2

DIODE APPLICATIONS

INTRODUCTION

In Chapter 1, you learned that a semiconductor diode is a device with a single *pn* junction. 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 data sheet is discussed for specific diodes.

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Explain and analyze the operation of half-wave rectifiers
- Explain and analyze the operation of full-wave rectifiers
- Explain and analyze the operation and characteristics of power supply filters and regulators
- Explain and analyze the operation of diode limiting and clamping circuits
- Explain and analyze the operation of diode voltage multipliers
- Interpret and use a diode data sheet
- Troubleshoot power supplies and diode circuits

KEY TERMS

Power supply

Filter

Regulator

Half-wave rectifier

Peak inverse voltage (PIV)

Full-wave rectifier

Ripple voltage

Line regulation

Load regulation

Limiter

Clamper

Troubleshooting

■■■ SYSTEM APPLICATION PREVIEW

As a technician for an electronics company, you are given the responsibility for the final design and testing of a power supply circuit board that your company plans to use in several of its products. You will apply your knowledge of diode circuits to the system application at the end of the chapter.

WWW. VISIT THE COMPANION WEBSITE

Study aids for this chapter are available at

http://www.prenhall.com/floyd

2–1 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. In this section, you will study the most basic type of rectifier, the half-wave rectifier.

After completing this section, you should be able to

- **Explain and analyze the operation of half-wave rectifiers**
- Describe a basic dc power supply and half-wave rectification
- Determine the average value of a half-wave rectified voltage
- Discuss the effect of barrier potential on a half-wave rectifier output
- Define *peak inverse voltage (PIV)*
- Describe the transformer-coupled half-wave rectifier

The Basic DC Power Supply

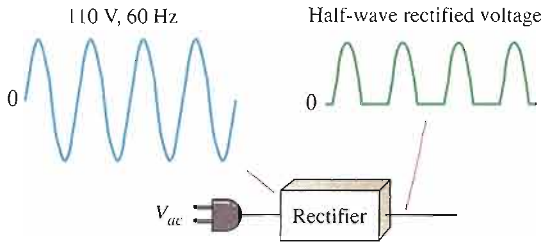
The dc **power supply** converts the standard 110 V, 60 Hz ac available at wall outlets into a constant dc voltage. It is one of the most common electronic circuits that you will find. The dc voltage produced by a power supply is used to power all types of electronic circuits, such as television receivers, stereo systems, VCRs, CD players, and most laboratory equipment.

Basic block diagrams for a rectifier and complete power supply are shown in Figure 2–1. The **rectifier** can be either a half-wave rectifier or a full-wave rectifier (covered in Section 2–2). The rectifier converts the ac input voltage to a pulsating dc voltage, which is half-wave rectified as shown in Figure 2–1(a). A block diagram for a complete power supply is shown in part (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 2–3. 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 device to more complex integrated circuits. The load is a circuit or device for which the power supply is producing the dc voltage and load current.

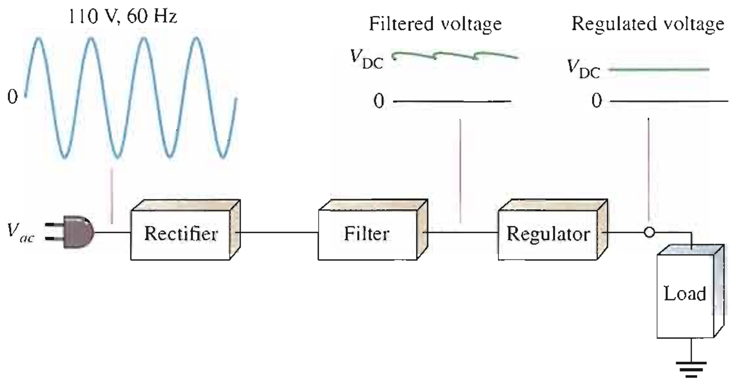
The Half-Wave Rectifier

Figure 2–2 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.

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 2–2(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).



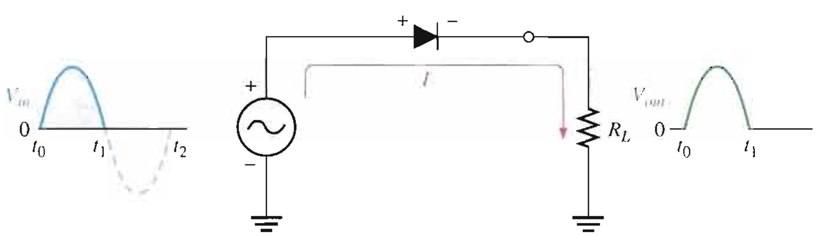
(a) Half-wave rectifier



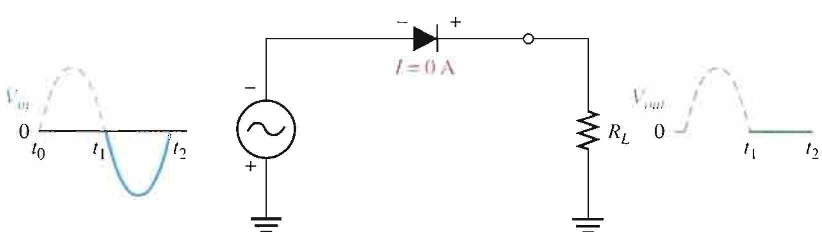
(b) Complete power supply with rectifier, filter, and regulator

FIGURE 2–1

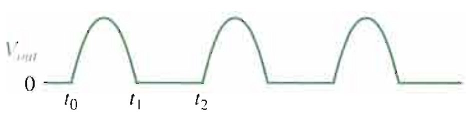
Block diagram of a rectifier and a dc power supply with a load.



(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 2–2

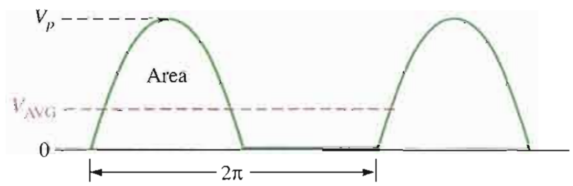
Half-wave rectifier operation. The diode is considered to be ideal.

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 2–3, and then dividing by 2π, the number of radians in a full cycle. The result of this is expressed in Equation 2–1, 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. See Appendix B for a detailed derivation.

Equation 2–1
$$V_{AVG} = \frac{V_p}{\pi}$$

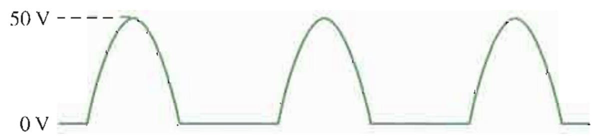
▶ FIGURE 2–3

Average value of the half-wave rectified signal.



EXAMPLE 2–1

What is the average value of the half-wave rectified voltage in Figure 2–4?



▲ FIGURE 2–4

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

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.

*Answers are at the end of the chapter.

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 2–5. The expression for the peak output voltage is

Equation 2–2
$$V_{p(out)} = V_{p(in)} - 0.7\text{ V}$$

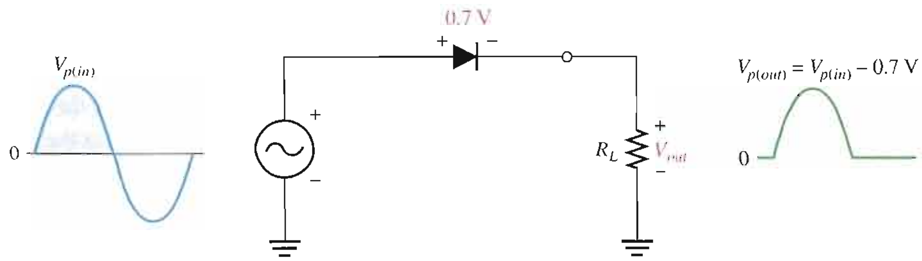


FIGURE 2–5

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 2–2

Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–6. The 1N4001 and 1N4003 are specific rectifier diodes.

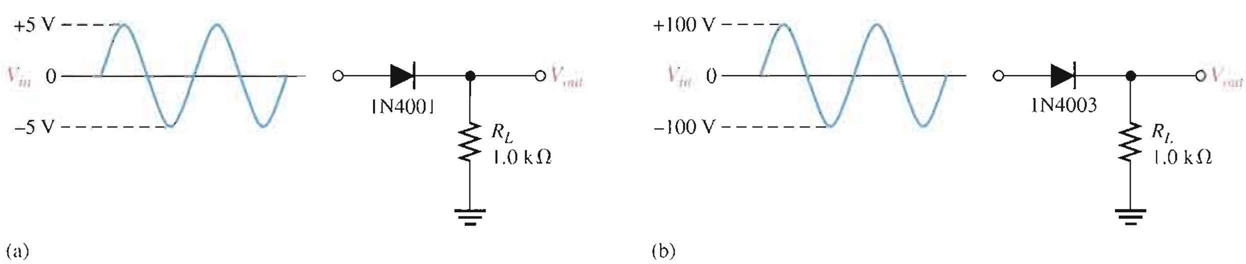


FIGURE 2–6

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 2–7. 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).

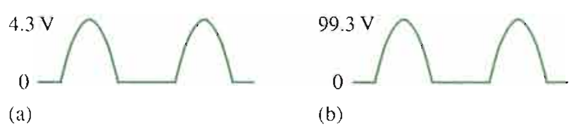


FIGURE 2–7

Output voltages for the circuits in Figure 2–6. Obviously, they are not shown on the same scale.

Related Problem Determine the peak output voltages for the rectifiers in Figure 2–6 if the peak input in part (a) is 3 V and the peak input in part (b) is 210 V.

Open the Multisim file E02-02 in the Examples folder on your CD-ROM. 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)

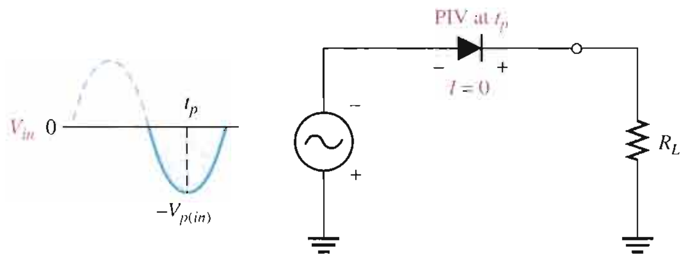
The **peak inverse voltage (PIV)** equals the peak value of the input voltage, and the diode must be capable of withstanding this amount of repetitive reverse voltage. For the diode in Figure 2–8, the maximum value of reverse voltage, designated as PIV, occurs at the peak of each negative alternation of the input voltage when the diode is reverse-biased.

Equation 2–3

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

▶ **FIGURE 2–8**

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.

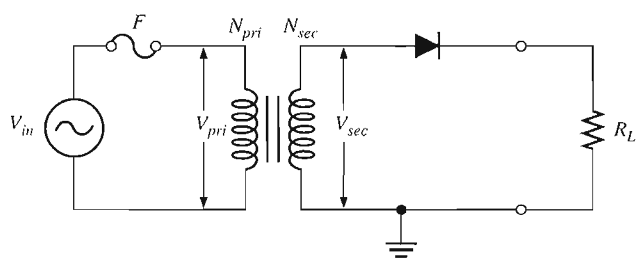


Half-Wave Rectifier with Transformer-Coupled Input Voltage

A transformer is often used to couple the ac input voltage from the source to the rectifier, as shown in Figure 2–9. Transformer coupling provides two advantages. First, it allows the source voltage to be stepped up or stepped down as needed. Second, the ac source is electrically isolated from the rectifier, thus preventing a shock hazard in the secondary circuit.

▶ **FIGURE 2–9**

Half-wave rectifier with transformer-coupled input voltage.



From your study of basic ac circuits recall that the secondary voltage of a transformer equals the turns ratio, n, times the primary voltage, as expressed in Equation 2–4. We will define the turns ratio as the ratio of secondary turns, N_{sec}, to the primary turns, N_{pri}: $n = N_{sec}/N_{pri}$.

Equation 2–4

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

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 2–2. Therefore, Equation 2–2 written in terms of $V_{p(sec)}$ is

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

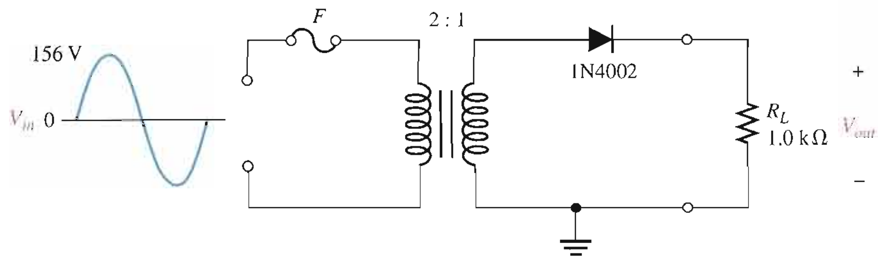
and Equation 2–3 in terms of $V_{p(sec)}$ is

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

EXAMPLE 2–3

Determine the peak value of the output voltage for Figure 2–10 if the turns ratio is 0.5.

