondary voltage less two diode drops.
 - ◆ The PIV for each diode in a bridge rectifier is approximately half that required for an equivalent center-tapped configuration and is equal to the peak output voltage plus one diode drop.

- Section 2–6**
- ◆ A capacitor-input filter provides a dc output approximately equal to the peak of its rectified input voltage.
 - ◆ Ripple voltage is caused by the charging and discharging of the filter capacitor.
 - ◆ The smaller the ripple voltage, the better the filter.
 - ◆ Regulation of output voltage over a range of input voltages is called *input or line regulation*.
 - ◆ Regulation of output voltage over a range of load currents is called *load regulation*.
- Section 2–7**
- ◆ Diode limiters cut off voltage above or below specified levels. Limiters are also called *clippers*.
 - ◆ Diode clampers add a dc level to an ac voltage.
- Section 2–8**
- ◆ Voltage multipliers are used in high-voltage, low-current applications such as for electron beam acceleration in CRTs and for particle accelerators.
 - ◆ A voltage multiplier uses a series of diode-capacitor stages.
 - ◆ Input voltage can be doubled, tripled, or quadrupled.
- Section 2–9**
- ◆ A datasheet provides key information about the parameters and characteristics of an electronic device.
 - ◆ A diode should always be operated below the absolute maximum ratings specified on the datasheet.
- Section 2–10**
- ◆ Many DMMs provide a diode test function.
 - ◆ DMMs display the diode drop when the diode is operating properly in forward bias.
 - ◆ Most DMMs indicate “OL” when the diode is open.
 - ◆ Troubleshooting is the application of logical thought combined with a thorough knowledge of the circuit or system to identify and correct a malfunction.
 - ◆ Troubleshooting is a three-step process of analysis, planning, and measurement.
 - ◆ Fault analysis is the isolation of a fault to a particular circuit or portion of a circuit.

KEY TERMS

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

Bias The application of a dc voltage to a diode to make it either conduct or block current.

Clamper A circuit that adds a dc level to an ac voltage using a diode and a capacitor.

DC power supply A circuit that converts ac line voltage to dc voltage and supplies constant power to operate a circuit or system.

Diode A semiconductor device with a single *pn* junction that conducts current in only one direction.

Filter In a power supply, the capacitor used to reduce the variation of the output voltage from a rectifier.

Forward bias The condition in which a diode conducts current.

Full-wave rectifier A circuit that converts an ac sinusoidal input voltage into a pulsating dc voltage with two output pulses occurring for each input cycle.

Half-wave rectifier A circuit that converts an ac sinusoidal input voltage into a pulsating dc voltage with one output pulse occurring for each input cycle.

Limiter A diode circuit that clips off or removes part of a waveform above and/or below a specified level.

Line regulation The change in output voltage of a regulator for a given change in input voltage, normally expressed as a percentage.

Load regulation The change in output voltage of a regulator for a given range of load currents, normally expressed as a percentage.

Peak inverse voltage (PIV) The maximum value of reverse voltage across a diode that occurs at the peak of the input cycle when the diode is reverse-biased.

Rectifier An electronic circuit that converts ac into pulsating dc; one part of a power supply.

Regulator An electronic device or circuit that maintains an essentially constant output voltage for a range of input voltage or load values; one part of a power supply.

Reverse bias The condition in which a diode prevents current.

Ripple voltage The small variation in the dc output voltage of a filtered rectifier caused by the charging and discharging of the filter capacitor.

Troubleshooting A systematic process of isolating, identifying, and correcting a fault in a circuit or system.

V-I characteristic A curve showing the relationship of diode voltage and current.

KEY FORMULAS

2-1	$I_F = \frac{V_{\text{BIAS}}}{R_{\text{LIMIT}}}$	Forward current, ideal diode model
2-2	$I_F = \frac{V_{\text{BIAS}} - V_F}{R_{\text{LIMIT}}}$	Forward current, practical diode model
2-3	$V_{\text{AVG}} = \frac{V_p}{\pi}$	Half-wave average value
2-4	$V_{p(\text{out})} = V_{p(\text{in})} - 0.7 \text{ V}$	Peak half-wave rectifier output (silicon)
2-5	$\text{PIV} = V_{p(\text{in})}$	Peak inverse voltage, half-wave rectifier
2-6	$V_{\text{AVG}} = \frac{2V_p}{\pi}$	Full-wave average value
2-7	$V_{\text{out}} = \frac{V_{\text{sec}}}{2} - 0.7 \text{ V}$	Center-tapped full-wave output
2-8	$\text{PIV} = 2V_{p(\text{out})} + 0.7 \text{ V}$	Peak inverse voltage, center-tapped rectifier
2-9	$V_{p(\text{out})} = V_{p(\text{sec})} - 1.4 \text{ V}$	Bridge full-wave output
2-10	$\text{PIV} = V_{p(\text{out})} + 0.7 \text{ V}$	Peak inverse voltage, bridge rectifier
2-11	$r = \frac{V_{r(\text{pp})}}{V_{\text{DC}}}$	Ripple factor
2-12	$V_{r(\text{pp})} \cong \left(\frac{1}{fR_L C} \right) V_{p(\text{rect})}$	Peak-to-peak ripple voltage, capacitor-input filter
2-13	$V_{\text{DC}} = \left(1 - \frac{1}{2fR_L C} \right) V_{p(\text{rect})}$	DC output voltage, capacitor-input filter
2-14	$\text{Line regulation} = \left(\frac{\Delta V_{\text{OUT}}}{\Delta V_{\text{IN}}} \right) 100\%$	
2-15	$\text{Load regulation} = \left(\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}} \right) 100\%$	

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

- The two regions of a diode are the anode and the collector.
- A diode can conduct current in two directions with equal ease.
- A diode conducts current when forward-biased.
- When reverse-biased, a diode ideally appears as a short.
- Two types of current in a diode are electron and hole.
- A basic half-wave rectifier consists of one diode.
- The output frequency of a half-wave rectifier is twice the input frequency.
- The diode in a half-wave rectifier conducts for half the input cycle.
- PIV stands for positive inverse voltage.
- Each diode in a full-wave rectifier conducts for the entire input cycle.
- The output frequency of a full-wave rectifier is twice the input frequency.
- A bridge rectifier uses four diodes.
- In a bridge rectifier, two diodes conduct during each half cycle of the input.
- The purpose of the capacitor filter in a rectifier is to convert ac to dc.
- The output voltage of a filtered rectifier always has some ripple voltage.

16. A smaller filter capacitor reduces the ripple.
17. Line and load regulation are the same.
18. A diode limiter is also known as a clipper.
19. The purpose of a clamper is to remove a dc level from a waveform.
20. Voltage multipliers use diodes and capacitors.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. When a diode is forward-biased and the bias voltage is increased, the forward current will
(a) increase (b) decrease (c) not change
2. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the practical model) will
(a) increase (b) decrease (c) not change
3. When a diode is reverse-biased and the bias voltage is increased, the reverse current (assuming the practical model) will
(a) increase (b) decrease (c) not change
4. When a diode is reverse-biased and the bias voltage is increased, the reverse current (assuming the complete model) will
(a) increase (b) decrease (c) not change
5. When a diode is forward-biased and the bias voltage is increased, the voltage across the diode (assuming the complete model) will
(a) increase (b) decrease (c) not change
6. If the forward current in a diode is increased, the diode voltage (assuming the practical model) will
(a) increase (b) decrease (c) not change
7. If the forward current in a diode is decreased, the diode voltage (assuming the complete model) will
(a) increase (b) decrease (c) not change
8. If the barrier potential of a diode is exceeded, the forward current will
(a) increase (b) decrease (c) not change
9. If the input voltage in Figure 2–28 is increased, the peak inverse voltage across the diode will
(a) increase (b) decrease (c) not change
10. If the turns ratio of the transformer in Figure 2–28 is decreased, the forward current through the diode will
(a) increase (b) decrease (c) not change
11. If the frequency of the input voltage in Figure 2–36 is increased, the output voltage will
(a) increase (b) decrease (c) not change
12. If the PIV rating of the diodes in Figure 2–36 is increased, the current through R_L will
(a) increase (b) decrease (c) not change
13. If one of the diodes in Figure 2–41 opens, the average voltage to the load will
(a) increase (b) decrease (c) not change
14. If the value of R_L in Figure 2–41 is decreased, the current through each diode will
(a) increase (b) decrease (c) not change
15. If the capacitor value in Figure 2–48 is decreased, the output ripple voltage will
(a) increase (b) decrease (c) not change
16. If the line voltage in Figure 2–51 is increased, ideally the +5 V output will
(a) increase (b) decrease (c) not change
17. If the bias voltage in Figure 2–55 is decreased, the positive portion of the output voltage will
(a) increase (b) decrease (c) not change
18. If the bias voltage in Figure 2–55 is increased, the negative portion of the output voltage will
(a) increase (b) decrease (c) not change

19. If the value of R_3 in Figure 2–61 is decreased, the positive output voltage will
 (a) increase (b) decrease (c) not change
20. If the input voltage in Figure 2–65 is increased, the peak negative value of the output voltage will
 (a) increase (b) decrease (c) not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 2–1

- The term *bias* means
 - the ratio of majority carriers to minority carriers
 - the amount of current across a diode
 - a dc voltage is applied to control the operation of a device
 - neither (a), (b), nor (c)
- To forward-bias a diode,
 - an external voltage is applied that is positive at the anode and negative at the cathode
 - an external voltage is applied that is negative at the anode and positive at the cathode
 - an external voltage is applied that is positive at the *p* region and negative at the *n* region
 - answers (a) and (c)
- When a diode is forward-biased,
 - the only current is hole current
 - the only current is electron current
 - the only current is produced by majority carriers
 - the current is produced by both holes and electrons
- Although current is blocked in reverse bias,
 - there is some current due to majority carriers
 - there is a very small current due to minority carriers
 - there is an avalanche current
- For a silicon diode, the value of the forward-bias voltage typically
 - must be greater than 0.3 V
 - must be greater than 0.7 V
 - depends on the width of the depletion region
 - depends on the concentration of majority carriers
- When forward-biased, a diode

(a) blocks current	(b) conducts current
(c) has a high resistance	(d) drops a large voltage

Section 2–2

- A diode is normally operated in

(a) reverse breakdown	(b) the forward-bias region
(c) the reverse-bias region	(d) either (b) or (c)
- The dynamic resistance can be important when a diode is

(a) reverse-biased	(b) forward-biased
(c) in reverse breakdown	(d) unbiased
- The *V-I* curve for a diode shows
 - the voltage across the diode for a given current
 - the amount of current for a given bias voltage
 - the power dissipation
 - none of these

Section 2–3

- Ideally, a diode can be represented by a

(a) voltage source	(b) resistance	(c) switch	(d) all of these
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11. In the practical diode model,
- (a) the barrier potential is taken into account
 - (b) the forward dynamic resistance is taken into account
 - (c) none of these
 - (d) both (a) and (b)
12. In the complete diode model,
- (a) the barrier potential is taken into account
 - (b) the forward dynamic resistance is taken into account
 - (c) the reverse resistance is taken into account
 - (d) all of these

Section 2-4

13. The average value of a half-wave rectified voltage with a peak value of 200 V is
(a) 63.7 V (b) 127.2 V (c) 141 V (d) 0 V
14. When a 60 Hz sinusoidal voltage is applied to the input of a half-wave rectifier, the output frequency is
(a) 120 Hz (b) 30 Hz (c) 60 Hz (d) 0 Hz
15. The peak value of the input to a half-wave rectifier is 10 V. The approximate peak value of the output is
(a) 10 V (b) 3.18 V (c) 10.7 V (d) 9.3 V
16. For the circuit in Question 15, the diode must be able to withstand a reverse voltage of
(a) 10 V (b) 5 V (c) 20 V (d) 3.18 V

Section 2-5

17. The average value of a full-wave rectified voltage with a peak value of 75 V is
(a) 53 V (b) 47.8 V (c) 37.5 V (d) 23.9 V
18. When a 60 Hz sinusoidal voltage is applied to the input of a full-wave rectifier, the output frequency is
(a) 120 Hz (b) 60 Hz (c) 240 Hz (d) 0 Hz
19. The total secondary voltage in a center-tapped full-wave rectifier is 125 V rms. Neglecting the diode drop, the rms output voltage is
(a) 125 V (b) 177 V (c) 100 V (d) 62.5 V
20. When the peak output voltage is 100 V, the PIV for each diode in a center-tapped full-wave rectifier is (neglecting the diode drop)
(a) 100 V (b) 200 V (c) 141 V (d) 50 V
21. When the rms output voltage of a bridge full-wave rectifier is 20 V, the peak inverse voltage across the diodes is (neglecting the diode drop)
(a) 20 V (b) 40 V (c) 28.3 V (d) 56.6 V

Section 2-6

22. The ideal dc output voltage of a capacitor-input filter is equal to
(a) the peak value of the rectified voltage
(b) the average value of the rectified voltage
(c) the rms value of the rectified voltage
23. A certain power-supply filter produces an output with a ripple of 100 mV peak-to-peak and a dc value of 20 V. The ripple factor is
(a) 0.05 (b) 0.005 (c) 0.00005 (d) 0.02
24. A 60 V peak full-wave rectified voltage is applied to a capacitor-input filter. If $f = 120$ Hz, $R_L = 10$ k Ω , and $C = 10$ μ F, the ripple voltage is
(a) 0.6 V (b) 6 mV (c) 5.0 V (d) 2.88 V
25. If the load resistance of a capacitor-filtered full-wave rectifier is reduced, the ripple voltage
(a) increases (b) decreases (c) is not affected (d) has a different frequency
26. Line regulation is determined by
(a) load current
(b) zener current and load current

- (c) changes in load resistance and output voltage
(d) changes in output voltage and input voltage
27. Load regulation is determined by
(a) changes in load current and input voltage
(b) changes in load current and output voltage
(c) changes in load resistance and input voltage
(d) changes in zener current and load current
- Section 2-7** 28. A 10 V peak-to-peak sinusoidal voltage is applied across a silicon diode and series resistor. The maximum voltage across the diode is
(a) 9.3 V (b) 5 V (c) 0.7 V (d) 10 V (e) 4.3 V
29. In a certain biased limiter, the bias voltage is 5 V and the input is a 10 V peak sine wave. If the positive terminal of the bias voltage is connected to the cathode of the diode, the maximum voltage at the anode is
(a) 10 V (b) 5 V (c) 5.7 V (d) 0.7 V
30. In a certain positive clamper circuit, a 120 V rms sine wave is applied to the input. The dc value of the output is
(a) 119.3 V (b) 169 V (c) 60 V (d) 75.6 V
- Section 2-8** 31. The input of a voltage doubler is 120 V rms. The peak-to-peak output is approximately
(a) 240 V (b) 60 V (c) 167 V (d) 339 V
32. If the input voltage to a voltage tripler has an rms value of 12 V, the dc output voltage is approximately
(a) 36 V (b) 50.9 V (c) 33.9 V (d) 32.4 V
- Section 2-10** 33. When a silicon diode is working properly in forward bias, a DMM in the diode test position will indicate
(a) 0 V (b) OL (c) approximately 0.7 V (d) approximately 0.3 V
34. When a silicon diode is open, a DMM will generally indicate
(a) 0 V (b) OL (c) approximately 0.7 V (d) approximately 0.3 V
35. In a rectifier circuit, if the secondary winding in the transformer opens, the output is
(a) 0 V (b) 120 V (c) less than it should be (d) unaffected
36. If one of the diodes in a bridge full-wave rectifier opens, the output is
(a) 0 V (b) one-fourth the amplitude of the input voltage
(c) a half-wave rectified voltage (d) a 120 Hz voltage
37. If you are checking a 60 Hz full-wave bridge rectifier and observe that the output has a 60 Hz ripple,
(a) the circuit is working properly (b) there is an open diode
(c) the transformer secondary is shorted (d) the filter capacitor is leaky

PROBLEMS

Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 2-1 Diode Operation

- To forward-bias a diode, to which region must the positive terminal of a voltage source be connected?
- Explain why a series resistor is necessary when a diode is forward-biased.