▶ FIGURE 2–10



Solution

$$V_{p(pri)} = V_{p(in)} = 156\text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.5(156\text{ V}) = 78\text{ V}$$

The rectified peak output voltage is

$$V_{p(out)} = V_{p(sec)} - 0.7\text{ V} = 78\text{ V} - 0.7\text{ V} = \mathbf{77.3\text{ V}}$$

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

Related Problem

(a) Determine the peak value of the output voltage for Figure 2–10 if $n = 2$ and $V_{p(in)} = 312$ V.

(b) What is the PIV across the diode?

(c) Describe the output voltage if the diode is turned around.

Open the Multisim file E02-03 in the Examples folder on your CD-ROM. For the specified input, measure the peak output voltage. Compare your measured result with the calculated value.

SECTION 2–1 REVIEW

Answers are at the end of the chapter.

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

2–2 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

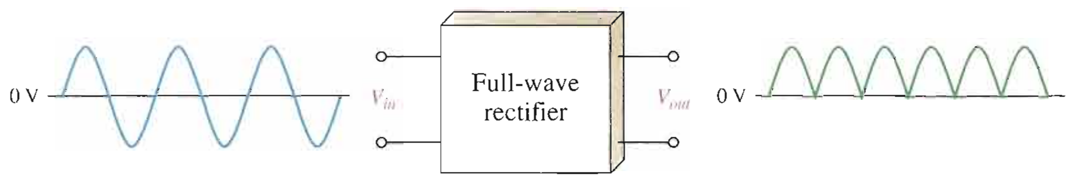
- **Explain and analyze the operation of full-wave rectifiers**

- Discuss how full-wave rectification differs from half-wave rectification
- Determine the average value of a full-wave rectified voltage
- Describe the operation of a center-tapped full-wave rectifier
- Explain how the transformer turns ratio affects the rectified output voltage
- Determine the peak inverse voltage (PIV)
- Describe the operation of a bridge full-wave rectifier
- Compare the center-tapped rectifier and the bridge rectifier

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 that pulsates every half-cycle of the input, as shown in Figure 2–11.

▶ FIGURE 2–11

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:

Equation 2–5

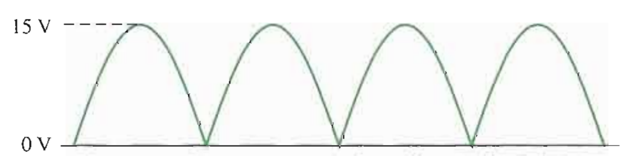
$$V_{AVG} = \frac{2V_p}{\pi}$$

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

EXAMPLE 2–4

Find the average value of the full-wave rectified voltage in Figure 2–12.

▶ FIGURE 2–12



Solution

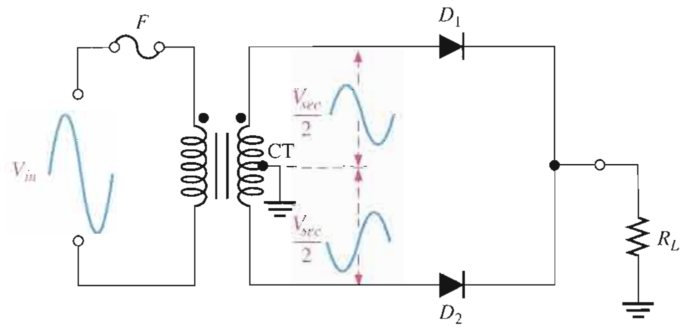
$$V_{AVG} = \frac{2V_p}{\pi} = \frac{2(15\text{ V})}{\pi} = \mathbf{9.55\ V}$$

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.

The Center-Tapped Full-Wave Rectifier

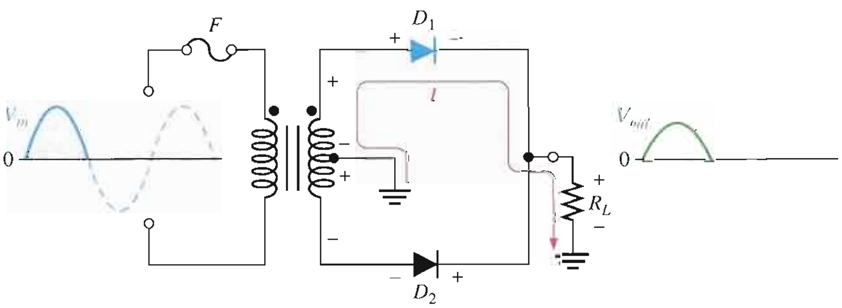
A **center-tapped rectifier** is a type of full-wave rectifier that uses two diodes connected to the secondary of a center-tapped transformer, as shown in Figure 2–13. The input voltage is coupled through the transformer to the center-tapped secondary. Half of the total secondary voltage appears between the center tap and each end of the secondary winding as shown.



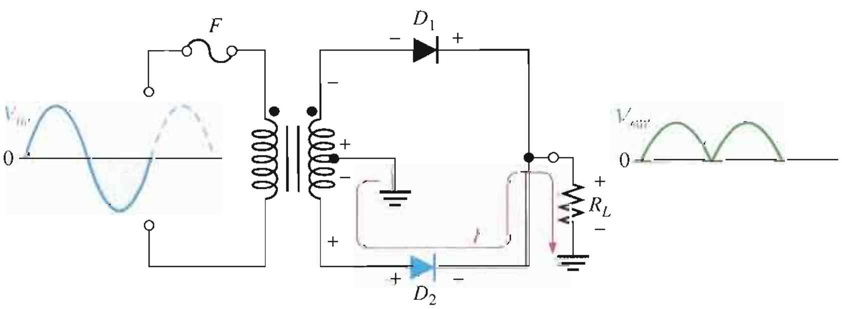
◄ **FIGURE 2–13**

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 2–14(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 2–14(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.



(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.

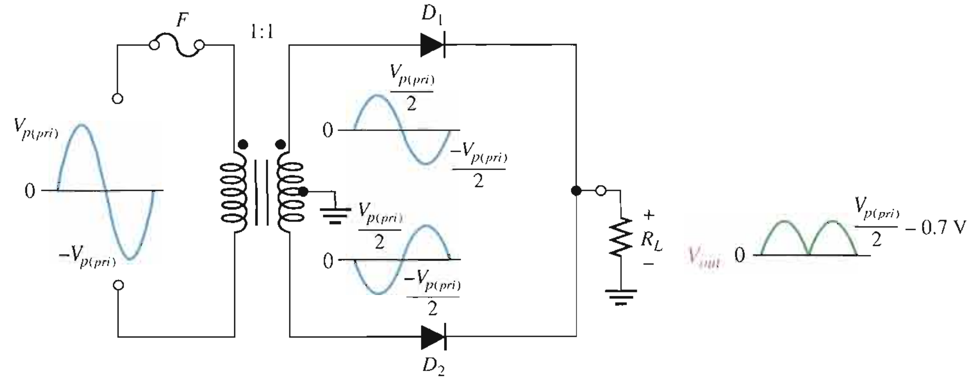
◄ **FIGURE 2–14**

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.

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 2–15. Half of the primary voltage appears across each half of the secondary winding ($V_{p(sec)} = V_{p(pri)}$). We will begin referring to the forward voltage due to the barrier potential as the **diode drop**.

FIGURE 2–15

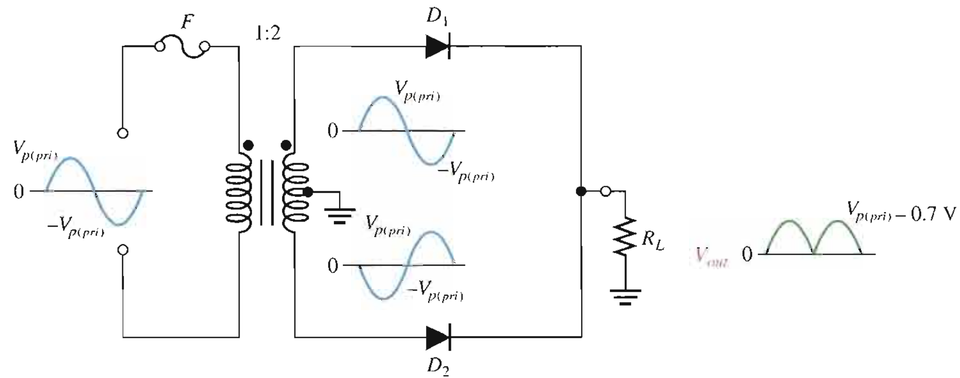
Center-tapped full-wave rectifier with a transformer turns ratio of 1. $V_{p(pri)}$ is the peak value of the primary voltage.



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 2–16. 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 2–16

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.

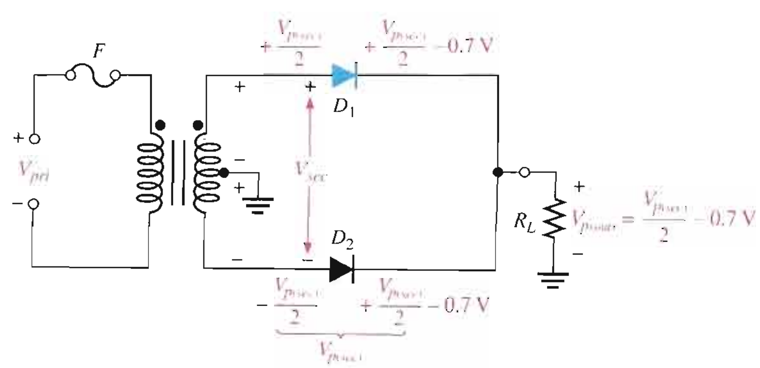
Equation 2–6

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

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 2–17 where D_2 is assumed to be reverse-biased and D_1 is assumed to be forward-biased to illustrate the concept.

FIGURE 2–17

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

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

Since $V_{p(out)} = V_{p(sec)}/2 - 0.7$ 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

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

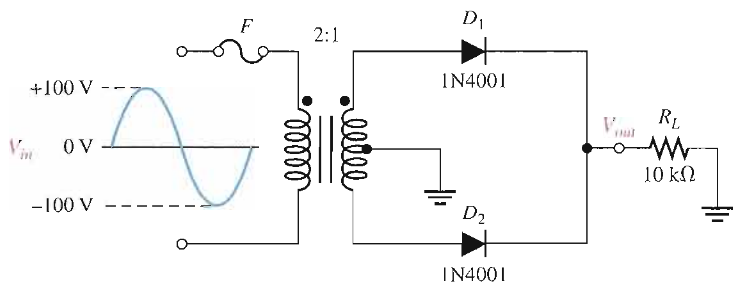
Equation 2–7

EXAMPLE 2–5

(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 2–18.

(b) What minimum PIV rating must the diodes have?

FIGURE 2–18

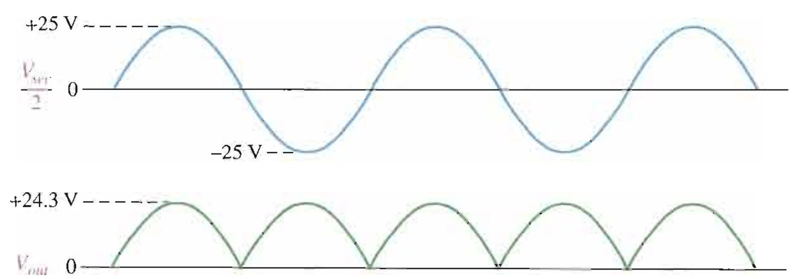


Solution **(a)** The transformer turns ratio $n = 0.5$. The total peak secondary voltage is

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

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 2–19.

FIGURE 2–19



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

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

Related Problem What diode PIV rating is required to handle a peak input of 160 V in Figure 2–18?

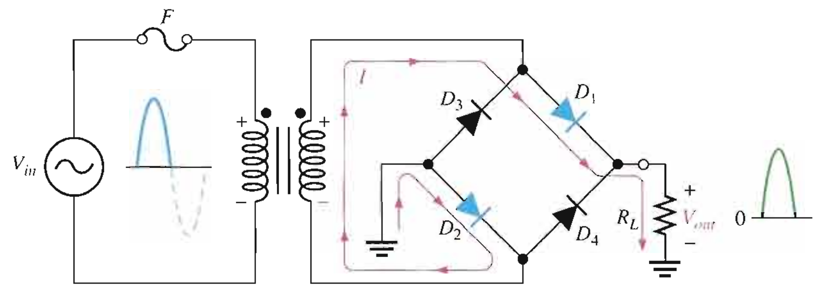
Open the Multisim file E02-05 in the Examples folder on your CD-ROM. For the specified input voltage, measure the voltage waveforms across each half of the secondary and across the load resistor. Compare with the results shown in the example.

The Bridge Full-Wave Rectifier

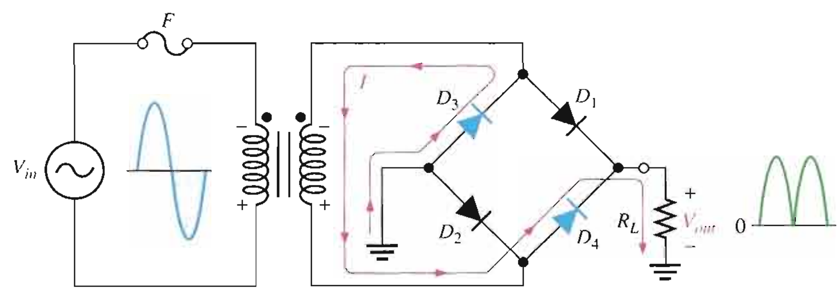
The **bridge rectifier** uses four diodes connected as shown in Figure 2–20. When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L that looks like the positive half of the input cycle. During this time, diodes D_3 and D_4 are reverse-biased.

FIGURE 2–20

Operation of a bridge rectifier.



(a) During the positive half-cycle of the input, D_1 and D_2 are forward-biased and conduct current. D_3 and D_4 are reverse-biased.

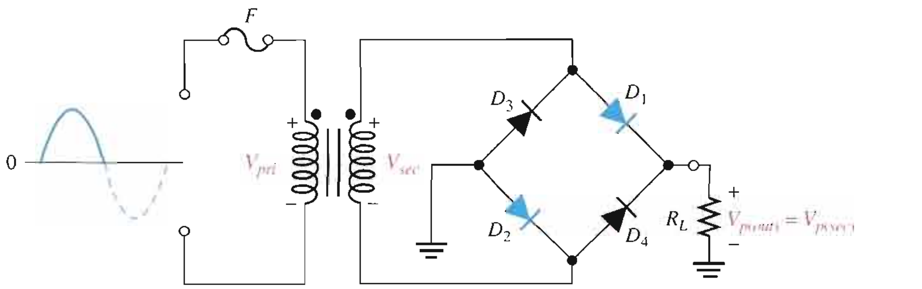


(b) During the negative half-cycle of the input, D_3 and D_4 are forward-biased and conduct current. D_1 and D_2 are reverse-biased.

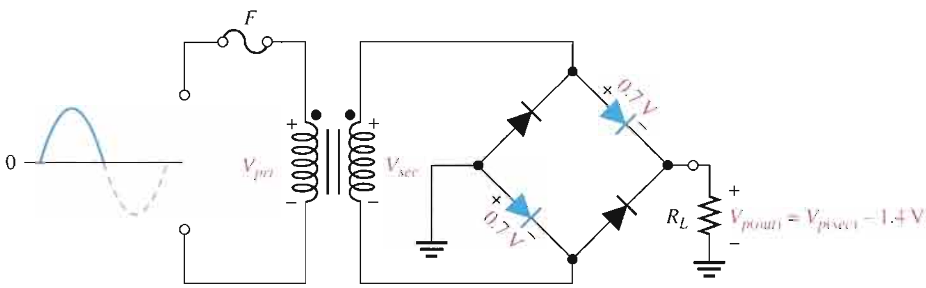
When the input cycle is negative as in Figure 2–20(b), diodes D_3 and D_4 are forward-biased and conduct current in the same direction through R_L as during the positive half-cycle. During the negative half-cycle, D_1 and D_2 are reverse-biased. A full-wave rectified output voltage appears across R_L as a result of this action.

Bridge Output Voltage A bridge rectifier with a transformer-coupled input is shown in Figure 2–21(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.

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



(a) Ideal diodes



(b) Practical diodes (Diode drops included)

FIGURE 2–21

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

As you can see in Figure 2–21(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 2–8

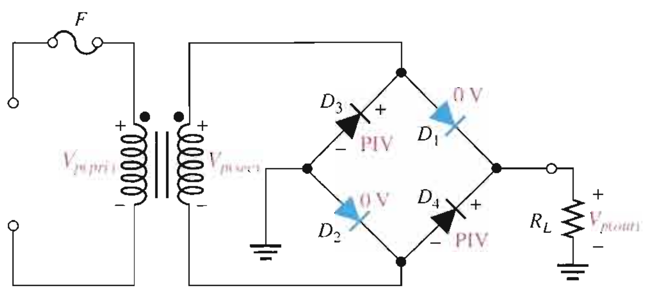
Peak Inverse Voltage Let's assume that D_1 and D_2 are forward-biased and examine the reverse voltage across D_3 and D_4. Visualizing D_1 and D_2 as shorts (ideal model), as in Figure 2–22(a), you can see that D_3 and D_4 have a peak inverse voltage equal to the peak secondary voltage. Since the output voltage is *ideally* equal to the secondary voltage,

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

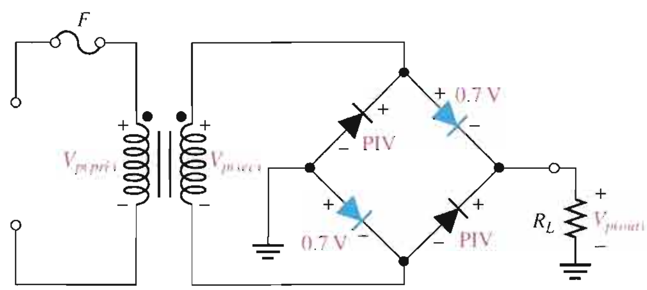
If the diode drops of the forward-biased diodes are included as shown in Figure 2–22(b), the peak inverse voltage across each reverse-biased diode in terms of $V_{p(out)}$ is

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

Equation 2–9



(a) For the ideal diode model (forward-biased diodes D_1 and D_2 are shown in blue), PIV = $V_{p(out)}$.



(b) For the practical diode model (forward-biased diodes D_1 and D_2 are shown in blue), PIV = $V_{p(out)}$ + 0.7 V.

FIGURE 2–22

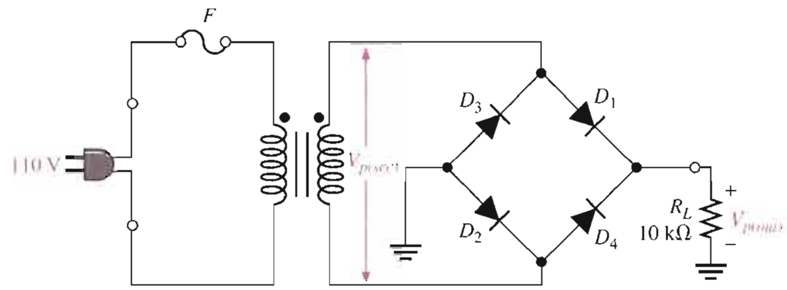
Peak inverse voltages across diodes D_3 and D_4 in a bridge rectifier during the positive half-cycle of the secondary voltage.

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.

EXAMPLE 2–6

Determine the peak output voltage for the bridge rectifier in Figure 2–23. 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 110 V across the primary.

▶ FIGURE 2–23



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 2–23 if the transformer produces an rms secondary voltage of 30 V. What is the PIV rating for the diodes?

Open the Multisim file E02-06 in the Examples folder on your CD-ROM. Measure the output voltage and compare to the calculated value.

SECTION 2–2 REVIEW

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?

2–3 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 the operation and characteristics of power supply filters and regulators**
- Explain the purpose of a filter
- Describe the capacitor-input filter
- Define *ripple voltage* and calculate the ripple factor
- Discuss surge current in a capacitor-input filter
- Discuss voltage 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 2–24 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*.

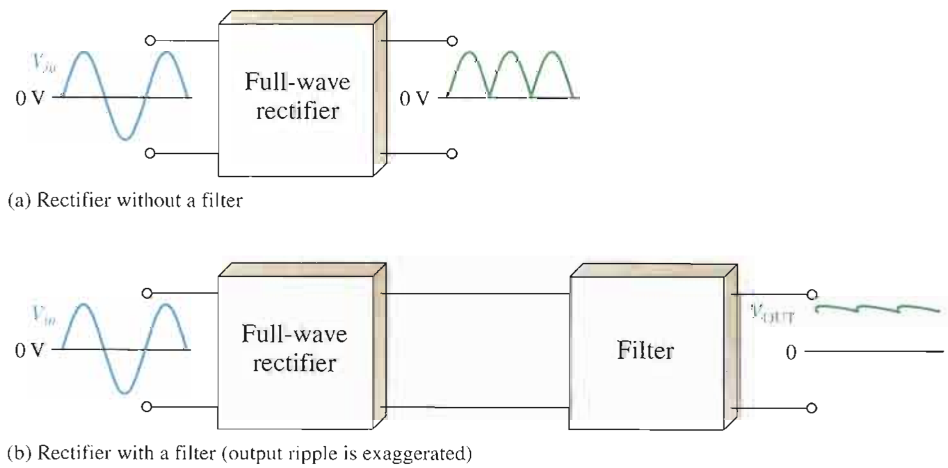


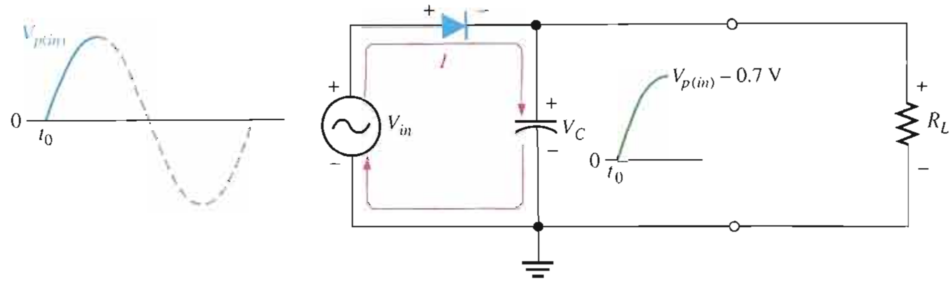
FIGURE 2–24
Power supply filtering.

Capacitor-Input Filter

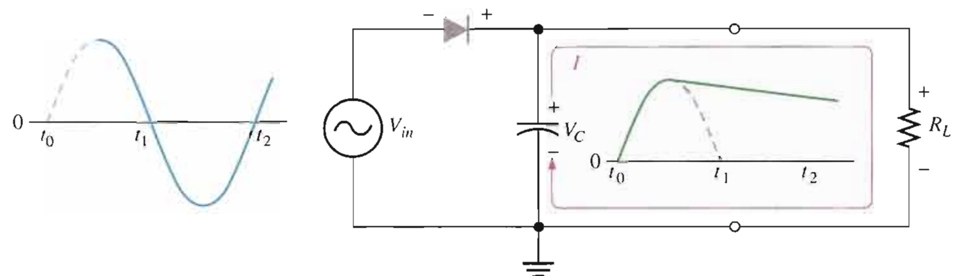
A half-wave rectifier with a capacitor-input filter is shown in Figure 2–25. The filter is simply a capacitor connected from the rectifier output to ground. R_L represents the equivalent resistance of a load. We will use the half-wave rectifier to illustrate the basic principle and then expand the concept to full-wave rectification.

FIGURE 2–25

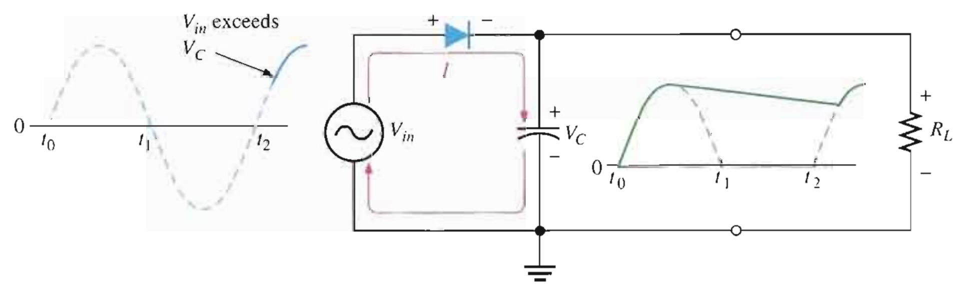
Operation of a half-wave rectifier with a capacitor-input filter. The current indicates charging or discharging of the capacitor.



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



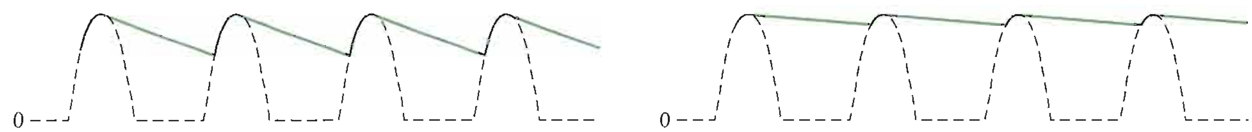
(b) The capacitor discharges through R_L after peak of positive alternation when the diode is reverse-biased. This discharging occurs during the portion of the input voltage indicated by the solid blue curve.



(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 blue curve.

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 2–25(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_LC 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.

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 2–26.



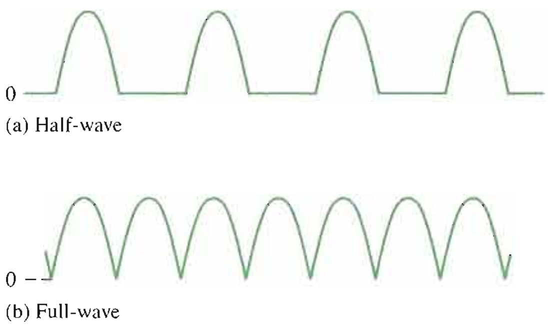
(a) Larger ripple means less effective filtering.