Section 2-2 Voltage-Current Characteristic of a Diode

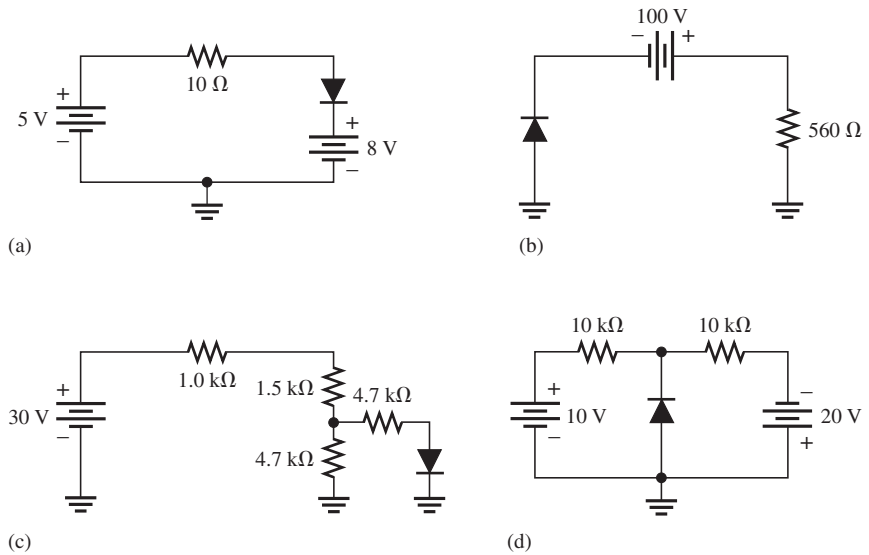
- Explain how to generate the forward-bias portion of the characteristic curve.
- What would cause the barrier potential of a silicon diode to decrease from 0.7 V to 0.6 V?

Section 2-3 Diode Models

5. Determine whether each silicon diode in Figure 2-92 is forward-biased or reverse-biased.
6. Determine the voltage across each diode in Figure 2-92, assuming the practical model.
7. Determine the voltage across each diode in Figure 2-92, assuming an ideal diode.
8. Determine the voltage across each diode in Figure 2-92, using the complete diode model with $r'_d = 10 \Omega$ and $r'_R = 100 \text{ M}\Omega$.

► **FIGURE 2-92**

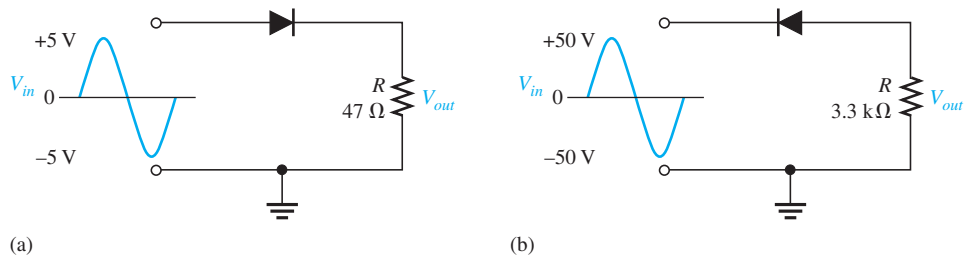
Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F02-92).



Section 2-4 Half-Wave Rectifiers

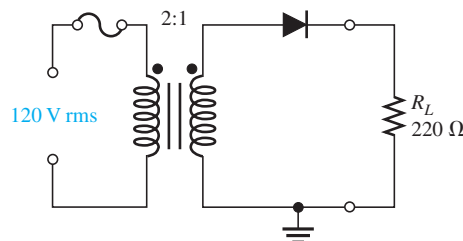
9. Draw the output voltage waveform for each circuit in Figure 2-93 and include the voltage values.

► **FIGURE 2-93**



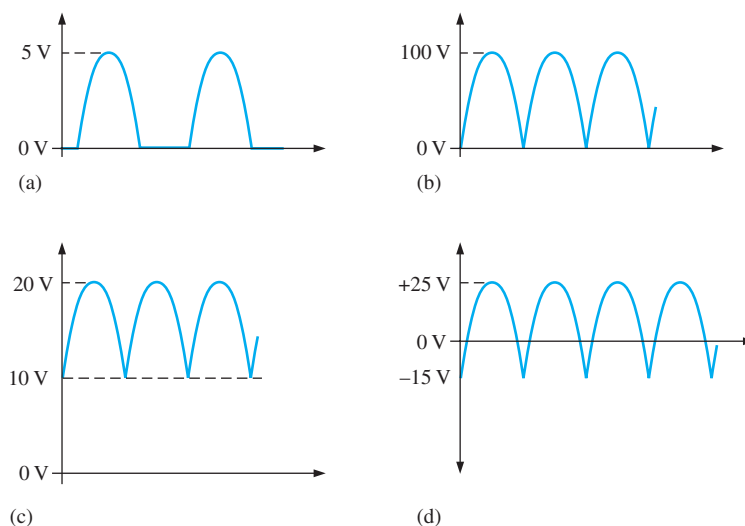
10. What is the peak inverse voltage across each diode in Figure 2-93?
11. Calculate the average value of a half-wave rectified voltage with a peak value of 200 V.
12. What is the peak forward current through each diode in Figure 2-93?
13. A power-supply transformer has a turns ratio of 5:1. What is the secondary voltage if the primary is connected to a 120 V rms source?
14. Determine the peak and average power delivered to R_L in Figure 2-94.

► **FIGURE 2-94**



Section 2-5 Full-Wave Rectifiers

15. Find the average value of each voltage in Figure 2-95.



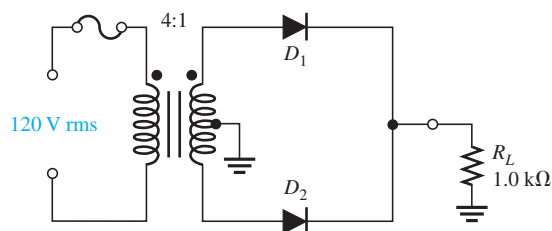
▲ FIGURE 2-95

16. Consider the circuit in Figure 2-96.

- What type of circuit is this?
- What is the total peak secondary voltage?
- Find the peak voltage across each half of the secondary.
- Sketch the voltage waveform across R_L .
- What is the peak current through each diode?
- What is the PIV for each diode?