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

▲ FIGURE 2–26

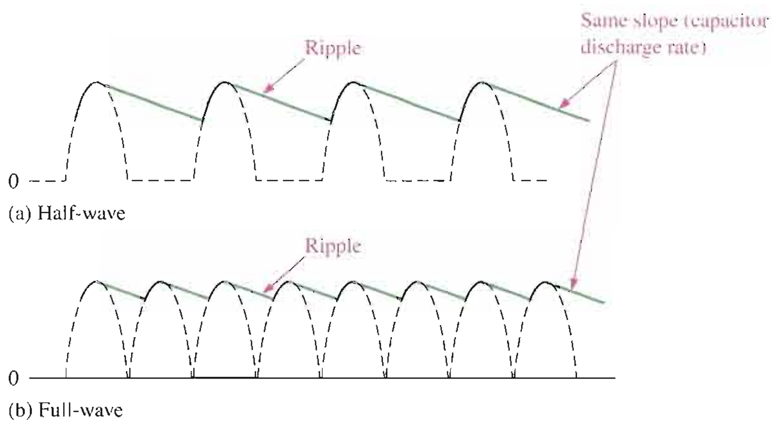
Half-wave ripple voltage (green line).

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 2–27. 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 2–28.



◄ FIGURE 2–27

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



◄ FIGURE 2–28

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

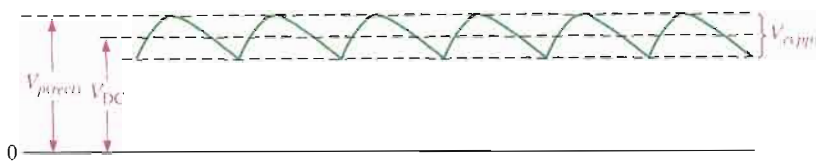
$$r = \frac{V_{r(pp)}}{V_{DC}}$$

Equation 2–10

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 2–29. 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 2–29

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 expressions. The variable $V_{p(rect)}$ is the unfiltered peak rectified voltage.

Equation 2–11

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)}$$

Equation 2–12

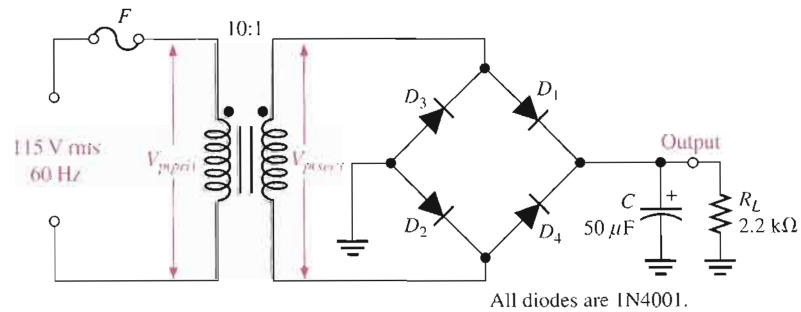
$$V_{DC} \cong \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)}$$

These expressions are derived in Appendix B.

EXAMPLE 2–7

Determine the ripple factor for the filtered bridge rectifier with a load as indicated in Figure 2–30.

▶ FIGURE 2–30



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

$$V_{p(pri)} = 1.414V_{rms} = 1.414(115\text{ V}) = 163\text{ V}$$

The peak secondary voltage is

$$V_{p(sec)} = nV_{p(pri)} = 0.1(163\text{ V}) = 16.3\text{ V}$$

The unfiltered peak full-wave rectified voltage is

$$V_{p(rect)} = V_{p(sec)} - 1.4\text{ V} = 16.3\text{ V} - 1.4\text{ V} = 14.9\text{ V}$$

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

$$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)} = \left(\frac{1}{(120\text{ Hz})(2.2\text{ k}\Omega)(50\ \mu\text{F})}\right)14.9\text{ V} = 1.13\text{ V}$$

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

$$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)} = \left(1 - \frac{1}{(240\text{ Hz})(2.2\text{ k}\Omega)(50\ \mu\text{F})}\right)14.9\text{ V} = 14.3\text{ V}$$

The resulting ripple factor is

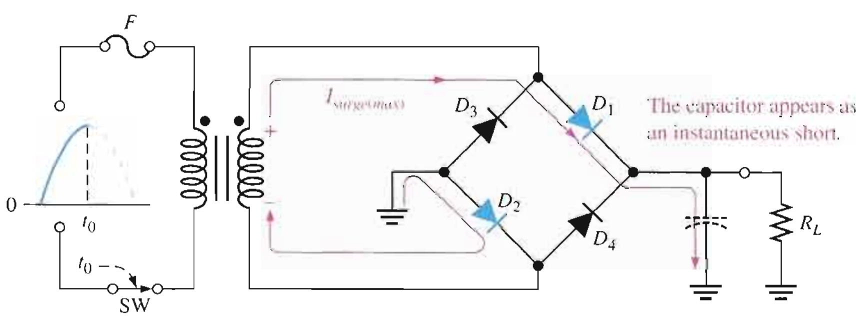
$$r = \frac{V_{r(pp)}}{V_{DC}} = \frac{1.13\text{ V}}{14.3\text{ V}} = \mathbf{0.079}$$

The percent ripple is 7.9%.

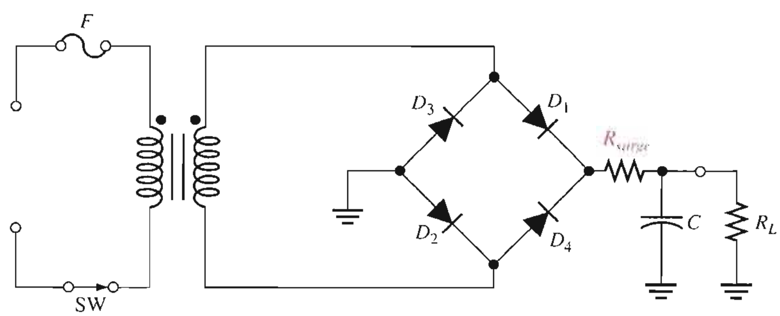
Related Problem Determine the peak-to-peak ripple voltage if the filter capacitor in Figure 2–30 is increased to 100 μF and the load resistance changes to 12 kΩ.

Open the Multisim file E02-07 in the Examples folder on your CD-ROM. 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 2–31(a) 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.



(a) Maximum surge current occurs when switch is closed at peak of an input cycle.



(b) A series resistor (R_{surge}) limits the surge current.

FIGURE 2–31

Surge current in a capacitor-input filter.

It is possible that the surge current could destroy the diodes, and for this reason a surge-limiting resistor is sometimes connected, as shown in Figure 2–31(b). The value of this resistor must be small compared to R_L. Also, the diodes must have a maximum forward surge current rating such that they can withstand the momentary surge of current. This rating is specified on diode data sheets as I_{FSM}. The minimum surge resistor value can be calculated as follows:

Equation 2–13

$$R_{surge} = \frac{V_{p(sec)} - 1.4\text{ V}}{I_{FSM}}$$

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 2–32. 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.

A basic fixed power supply with a +5 V voltage regulator is shown in Figure 2–33. Specific integrated circuit fixed three-terminal regulators are covered in Chapter 18.

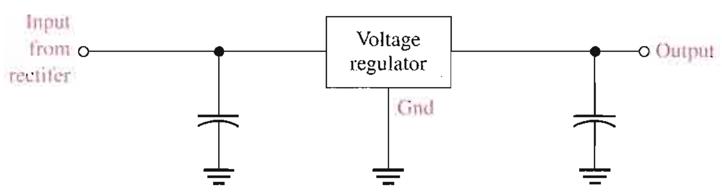


FIGURE 2–32

A voltage regulator with input and output capacitors.

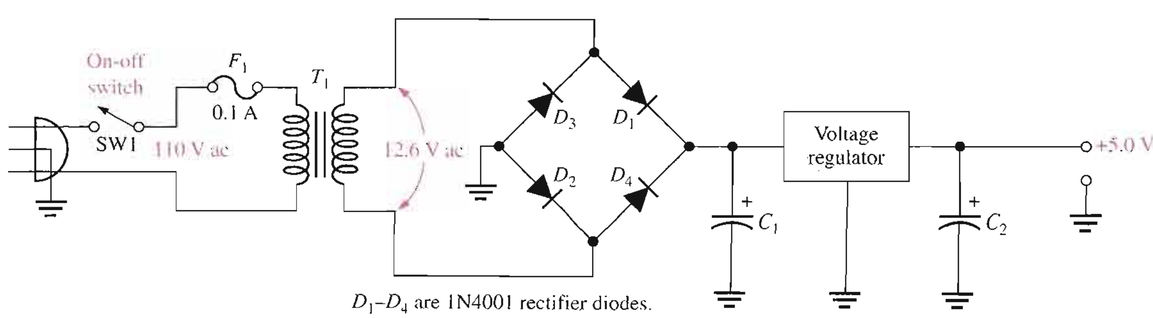


FIGURE 2–33

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** 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.

$$\text{Line regulation} = \left(\frac{\Delta V_{\text{OUT}}}{\Delta V_{\text{IN}}}\right)100\%$$

Equation 2–14

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:

$$\text{Load regulation} = \left(\frac{V_{\text{NL}} - V_{\text{FL}}}{V_{\text{FL}}}\right)100\%$$

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 2–8

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

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

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 2–3 REVIEW

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?

2–4 DIODE LIMITING AND CLAMPING CIRCUITS

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 limiting and clamping circuits**
- Explain the operation of diode limiters
- Determine the output voltage of a biased limiter
- Use voltage-divider bias to set the limiting level
- Explain the operation of diode clampers

Diode Limiters

Figure 2–34(a) shows a diode **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. Because the cathode is at ground potential (0 V), the anode cannot exceed 0.7 V (assuming silicon). So point A is limited to +0.7 V when the input voltage exceeds this 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:

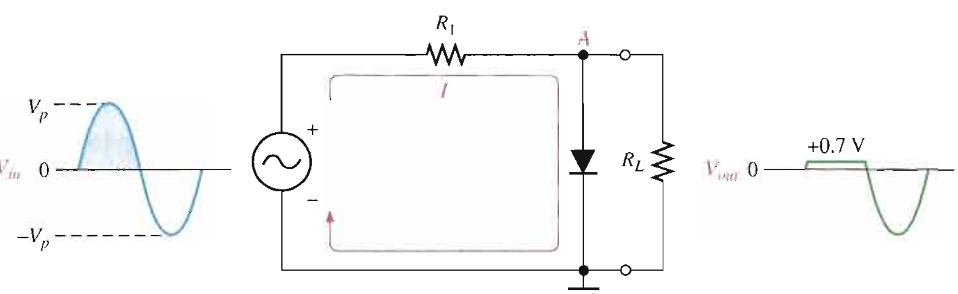
$$V_{out} = \left(\frac{R_L}{R_1 + R_L}\right)V_{in}$$

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

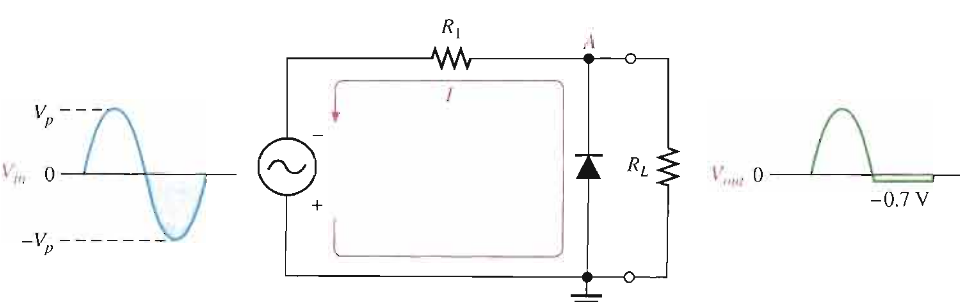
If the diode is turned around, as in Figure 2–34(b), the negative part of the input voltage is clipped off. When the diode is forward-biased during the negative part of the input voltage, point A is held at −0.7 V by the diode drop. When the input voltage goes above −0.7 V, the diode is no longer forward-biased; and a voltage appears across R_L proportional to the input voltage.

▶ **FIGURE 2–34**

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.

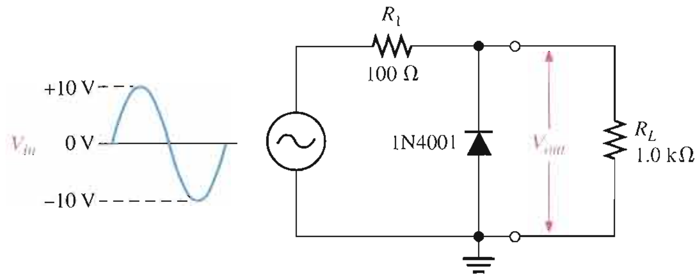


(b) Limiting of the negative alternation. The diode is forward-biased during the negative alternation (below −0.7 V) and reverse-biased during the positive alternation.