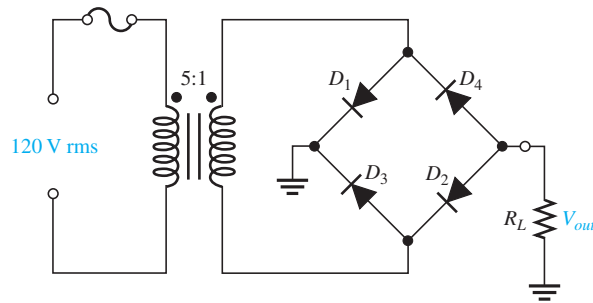


▶ FIGURE 2-96



- Calculate the peak voltage across each half of a center-tapped transformer used in a full-wave rectifier that has an average output voltage of 120 V.
- Show how to connect the diodes in a center-tapped rectifier in order to produce a negative-going full-wave voltage across the load resistor.
- What PIV rating is required for the diodes in a bridge rectifier that produces an average output voltage of 50 V?
- The rms output voltage of a bridge rectifier is 20 V. What is the peak inverse voltage across the diodes?
- Draw the output voltage waveform for the bridge rectifier in Figure 2-97. Notice that all the diodes are reversed from circuits shown earlier in the chapter.

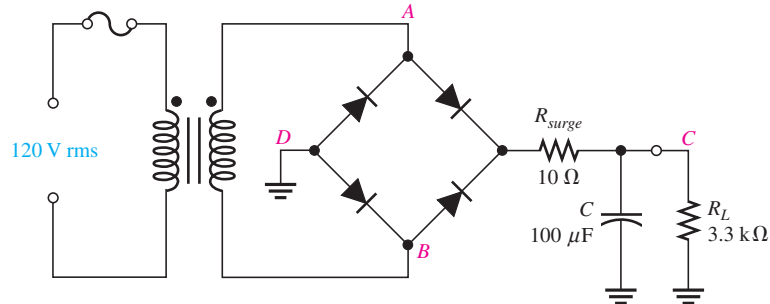
▶ FIGURE 2-97



Section 2-6 Power Supply Filters and Regulators

22. A certain rectifier filter produces a dc output voltage of 75 V with a peak-to-peak ripple voltage of 0.5 V. Calculate the ripple factor.
23. A certain full-wave rectifier has a peak output voltage of 30 V. A 50 μF capacitor-input filter is connected to the rectifier. Calculate the peak-to-peak ripple and the dc output voltage developed across a 600 Ω load resistance.
24. What is the percentage of ripple for the rectifier filter in Problem 23?
25. What value of filter capacitor is required to produce a 1% ripple factor for a full-wave rectifier having a load resistance of 1.5 k Ω ? Assume the rectifier produces a peak output of 18 V.
26. A full-wave rectifier produces an 80 V peak rectified voltage from a 60 Hz ac source. If a 10 μF filter capacitor is used, determine the ripple factor for a load resistance of 10 k Ω .
27. Determine the peak-to-peak ripple and dc output voltages in Figure 2-98. The transformer has a 36 V rms secondary voltage rating, and the line voltage has a frequency of 60 Hz.
28. Refer to Figure 2-98 and draw the following voltage waveforms in relationship to the input waveforms: V_{AB} , V_{AD} , and V_{CD} . A double letter subscript indicates a voltage from one point to another.
29. If the no-load output voltage of a regulator is 15.5 V and the full-load output is 14.9 V, what is the percent load regulation?
30. Assume a regulator has a percent load regulation of 0.5%. What is the output voltage at full-load if the unloaded output is 12.0 V?