EXAMPLE 2–9

What would you expect to see displayed on an oscilloscope connected across R_L in the limiter shown in Figure 2–35?

▶ FIGURE 2–35



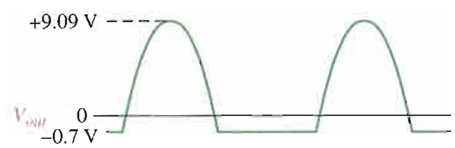
Solution The diode is forward-biased and conducts when the input voltage goes below −0.7 V. So, for the negative limiter, determine the peak output voltage across R_L by the following equation:

$$V_{p(out)} = \left(\frac{R_L}{R_1 + R_L}\right)V_{p(in)} = \left(\frac{1.0\text{ k}\Omega}{1.1\text{ k}\Omega}\right)10\text{ V} = 9.09\text{ V}$$

The scope will display an output waveform as shown in Figure 2–36.

▶ FIGURE 2–36

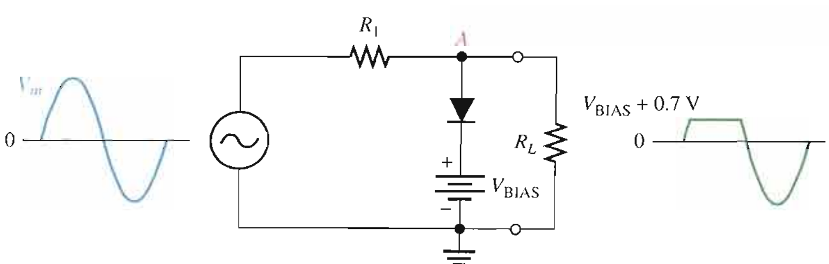
Output voltage waveform for Figure 2–35.



Related Problem Describe the output waveform for Figure 2–35 if R_L is changed to 680 Ω.

Open the Multisim file E02-09 in the Examples folder on your CD-ROM. 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 2–37. The voltage at point A must equal V_{BIAS} + 0.7 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_{BIAS} + 0.7 V so that all input voltage above this level is clipped off.



◀ FIGURE 2–37

A positive limiter.

To limit a voltage to a specified negative level, the diode and bias voltage must be connected as in Figure 2–38. In this case, the voltage at point A must go below $-V_{BIAS} - 0.7\text{ V}$ to forward-bias the diode and initiate limiting action as shown.

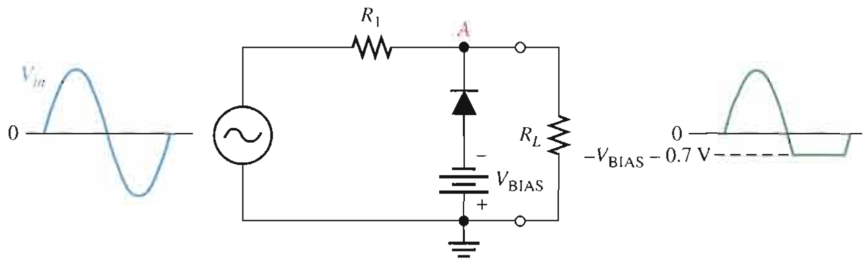
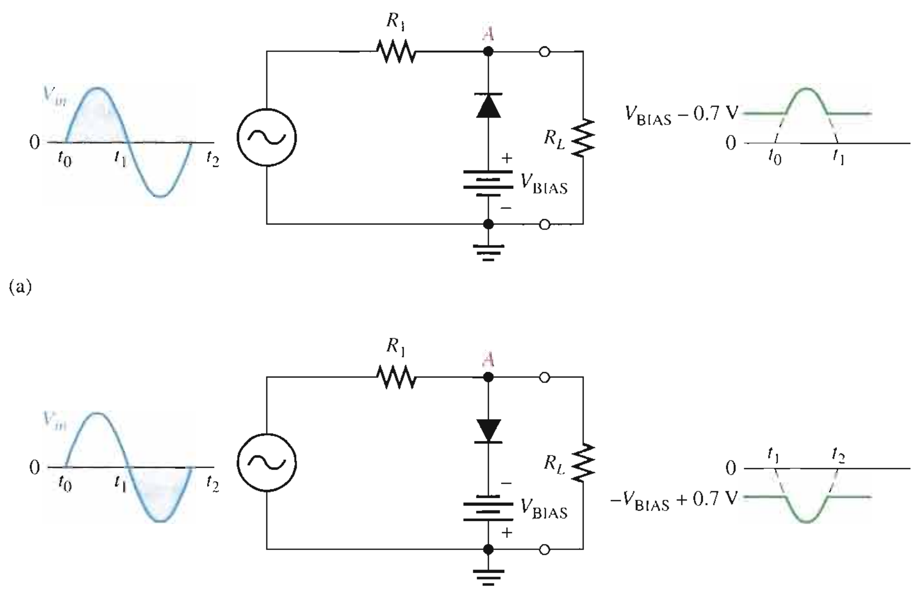


FIGURE 2–38

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 $V_{BIAS} - 0.7\text{ V}$, as shown by the output waveform in Figure 2–39(a). Similarly, the negative limiter can be modified to limit the output voltage to the portion of the input voltage waveform below $-V_{BIAS} + 0.7\text{ V}$, as shown by the output waveform in part (b).

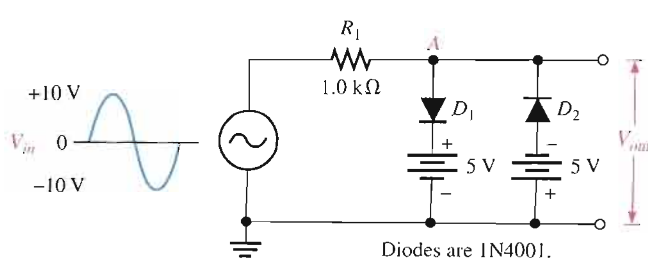
FIGURE 2–39



EXAMPLE 2–10

Figure 2–40 shows a circuit combining a positive limiter with a negative limiter. Determine the output voltage waveform.

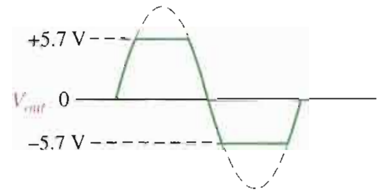
FIGURE 2–40



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 2–41.

FIGURE 2–41

Output voltage waveform for Figure 2–40.



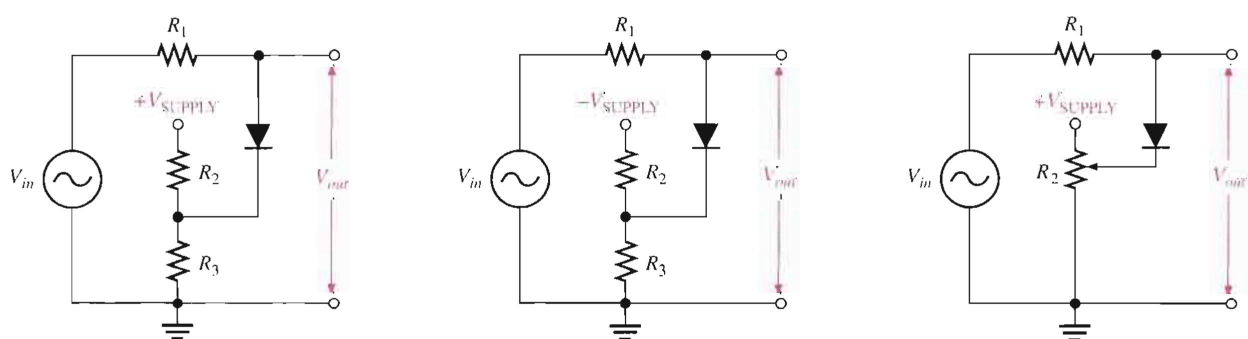
Related Problem Determine the output voltage waveform in Figure 2–40 if both dc sources are 10 V and the input voltage has a peak value of 20 V.

Open the Multisim file E02-10 in the Examples folder on your CD-ROM. 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 2–42. The bias voltage is set by the resistor values according to the voltage-divider formula.

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

A positively biased limiter is shown in Figure 2–42(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) Positive limiter (b) Negative limiter (c) Variable positive limiter

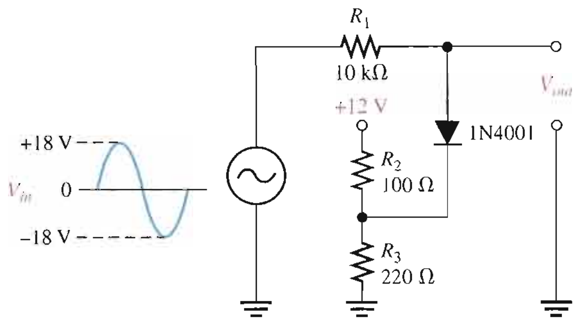
FIGURE 2–42

Diode limiters implemented with voltage-divider bias.

EXAMPLE 2–11

Describe the output voltage waveform for the diode limiter in Figure 2–43.

▶ FIGURE 2–43

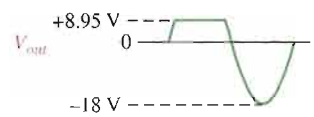


Solution The circuit is a positive limiter. Use the voltage-divider formula to determine the bias voltage.

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

The output voltage waveform is shown in Figure 2–44. The positive part of the output voltage waveform is limited to $V_{BIAS} + 0.7$ V.

▶ FIGURE 2–44



Related Problem How would you change the voltage divider in Figure 2–43 to limit the output voltage to +6.7 V?

Open the Multisim file E02-11 in the Examples folder on your CD-ROM. 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 2–45 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 ($V_{p(in)} - 0.7$ V), as shown in Figure 2–45(a). Just after the negative peak, the diode is reverse-biased. This is because the cathode is held near $V_{p(in)} - 0.7$ 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. For good clamping action, the RC time constant should be at least ten times the period of the input frequency.

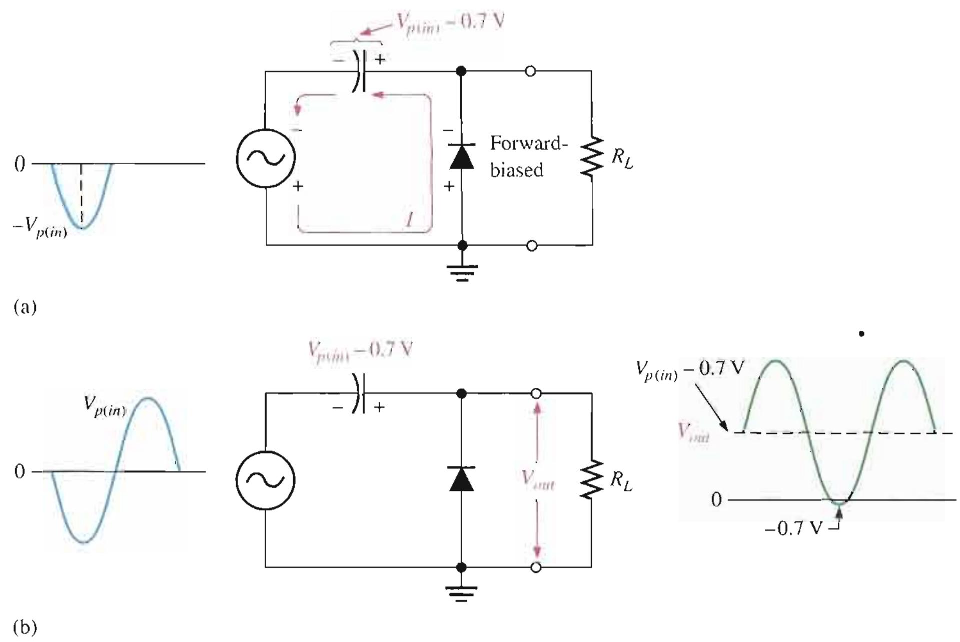


FIGURE 2-45

Positive clamper operation.

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 2–45(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 2–46.

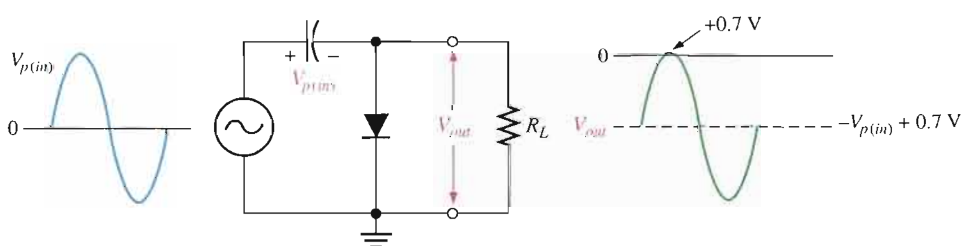


FIGURE 2-46

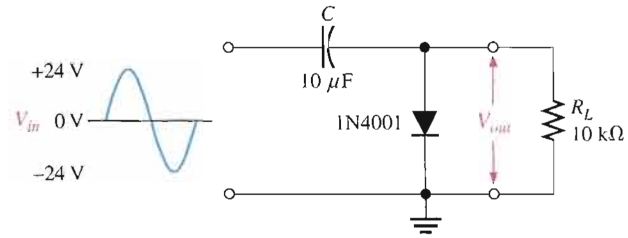
Negative clamper.