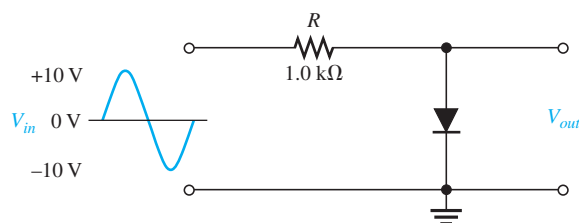
▶ FIGURE 2-98



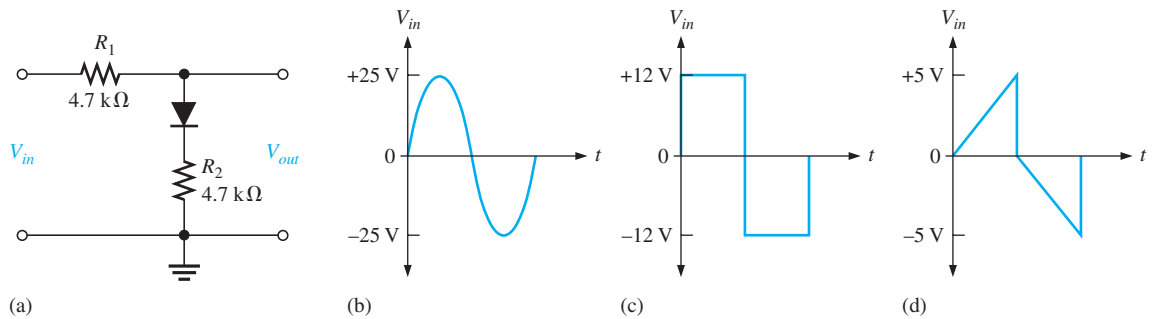
Section 2-7 Diode Limiters and Clambers

31. Determine the output waveform for the circuit of Figure 2-99.

▶ FIGURE 2-99

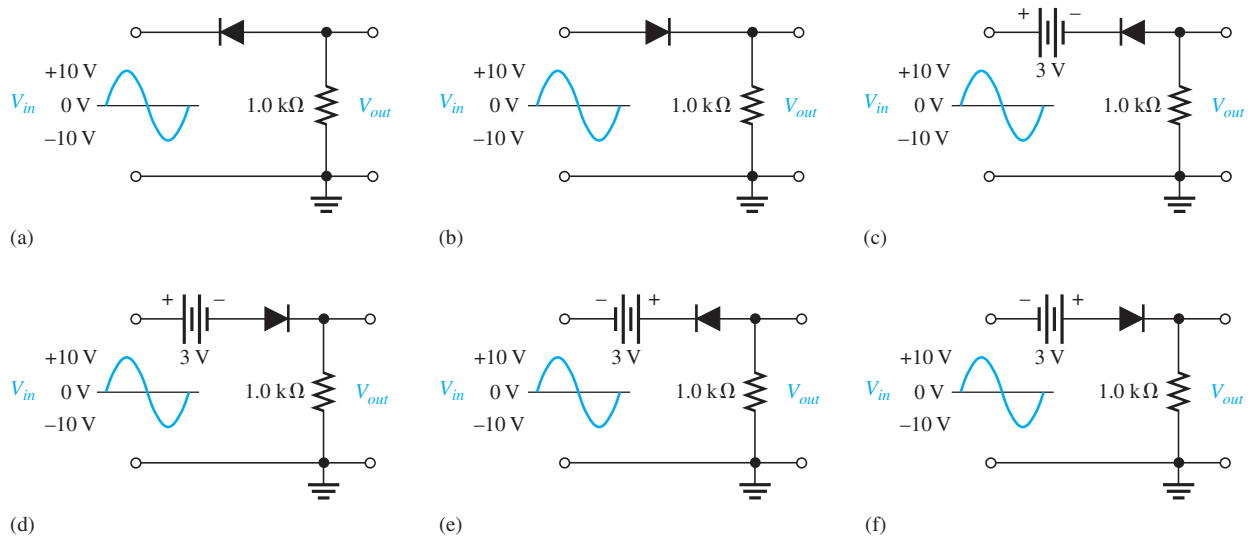


32. Determine the output voltage for the circuit in Figure 2–100(a) for each input voltage in (b), (c), and (d).



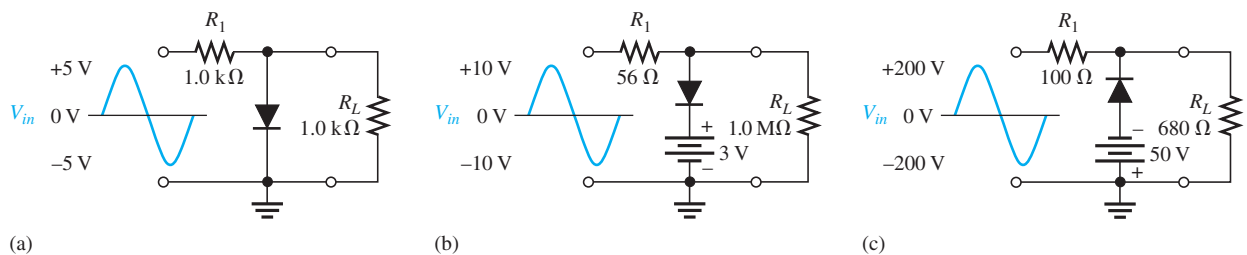
▲ FIGURE 2–100

33. Determine the output voltage waveform for each circuit in Figure 2–101.



▲ FIGURE 2–101

34. Determine the R_L voltage waveform for each circuit in Figure 2–102.

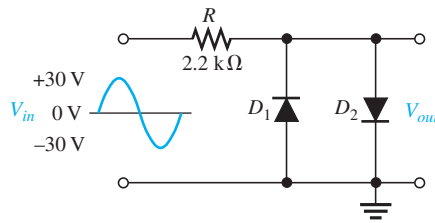


▲ FIGURE 2–102

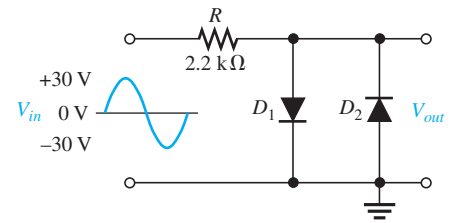
35. Draw the output voltage waveform for each circuit in Figure 2–103.

36. Determine the peak forward current through each diode in Figure 2–103.

▶ FIGURE 2-103



(a)

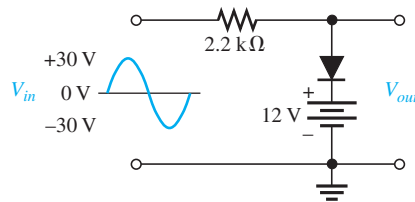


(b)

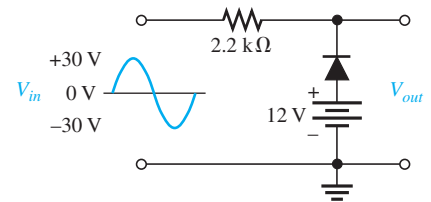
37. Determine the peak forward current through each diode in Figure 2-104.

38. Determine the output voltage waveform for each circuit in Figure 2-104.

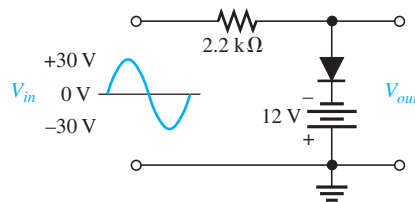
▶ FIGURE 2-104



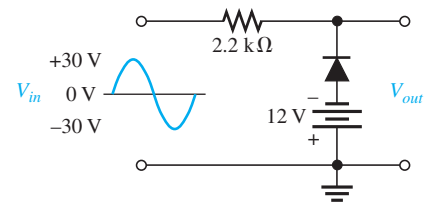
(a)



(b)



(c)

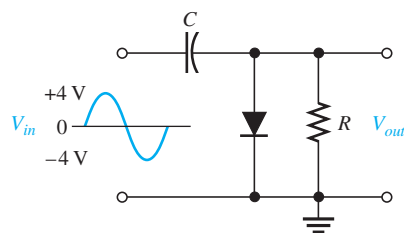


(d)

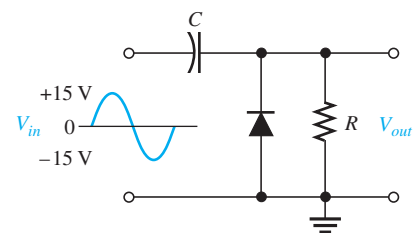
39. Describe the output waveform of each circuit in Figure 2-105. Assume the RC time constant is much greater than the period of the input.

40. Repeat Problem 39 with the diodes turned around.

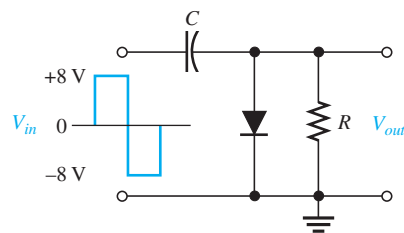
▶ FIGURE 2-105



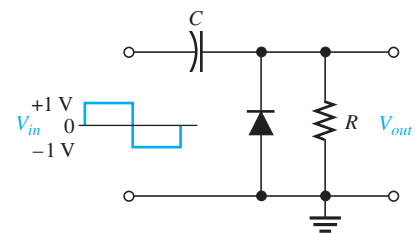
(a)



(b)



(c)



(d)

Section 2–8 Voltage Multipliers

41. A certain voltage doubler has 20 V rms on its input. What is the output voltage? Draw the circuit, indicating the output terminals and PIV rating for the diode.
42. Repeat Problem 41 for a voltage tripler and quadrupler.

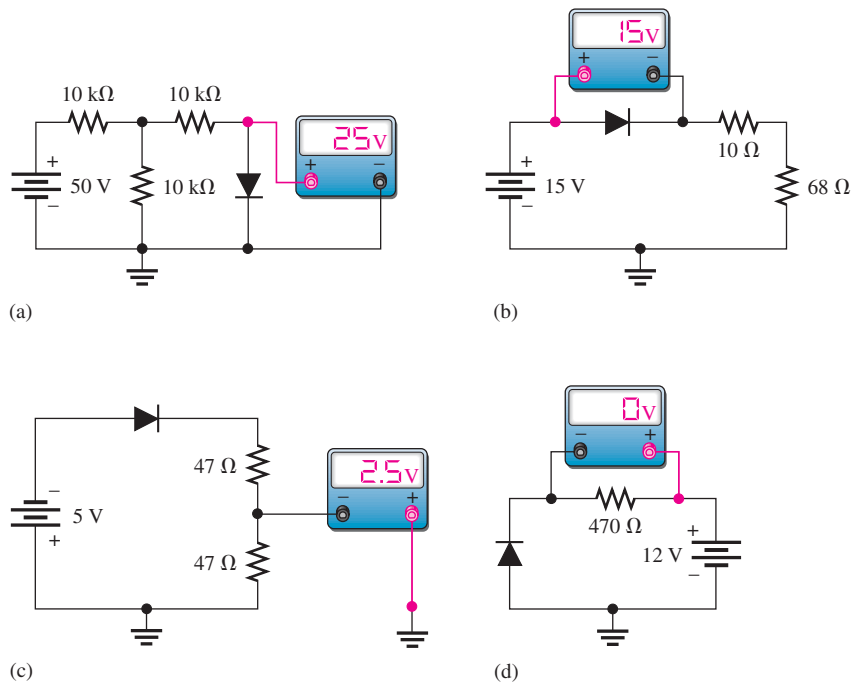
Section 2–9 The Diode Datasheet

43. From the datasheet in Figure 2–71, determine how much peak inverse voltage that a 1N4002 diode can withstand.
44. Repeat Problem 43 for a 1N4007.
45. If the peak output voltage of a bridge full-wave rectifier is 50 V, determine the minimum value of the load resistance that can be used when 1N4002 diodes are used.

Section 2–10 Troubleshooting

46. Consider the meter indications in each circuit of Figure 2–106, and determine whether the diode is functioning properly, or whether it is open or shorted. Assume the ideal model.