A Clamper Application A clamping circuit is often used in television receivers as a dc restorer. The incoming composite video signal is normally processed through capacitively coupled amplifiers that eliminate the dc component, thus losing the black and white reference levels and the blanking level. Before being applied to the picture tube, these reference levels must be restored.

EXAMPLE 2-12

What is the output voltage that you would expect to observe across R_L in the clamping circuit of Figure 2–47? Assume that RC is large enough to prevent significant capacitor discharge.

FIGURE 2-47



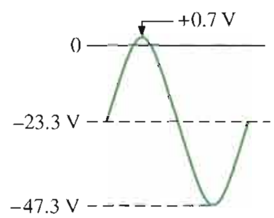
Solution Ideally, a negative dc value equal to the input peak less the diode drop is inserted by the clamping circuit.

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

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 V, as shown in Figure 2–48.

FIGURE 2-48

Output waveform across R_L for Figure 2-47.



Related Problem What is the output voltage that you would observe across R_L in Figure 2–47 for C = 22 μF and R_L = 18 kΩ?

Open the Multisim file E02-12 in the Examples folder on your CD-ROM. For the specified input, measure the output waveform. Compare with the waveform shown in the example.

SECTION 2-4 REVIEW

1. Discuss how diode limiters and diode clampers 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?

2-5 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 TV receivers.

After completing this section, you should be able to

- **Explain and analyze the operation of diode voltage multipliers**
- Discuss voltage doublers
- Discuss voltage triplers
- Discuss voltage quadruplers

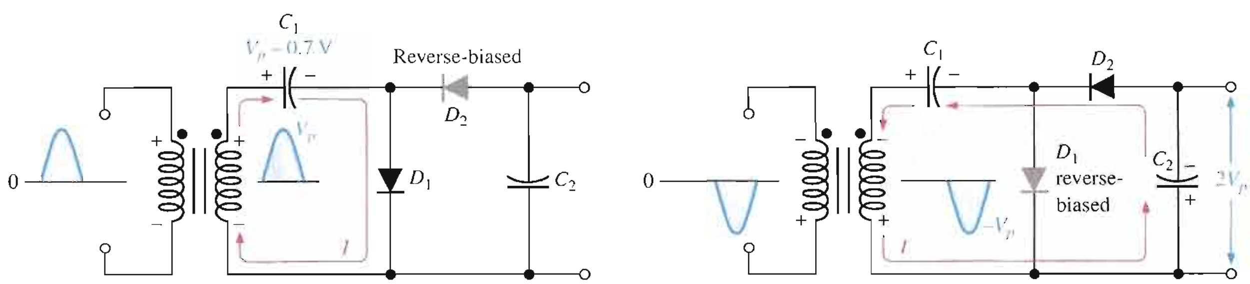
Voltage Doubler

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 2–49. 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,

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



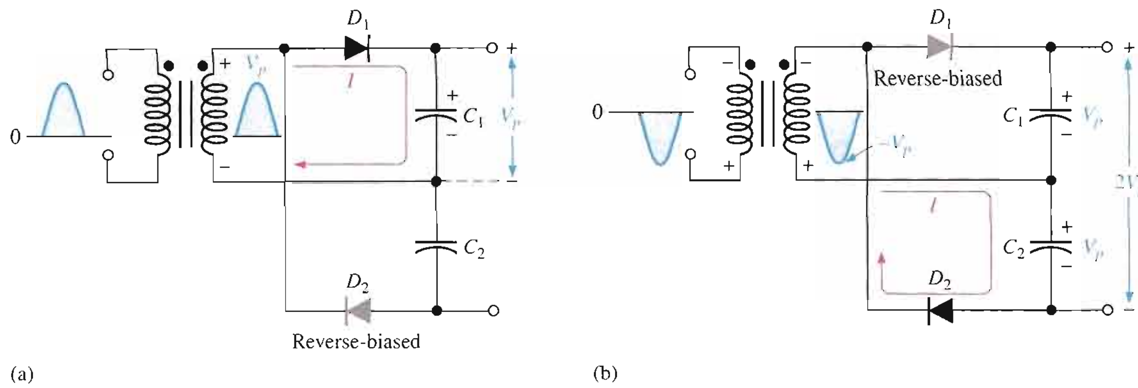
(a) (b)

FIGURE 2–49

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 $2V_p$.

Full-Wave Voltage Doubler A full-wave doubler is shown in Figure 2–50. 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 2–50**

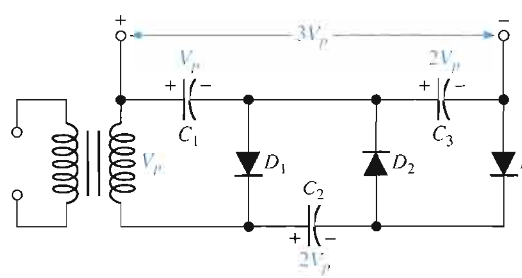
Full-wave voltage doubler operation.

Voltage Tripler

The addition of another diode-capacitor section to the half-wave voltage doubler creates a voltage tripler, as shown in Figure 2–51. 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 2–51**

Voltage tripler.

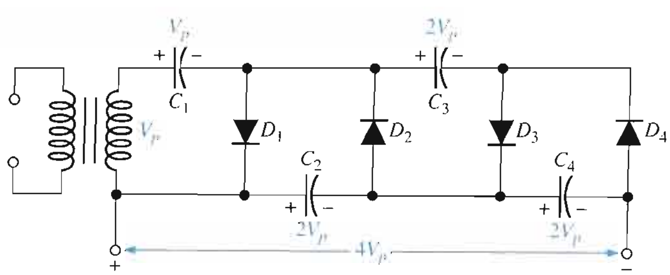


Voltage Quadrupler

The addition of still another diode-capacitor section, as shown in Figure 2–52, 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 2–52**

Voltage quadrupler.



SECTION 2–5 REVIEW

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?

2–6 THE DIODE DATA SHEET

A manufacturer's data sheet gives detailed information on a device so that it can be used properly in a given application. A typical data sheet provides maximum ratings, electrical characteristics, mechanical data, and graphs of various parameters. In this section, we use a specific example to illustrate a typical data sheet.

After completing this section, you should be able to

- **Interpret and use a diode data sheet**
- Identify maximum voltage and current ratings
- Determine the electrical characteristics of a diode
- Analyze graphical data
- Select an appropriate diode for a given set of specifications

Table 2–1 shows the maximum ratings for a certain series of rectifier diodes (1N4001 through 1N4007). These are the absolute maximum values under which the diode can be operated without damage to the device. For greatest reliability and longer life, the diode should always be operated well under these maximums. Generally, the maximum ratings are specified at 25°C and must be adjusted downward for higher temperatures.

An explanation of the parameters from Table 2–1 follows.

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

V_R The maximum reverse dc voltage that can be applied across the diode.

V_{RSM} The maximum peak value of nonrepetitive reverse voltage that can be applied across the diode.

I_O The maximum average value of a 60 Hz rectified forward current.

I_{FSM} The maximum peak value of nonrepetitive (one cycle) forward surge current. The graph in Figure 2–53 expands on this parameter to show values for more than one cycle at temperatures of 25°C and 175°C. The dashed lines represent values where typical failures occur.

T_A Ambient temperature (temperature of surrounding air).

T_J The operating junction temperature.

T_{stg} The storage junction temperature.

Table 2–2 lists typical and maximum values of certain electrical characteristics. These items differ from the maximum ratings in that they are not selected by design but are the result of operating the diode under specified conditions. A brief explanation of these parameters follows the table.

TABLE 2–1

Maximum ratings.

RATING	SYMBOL	1N4001	1N4002	1N4003	1N4004	1N4005	1N4006	1N4007	UNIT
Peak repetitive reverse voltage Working peak reverse voltage DC blocking voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
Nonrepetitive peak reverse voltage	V_{RSM}	60	120	240	480	720	1000	1200	V
rms reverse voltage	$V_{R(rms)}$	35	70	140	280	420	560	700	V
Average rectified forward current (single-phase, resistive load, 60 Hz, $T_A = 75°C$)	I_O				1.0				A
Nonrepetitive peak surge current (surge applied at rated load conditions)	I_{FSM}				30 (for 1 cycle)				A
Operating and storage junction temperature range	T_J, T_{stg}				−65 to +175				°C

FIGURE 2–53

Nonrepetitive forward surge current capability.

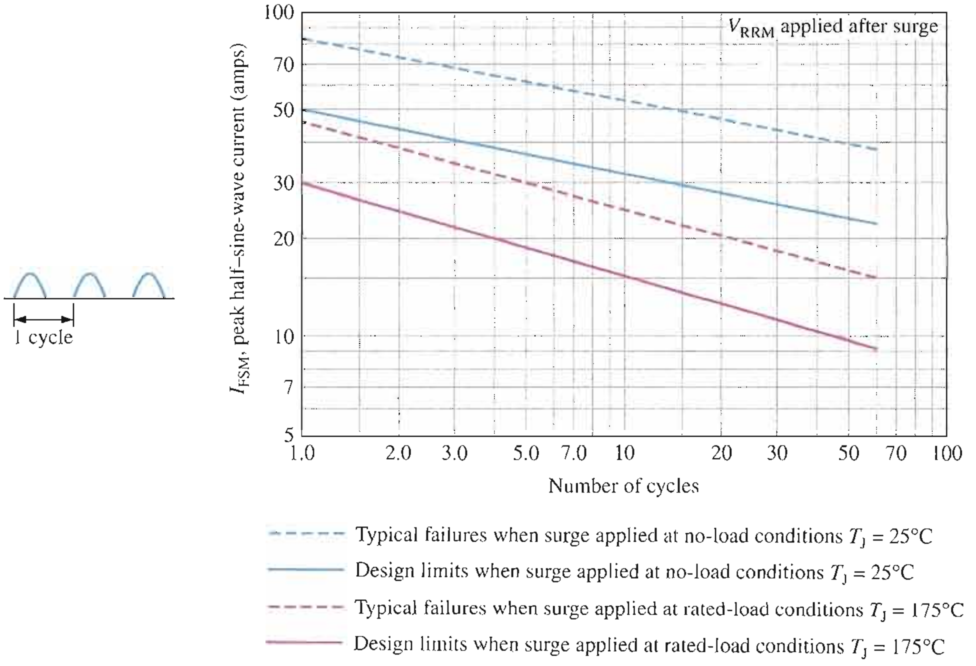


TABLE 2–2

Electrical characteristics.

CHARACTERISTICS AND CONDITIONS	SYMBOL	TYPICAL	MAXIMUM	UNIT
Maximum instantaneous forward voltage drop (I_F = 1 A, T_J = 25°C)	v_F	0.93	1.1	V
Maximum full-cycle average forward voltage drop (I_O = 1 A, T_L = 75°C, 1 inch leads)	$V_{F(avg)}$	—	0.8	V
Maximum reverse current (rated dc voltage)	I_R			μA
T_J = 25°C		0.05	10.0	
T_J = 100°C		1.0	50.0	
Maximum full-cycle average reverse current (I_O = 1 A, T_L = 75°C, 1 inch leads)	$I_{R(avg)}$	—	30.0	μA

v_F The instantaneous voltage across the forward-biased diode when the forward current is 1 A at 25°C. Figure 2–54 shows how the forward voltages vary with forward current.

$V_{F(avg)}$ The maximum forward voltage drop averaged over a full cycle.

I_R The maximum current when the diode is reverse-biased with a dc voltage.

$I_{R(avg)}$ The maximum reverse current averaged over one cycle (when reverse-biased with an ac voltage).

T_L The lead temperature.