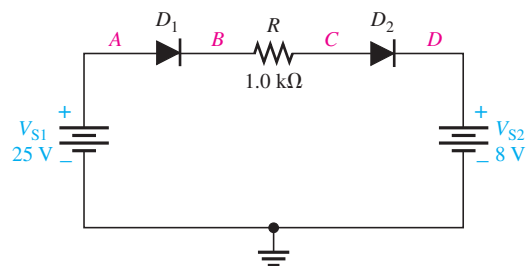
► FIGURE 2–106



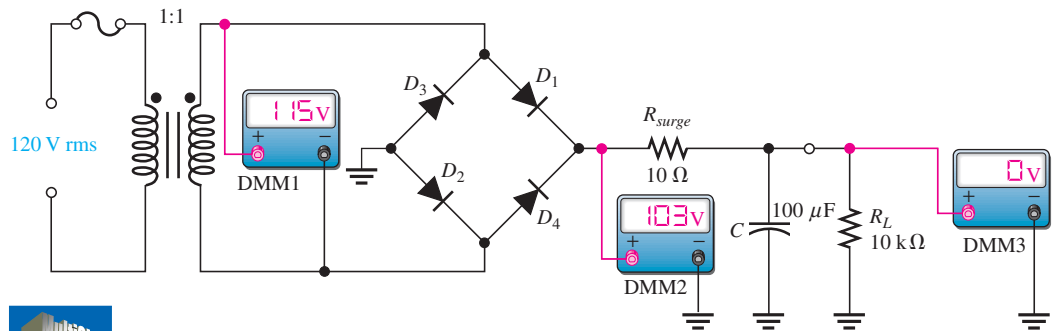
47. Determine the voltage with respect to ground at each point in Figure 2–107. Assume the practical model.
48. If one of the diodes in a bridge rectifier opens, what happens to the output?



► FIGURE 2–107

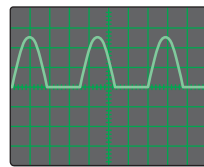


49. From the meter readings in Figure 2–108, determine if the rectifier is functioning properly. If it is not, determine the most likely failure(s).

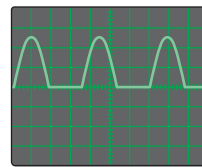


▲ FIGURE 2–108

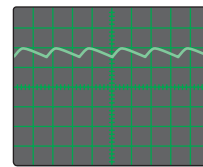
50. Each part of Figure 2–109 shows oscilloscope displays of various rectifier output voltages. In each case, determine whether or not the rectifier is functioning properly and if it is not, determine the most likely failure(s).



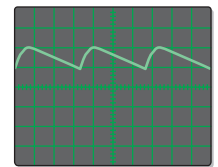
(a) Output of a half-wave unfiltered rectifier



(b) Output of a full-wave unfiltered rectifier



(c) Output of a full-wave filter

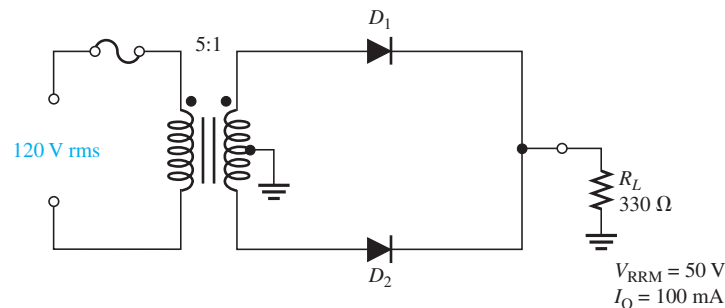


(d) Output of same full-wave filter as part (c)

▲ FIGURE 2–109

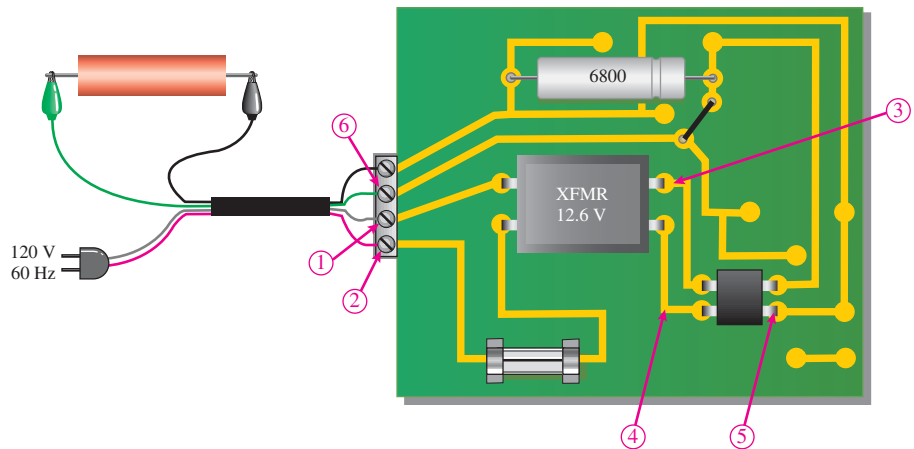
51. Based on the values given, would you expect the circuit in Figure 2–110 to fail? If so, why?

► FIGURE 2–110



APPLICATION ACTIVITY PROBLEMS

52. Determine the most likely failure(s) in the circuit of Figure 2–111 for each of the following symptoms. State the corrective action you would take in each case. The transformer has a rated output of 10 V rms.
- No voltage from test point 1 to test point 2
 - No voltage from test point 3 to test point 4
 - 8 V rms from test point 3 to test point 4
 - Excessive 120 Hz ripple voltage at test point 6
 - There is a 60 Hz ripple voltage at test point 6
 - No voltage at test point 6



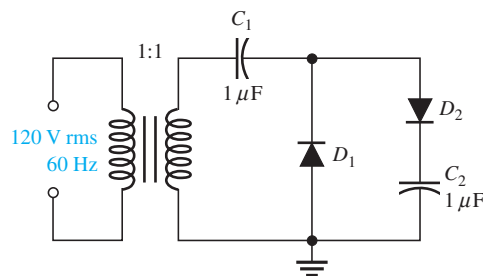
▲ FIGURE 2-111

53. In testing the power supply circuit in Figure 2-111 with a $10\text{ k}\Omega$ load resistor connected, you find the voltage at the positive side of the filter capacitor to have a 60 Hz ripple voltage. You replace the bridge rectifier and check the point again but it still has the 60 Hz ripple. What now?
54. Suppose the bridge rectifier in Figure 2-111 is connected backwards such that the transformer secondary is now connected to the output pins instead of the input pins. What will be observed at test point 6?

ADVANCED PROBLEMS

55. A full-wave rectifier with a capacitor-input filter provides a dc output voltage of 35 V to a $3.3\text{ k}\Omega$ load. Determine the minimum value of filter capacitor if the maximum peak-to-peak ripple voltage is to be 0.5 V.
56. A certain unfiltered full-wave rectifier with 120 V, 60 Hz input produces an output with a peak of 15 V. When a capacitor-input filter and a $1.0\text{ k}\Omega$ load are connected, the dc output voltage is 14 V. What is the peak-to-peak ripple voltage?
57. For a certain full-wave rectifier, the measured surge current in the capacitor filter is 50 A. The transformer is rated for a secondary voltage of 24 V with a 120 V, 60 Hz input. Determine the value of the surge resistor in this circuit.
58. Design a full-wave rectifier using an 18 V center-tapped transformer. The output ripple is not to exceed 5% of the output voltage with a load resistance of $680\ \Omega$. Specify the $I_{F(AV)}$ and PIV ratings of the diodes and select an appropriate diode from the datasheet in Figure 2-71.
59. Design a filtered power supply that can produce dc output voltages of $+9\text{ V} \pm 10\%$ and $-9\text{ V} \pm 10\%$ with a maximum load current of 100 mA. The voltages are to be switch selectable across one set of output terminals. The ripple voltage must not exceed 0.25 V rms.
60. Design a circuit to limit a 20 V rms sinusoidal voltage to a maximum positive amplitude of 10 V and a maximum negative amplitude of -5 V using a single 14 V dc voltage source.
61. Determine the voltage across each capacitor in the circuit of Figure 2-112.