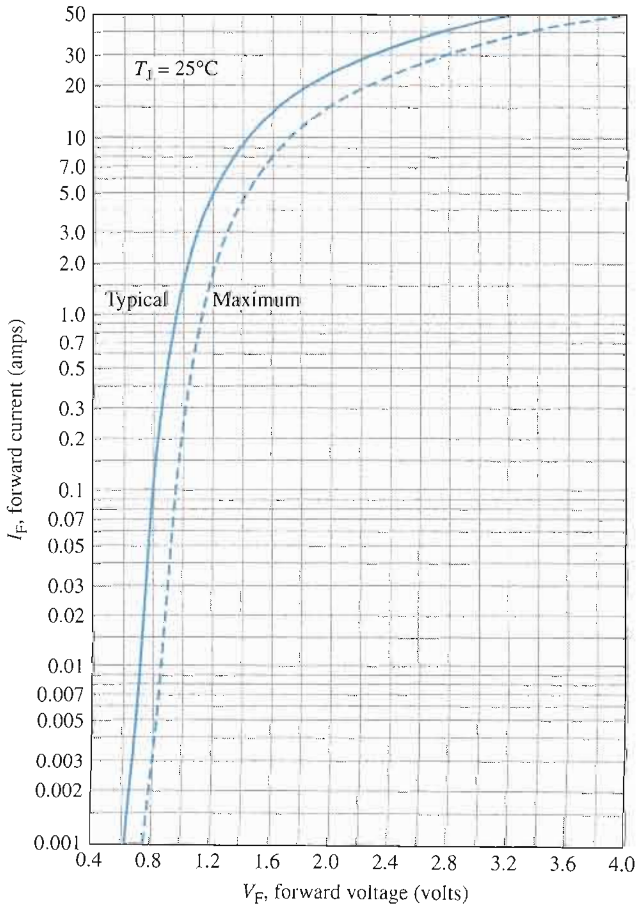
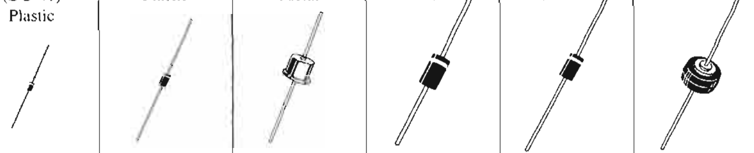


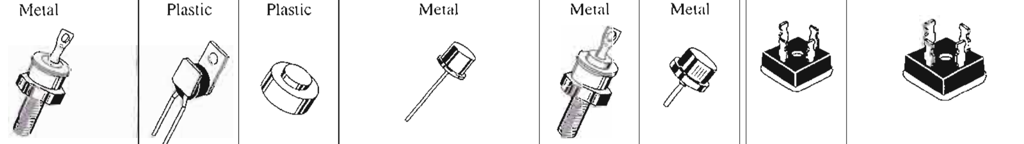
FIGURE 2–54

Forward voltage (V_F) versus forward current (I_F).

Figure 2–55 shows a selection of rectifier diodes arranged in order of increasing I_O, I_{FSM}, and V_{RRM} ratings.



V_{RRM} (Volts)	I_O, Average Rectified Forward Current (Amperes) 1.0	1.5	3.0	3.0	3.0	6.0
	59-03 (DO-41) Plastic	59-04 Plastic	60-01 Metal	267-03 Plastic	267-02 Plastic	194-04 Plastic
50	1N4001	1N5391	1N4719	MR500	1N5400	MR750
100	1N4002	1N5392	1N4720	MR501	1N5401	MR751
200	1N4003	1N5393 MR5059	1N4721	MR502	1N5402	MR752
400	1N4004	1N5395 MR5060	1N4722	MR504	1N5404	MR754
600	1N4005	1N5397 MR5061	1N4723	MR506	1N5406	MR756
800	1N4006	1N5398	1N4724	MR508		MR758
1000	1N4007	1N5399	1N4725	MR510		MR760
I_{FSM} (Amps)	30	50	300	100	200	400
T_A @ Rated I_O (°C)	75	$T_L = 70$	75	95	$T_L = 105$	60
T_C @ Rated I_O (°C)						
T_J (Max) (°C)	175	175	175	175	175	175



V_{RRM} (Volts)	I_O, Average Rectified Forward Current (Amperes) 12	20	24	25	30	30	40	50	25	35	40
	245A-02 (DO-203AA) Metal		339-02 Plastic	193-04 Plastic	43-02 (DO-21) Metal		42A-01 (DO-203AB) Metal	43-04 Metal	309A-03	309A-02	
50	MR1120 1N1199,A,B	MR2000	MR2400	MR2500	1N3491	1N3659	1N1183A	MR5005	MDA2500	MDA3500	
100	MR1121 1N1200,A,B	MR2001	MR2401	MR2501	1N3492	1N3660	1N1184A	MR5010	MDA2501	MDA3501	
200	MR1122 1N1202,A,B	MR2002	MR2402	MR2502	1N3493	1N3661	1N1186A	MR5020	MDA2502	MDA3502	MDA4002
400	MR1124 1N1204,A,B	MR2004	MR2404	MR2504	1N3495	1N3663	1N1188A	MR5040	MDA2504	MDA3504	MDA4004
600	MR1126 1N1206,A,B	MR2006	MR2406	MR2506			1N1190A		MDA2506	MDA3506	MDA4006
800	MR1128	MR2008		MR2508					MDA2508	MDA3508	MDA4008
1000	MR1130	MR2010		MR2510					MDA2510	MDA3510	
I_{FSM} (Amps)	300	400	400	400	300	400	800	600	400	400	800
T_A @ Rated I_O (°C)											
T_C @ Rated I_O (°C)	150	150	125	150	130	100	150	150	55	55	35
T_J (Max) (°C)	190	175	175	175	175	175	190	195	175	175	175

▲ FIGURE 2–55

A selection of rectifier diodes based on maximum ratings of I_O, I_{FSM}, and V_{RRM}.

SECTION 2–6 REVIEW

1. List the three rating categories typically given on all diode data sheets.
2. Define each of the following parameters: V_F, I_R, I_O.
3. Define I_{FSM}, V_{RRM}, and V_{RSM}.
4. From Figure 2–55, select a diode to meet the following specifications: $I_O = 3$ A, $I_{FSM} = 300$ A, and $V_{RRM} = 100$ V.

2–7 TROUBLESHOOTING

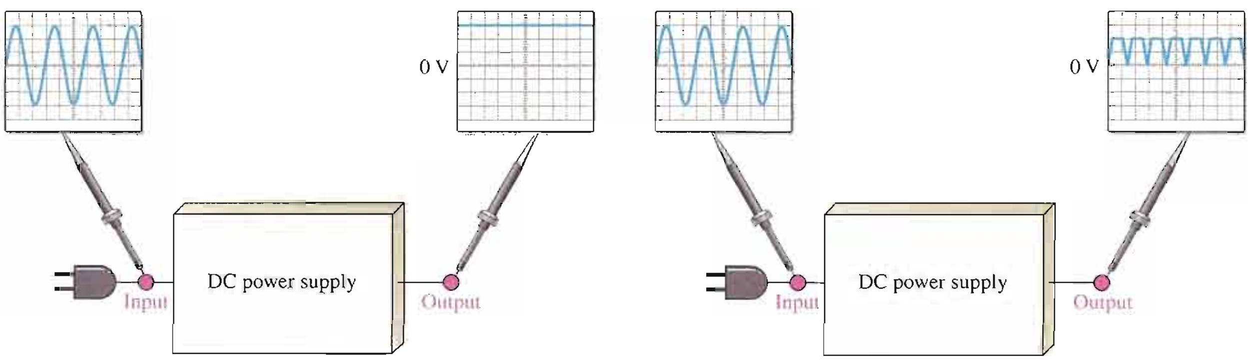
This section provides a general overview and application of an approach to troubleshooting. Specific troubleshooting examples of the power supply and diode circuits are covered.

After completing this section, you should be able to

- **Troubleshoot power supplies and diode circuits**
- Use analysis to evaluate a problem based on symptoms
- Eliminate basic problems that can be detected by observation
- Plan an approach to determining what the fault is in a circuit or system
- Make appropriate measurements to isolate a fault
- Recognize symptoms caused by certain types of component failures

Troubleshooting is the application of logical thinking combined with a thorough knowledge of circuit or system operation to correct a malfunction. A basic 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 2–56(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.



(a) The correct dc output voltage is measured.

(b) An incorrect voltage is measured at the output. The input voltage is correct.

▲ FIGURE 2–56

Block representations of functioning and nonfunctioning power supplies.

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 2–56(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.

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

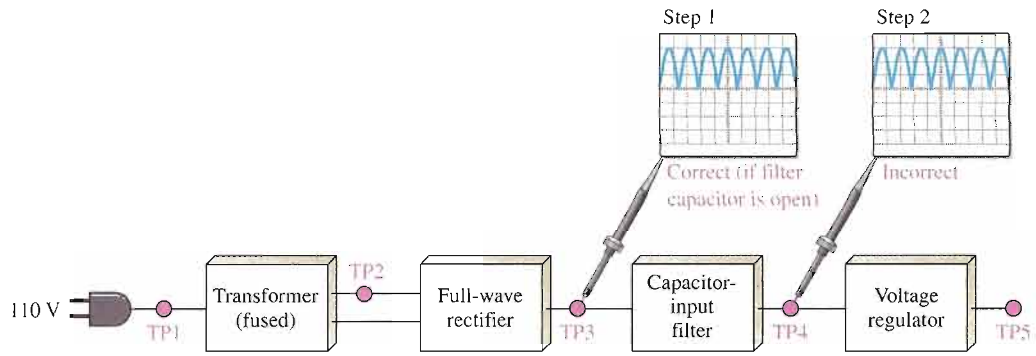
In this phase, you must consider how you will attack the problem. There are three possible approaches to troubleshooting most circuits or systems.

1. Start at the input 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 2–57 with the measurements indicating a particular fault (open filter capacitor in this case). At test point 3 (TP3) you observe a full-wave rectified voltage that indicates that the transformer and rectifier are working properly. This measurement also indicates that the filter capacitor is open, which is verified by the full-wave voltage at TP4. If the filter were working properly, you would measure a dc voltage at both TP3 and TP4. If the filter capacitor were shorted, you would observe no voltage at all of the test points except TP1 because the fuse would most likely be blown. A short

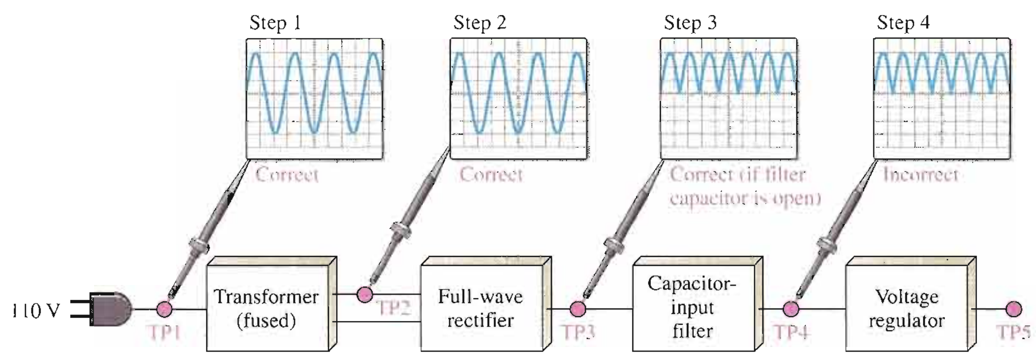


▲ **FIGURE 2–57**

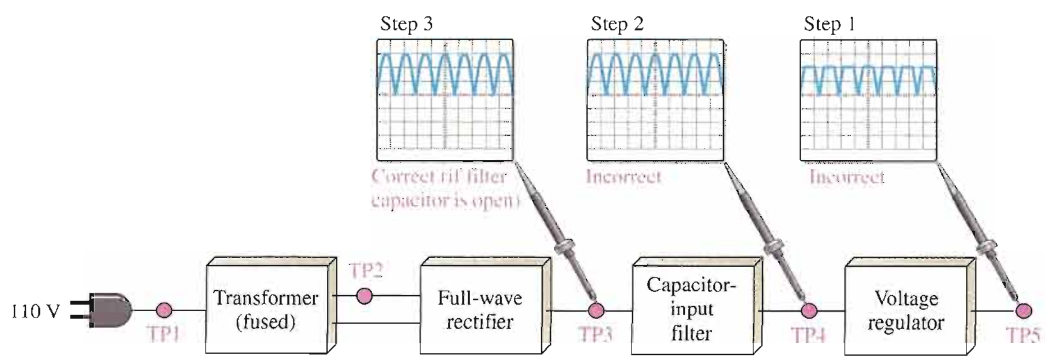
Example of the half-splitting approach. An open filter capacitor is indicated.

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 2–57, the half-splitting method took two measurements to isolate the fault to the open filter capacitor. If you had started from the power supply input, it would have taken four measurements; and if you had started at the final output, it would have taken three measurements, as illustrated in Figure 2–58.



(a) Measurements starting at the power supply input.



(b) Measurements starting at the regulator output.

▲ **FIGURE 2–58**

In this particular case, the two other approaches require more measurements than the half-splitting approach in Figure 2–57.

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 2–59. 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.

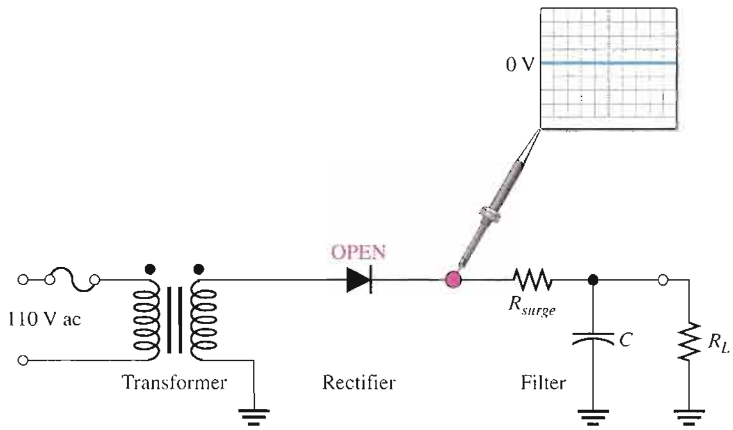


FIGURE 2–59

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 2–60. If either of the two diodes is open, the output voltage will have a larger than normal ripple voltage at 60 Hz rather than at 120 Hz, as indicated.