► FIGURE 2-112





MULTISIM TROUBLESHOOTING PROBLEMS

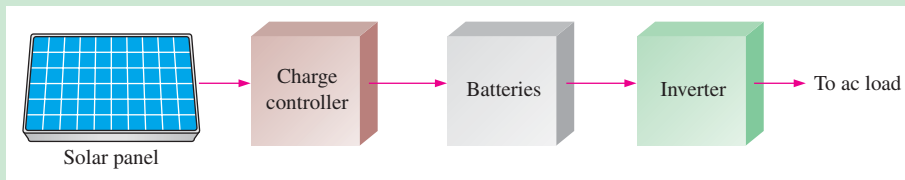
These file circuits are in the Troubleshooting Problems folder on the companion website.

62. Open file TSP02-62 and determine the fault.
63. Open file TSP02-63 and determine the fault.
64. Open file TSP02-64 and determine the fault.
65. Open file TSP02-65 and determine the fault.
66. Open file TSP02-66 and determine the fault.
67. Open file TSP02-67 and determine the fault.
68. Open file TSP02-68 and determine the fault.
69. Open file TSP02-69 and determine the fault.
70. Open file TSP02-70 and determine the fault.
71. Open file TSP02-71 and determine the fault.
72. Open file TSP02-72 and determine the fault.
73. Open file TSP02-73 and determine the fault.
74. Open file TSP02-74 and determine the fault.
75. Open file TSP02-75 and determine the fault.
76. Open file TSP02-76 and determine the fault.
77. Open file TSP02-77 and determine the fault.
78. Open file TSP02-78 and determine the fault.
79. Open file TSP02-79 and determine the fault.



GreenTech Application 2: Solar Power

In GreenTech Application 1, the photovoltaic cell and a basic solar power system were introduced. The block diagram is shown again in Figure GA2–1. You learned that the basic components of a solar-powered system were the solar panel, the charge controller, the batteries, and the inverter. Now we will continue the solar power coverage by focusing on the charge controller and batteries.



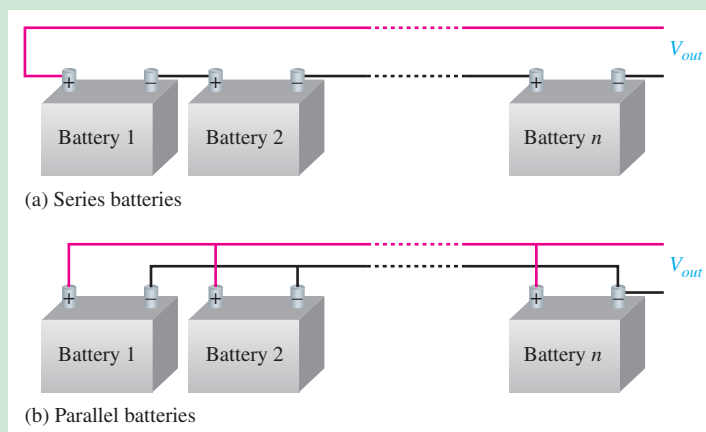
◀ FIGURE GA2–1

The Batteries

Deep-cycle (deep discharge) sealed lead-acid batteries are the most common batteries in solar power systems because their initial cost is lower and they are readily available. Unlike automobile batteries, which are shallow-cycle, deep-cycle batteries can be repeatedly discharged by as much as 80 percent of their capacity, although they will have a longer life if the cycles are shallower.

Deep-cycle batteries are required in solar power systems simply because the sunlight is not at its maximum all of the time—it is an intermittent energy source. When the light intensity from the sun decreases because of clouds or goes away entirely at night, the output from a solar panel drops drastically or goes to zero. During the periods of low light or no light, the batteries will discharge significantly when a load is connected. Typically, the voltage output of a solar panel must be at least 13.6 V to charge a 12 V battery. Solar panels are usually rated at voltages higher than the nominal output. For example, most 12 V solar panels produce 16 V to 20 V at optimal light conditions. The higher voltage outputs are necessary so that the solar panel will still produce a sufficient charging voltage during some nonoptimal conditions.

Battery Connections Batteries can be connected in series to increase the output voltage and in parallel to increase the ampere-hour capacity, as illustrated in Figure GA2–2 for any number of batteries. Several series connections of batteries can be connected in parallel to achieve both an increase in amp-hrs and output voltage. For example, assume a system uses 12 V, 200 Ah batteries. If the system requires 12 V and 600 Ah, three parallel-connected batteries are used. If the system requires 24 V and 200 Ah, two series-connected batteries are used. If 24 V and 600 Ah are needed, three pairs of series batteries are connected in parallel.



◀ FIGURE GA2–2

The Charge Controller

A solar charge controller is needed in solar power systems that use batteries to store the energy, with the exception of very low-power systems. The solar charge controller regulates the power from the solar panels primarily to prevent overcharging the batteries. Overcharging batteries reduce battery life and may damage the batteries.

Generally, there is no need for a charge controller with trickle-charge solar panels, such as those that produce five watts or less. A good rule-of-thumb is that if the solar panel produces about two watts or less for each 50 battery amp-hrs (Ah), then you don't need one. A charge controller is required if the solar panel produces more than two watts for each 50 Ah of battery rating. For example, a 12 V battery rated at 120 Ah will not require a charge controller, as the following calculation shows, because the solar power is less than 5 W.

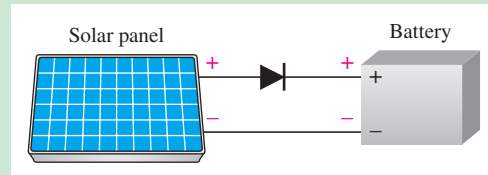
$$\left(\frac{\text{Specified Ah}}{50 \text{ Ah}}\right)2 \text{ W} = \text{Solar panel power}$$

$$\left(\frac{120 \text{ Ah}}{50 \text{ Ah}}\right)2 \text{ W} = (2.4)2 \text{ W} = 4.8 \text{ W}$$

In this case, the charging circuit is shown in Figure GA2-3. The diode prevents the battery from discharging back through the solar panel when the panel voltage drops below the battery voltage. For example, when the solar panel is producing 16 V, the diode is forward-biased and the battery is charging. When the battery voltage is 12 V and the panel output drops to less than 12.7 V, the diode is reverse-biased and the battery cannot discharge back through the solar cells.

► FIGURE GA2-3

Simple trickle charging in a small solar system (less than 5 W).

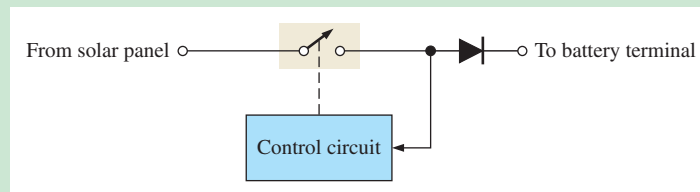


For solar systems of more than about 5 W, a charge controller is necessary. Basically, charge controllers regulate the 16–20 V output of the typical 12 V solar panel down to what the battery needs depending on the amount of battery charge, the type of battery, and the temperature. Solar panels produce more voltage at cooler temperatures.

Types of Charge Controllers Three basic types of charge controllers are on/off, PWM, and MPPT. The most basic controller is the *on/off* type, which simply monitors the battery voltage and stops the charging when the battery voltage reaches a specified level in order to prevent overcharging. It then restarts the charging once the battery voltage drops below a pre-determined value. Figure GA2-4 shows the basic concept. The switch shown represents a transistor that is turned on and off. (You will study transistors beginning in Chapter 4.) The voltage of the battery is fed back to the control circuit. When the voltage is below a set low value, the control circuit turns the switch *on* to charge the battery. When the battery charges to a set high value, the control circuit turns the switch *off*. The diode prevents discharge back through the control circuit when the output of the panel is lower than the battery.

► FIGURE GA2-4

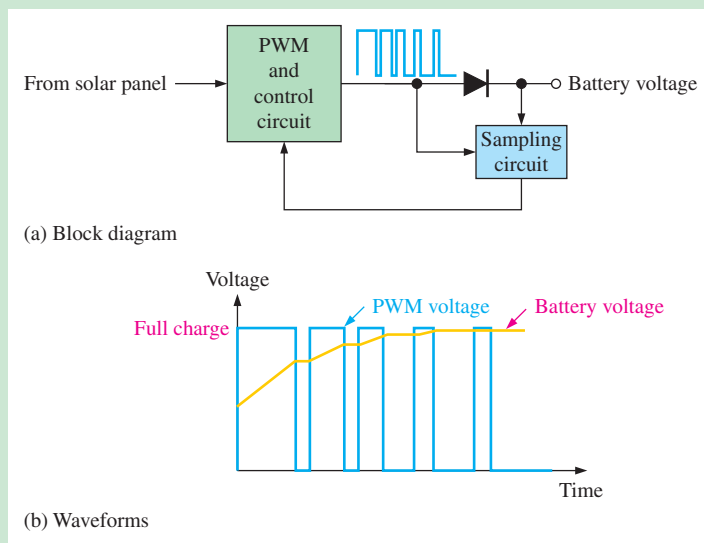
Basic concept of the on/off charge controller.



PWM (pulse width modulation) charge controllers gradually reduce the amount of power applied to the batteries as the batteries get closer to full charge. This type of controller allows the batteries to be more fully charged with less stress on the batteries. This extends

the life of the batteries and constantly maintains the batteries in a fully charged state (called “float”) during sunlight hours. The PWM controller produces a series of pulses to charge the batteries instead of a constant charge. The battery voltage is constantly monitored to determine how to adjust the frequency of the pulses and the pulse widths. When the batteries are fully charged and there is no load to drain them, the controller produces very short pulses at a low rate or no pulses at all. When the batteries are discharged, long pulses at a high rate are sent or the controller may go into a constant-charging mode, depending on the amount of discharge.

Figure GA2–5 shows the basic concept of a PWM charge controller. In part (a), the PWM and control circuit produces pulses based on the input from the sampling circuit. The sampling circuit determines the actual battery voltage by sampling the voltage between pulses. The diode acts as a rectifier and also blocks discharge of the battery back through the charger at night. Part (b) demonstrates how the battery charges during each pulse and how the width and the time between pulses change as the battery charges.



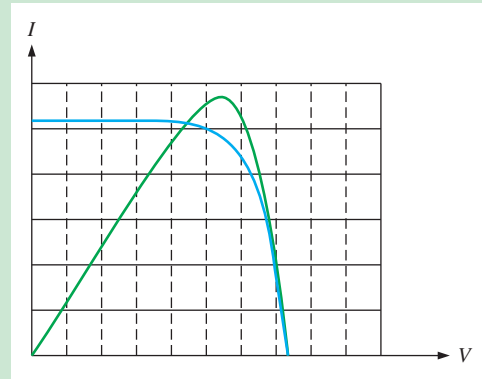
◀ FIGURE GA2–5

Basic concept of a PWM charge controller.

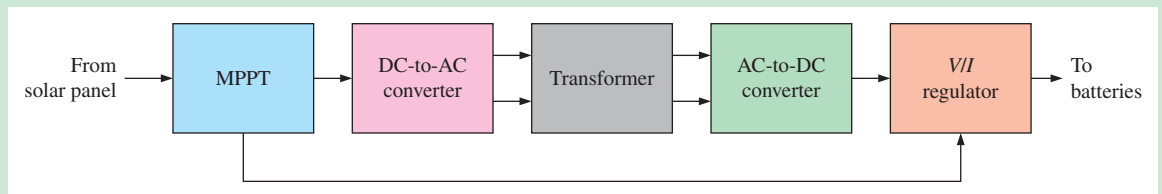
As you have learned, the output voltage of a solar panel varies greatly with the amount of sunlight and with the air temperature. For this reason, solar panels with voltage ratings higher than the battery voltage must be used in order to provide sufficient charging voltage to the battery under less than optimum conditions. As mentioned earlier, a 12 V solar panel may produce 20 V under optimum conditions but can produce only a certain amount of current. For example, if a solar panel can produce 8 A at 20 V, it is rated at 160 W. Batteries like to be charged at a voltage a little higher than their rated voltage. If a 12 V battery is being charged at 14 V, and it is drawing the maximum 8 A from the solar panel, the power delivered to the battery is $8 \text{ A} \times 14 \text{ V} = 112 \text{ W}$ instead of the 160 W produced by the solar panel at 20 V. The batteries only stored 70% of the available energy because the 12 V battery cannot operate at 20 V.

MPPT (maximum power point tracker) charge controllers eliminate much of the energy loss found in the other types of controllers and produce much higher efficiencies. The MPPT continuously tracks the input voltage and current from the solar panel to determine when the peak input power occurs and then adjusts the voltage to the battery to optimize the charging. This results in a maximum power transfer from the solar panel to the battery. In Figure GA2–6, the blue curve is the voltage–current characteristic for a certain solar panel under a specified condition of incident light. The green curve is the power showing where the peak occurs, which is in the knee of the V - I curve. If the incident light decreases, the curves will shift down.

► **FIGURE GA2-6**
 Example of a solar panel *V-I* and power curves.



The MPPT is basically a DC-to-DC converter. A simplified block diagram showing the basic functional concept is shown in Figure GA2-7. Although there are several ways in which the MPPT can be implemented, the figure illustrates the basic functions. The DC/AC converter, the transformer, and the AC/DC converter isolate the dc input from the dc output, so the output can be adjusted for maximum power. For example, if a 160 W solar panel produces 20 V at 8 A, it needs to be reduced to approximately 13.6 V to charge a 12 V battery. A normal charger will not be able to provide more than 8 A at 13.6 V (or 109 W), which means the panel is not being used efficiently and only 76% of the available power from the solar panel is used. An MPPT charge controller can supply about 11 A at 13.6 V (150 W), thus decreasing the charging time and producing a better match between the panel and the battery. In this case, the panel is being used more efficiently because it is able to deliver about 94% of the available power to the battery.



▲ **FIGURE GA2-7**
 Basic concept of an MPPT charge controller.

QUESTIONS

Some questions may require research beyond the content of this coverage. Answers can be found at www.pearsonhighered.com/floyd.

1. Why must deep-cycle batteries be used in solar power systems?
2. Why should a 12 V battery be charged at a higher than its rated voltage?
3. Which type of charge controller is the most efficient?
4. What range in terms of power is commercially available in charge controllers?
5. Two 12 V, 250 Ah batteries are connected in series and then connected in parallel with two more series-connected batteries of the same type. What is the total output voltage and Ah rating of the battery array?



The following websites are recommended for viewing charge controllers in action. Many other websites are also available.

<http://www.youtube.com/watch?v=iifz1DxeaDQ>

<http://www.youtube.com/watch?v=P2XSbDRi6wo>

<http://www.youtube.com/watch?v=ITDh4aKXd80&feature=related>