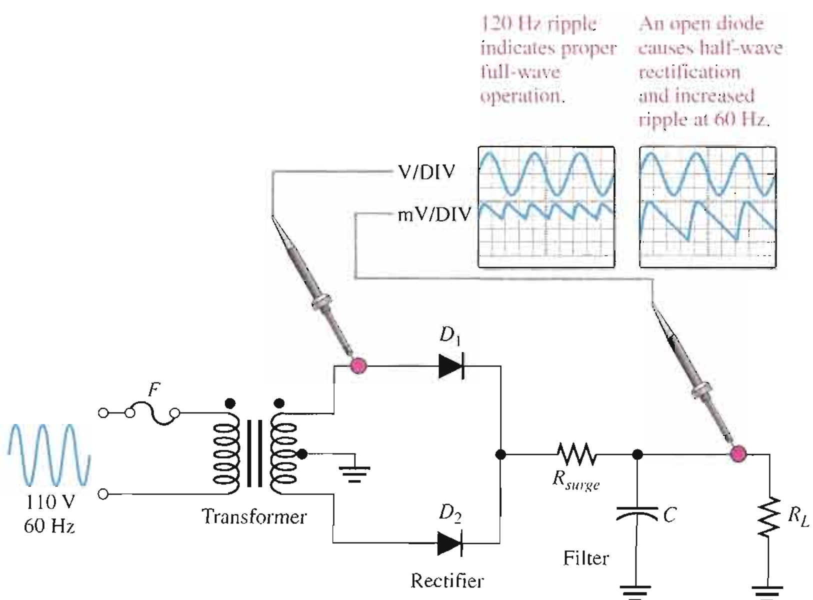


FIGURE 2–60

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

Another fault that will cause the same symptom is an open in one of the halves of 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 2–60 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 2–60, 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 2–61. The open diode prevents current through R_L during half of the input voltage cycle. The result is half-wave rectification, which produces an increase in ripple voltage at 60 Hz.

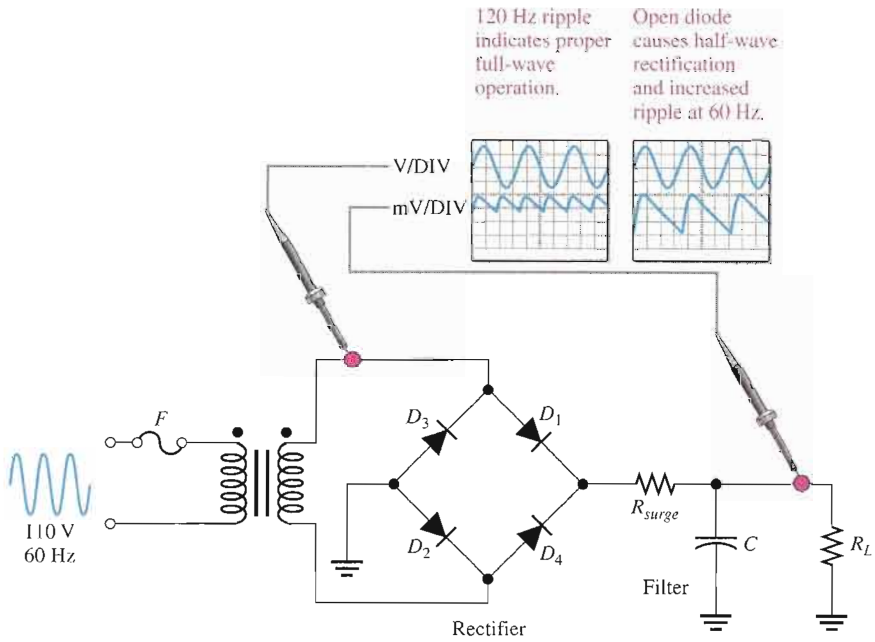


FIGURE 2–61
Effect of an open diode in a bridge rectifier.

Effects of a Faulty Filter Capacitor Three types of defects of a filter capacitor are illustrated in Figure 2–62.

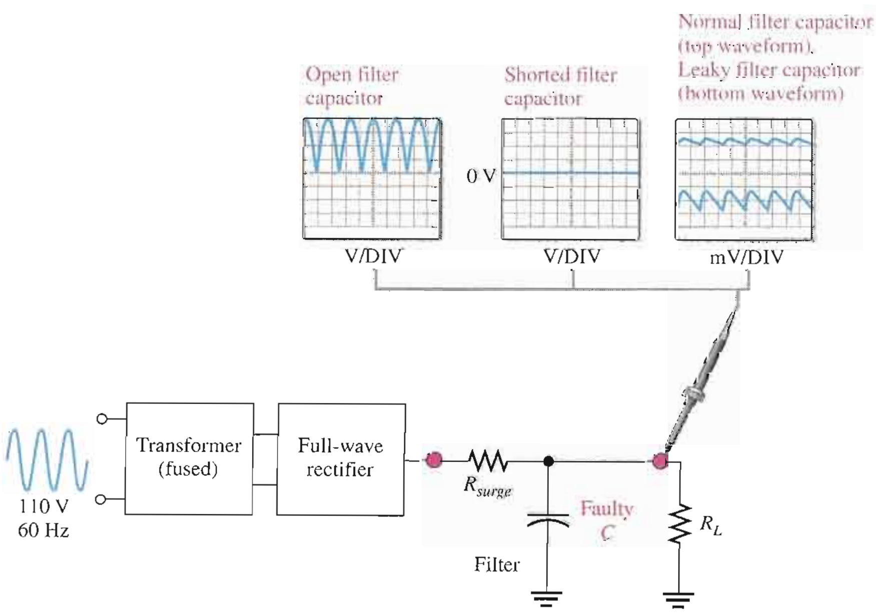


FIGURE 2–62
Effects of a faulty filter capacitor.

- *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.

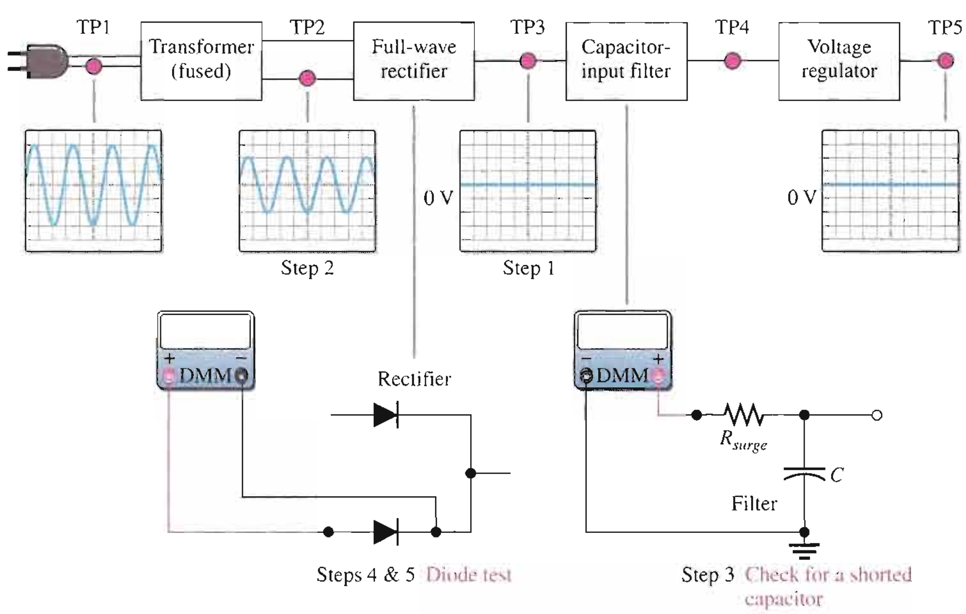
Effects of a Faulty Transformer An open primary or secondary winding of a power supply transformer results in an output of 0 V, as mentioned before.

A partially shorted primary winding (which is much less likely than an open) results in an increased rectifier output voltage because the turns ratio of the transformer is effectively increased. A partially shorted secondary winding results in a decreased rectifier output voltage because the turns ratio is effectively decreased.

EXAMPLE 2–13

You are troubleshooting the power supply shown in the block diagram of Figure 2–63. 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, as indicated. You decide to use the half-splitting method using the scope. What is the problem?

▶ FIGURE 2–63



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 3 (TP3). 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 2 (TP2) 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, both of the diodes must be open.

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 your CD-ROM.

1. Open file TSE02-01. Determine if the circuit is working properly and, if not, determine the fault.
2. Open file TSE02-02. Determine if the circuit is working properly and, if not, determine the fault.
3. Open file TSE02-03. Determine if the circuit is working properly and, if not, determine the fault.

SECTION 2–7 REVIEW

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

SYSTEM APPLICATION

Assume you are working for an electronics manufacturing company as an electronics technician. Your company designs, manufactures, and tests a wide variety of products. Your first on-the-job assignment is to develop and test a dc power supply that will be used in several different products such as an industrial counting system, a security alarm system, a voice intercom system, and a public address system. You will apply the knowledge you have gained to this point to complete your assignment.

The Power Supply Circuit

The dc power supply that will be produced by your company is shown in Figure 2–64. This is to be a universal design that can be used in several different systems with some modifications. In its basic form, this power supply is to be unregulated. Later modifications will include a regulator. The basic specifications are as follows:

1. Input voltage: 115 V rms at 60 Hz
2. Output voltage (unregulated): 12 V dc ± 10%
3. Maximum ripple factor: 3%
4. Maximum load current: 250 mA

The Components

- *Transformer* Transformers are usually specified according to their rms output (secondary) voltage. Based on the power supply specifications, select a power transformer from the following list: 24 V, 18 V, 12.6 V, 12 V, 9 V, and 6.3 V.
- *Diodes* Select a diode type to be used in the rectifier bridge with minimum I_O, I_{FSM}, and V_{RRM} required to do the job. Refer to the diode selection chart in Figure 2–55.
- *Surge resistor* Determine a value of surge resistor based on the I_{FSM} of the selected diodes. Use the next higher standard value but keep it as small as possible to minimize voltage drop. Refer to the table of standard values in Appendix A.
- *Primary fuse* Determine the smallest fuse rating that will handle the normal current but will blow if the load current exceeds its normal maximum or if the rectifier output is shorted. You can determine the turns ratio from the voltage ratings and use the basic formula learned in ac circuits to find the primary current. Select from the following standard fuse values: 250 mA, 500 mA, 1 A, 2 A, 3 A, 5 A, 7.5 A, and 10 A.
- *Filter Capacitor* Select a minimum value of filter capacitor to meet the ripple factor requirements with a maximum load current (minimum load resistance). Choose from the following standard value electrolytics: 1 μF, 4.7 μF, 10 μF, 33 μF, 47 μF, 100 μF, 220 μF, 470 μF, 1000 μF, 1500 μF, 3300 μF, 4700 μF, 6800 μF, and 10,000 μF.

The Schematic

Complete the preliminary schematic in Figure 2–64 by adding component values and/or part numbers.

The Printed Circuit Board

- Check out the printed circuit board in Figure 2–65 to verify that it is correct according to the schematic. All black resistor bands indicate an unspecified value that you have determined.
- Label a copy of the board with the component and input/output designations in agreement with the schematic.

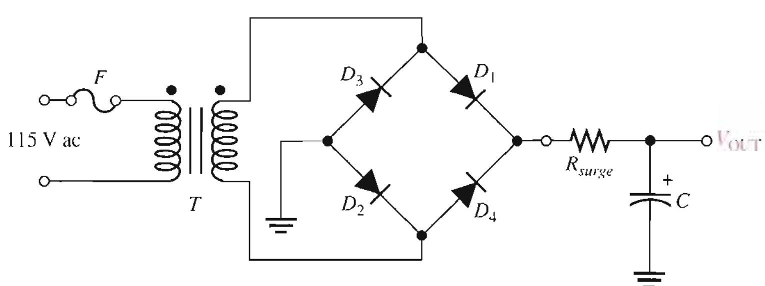
A Test Procedure

Develop a step-by-step set of instructions on how to completely check the power supply board for proper operation using the test points (circled numbers) indicated in the test bench setup of Figure 2–66. Specify voltage values and appropriate waveforms for all the measurements to be made. Provide a fault analysis for all possible component failures.

Troubleshooting

A preliminary manufacturing run of the assembled power supply boards are coming off the assembly line. Three boards have been found to be defective. Troubleshooting techniques must be used to determine the problems.

The test bench setup is shown in Figure 2–66. Based on the sequence of



▲ FIGURE 2–64

Power supply preliminary schematic.

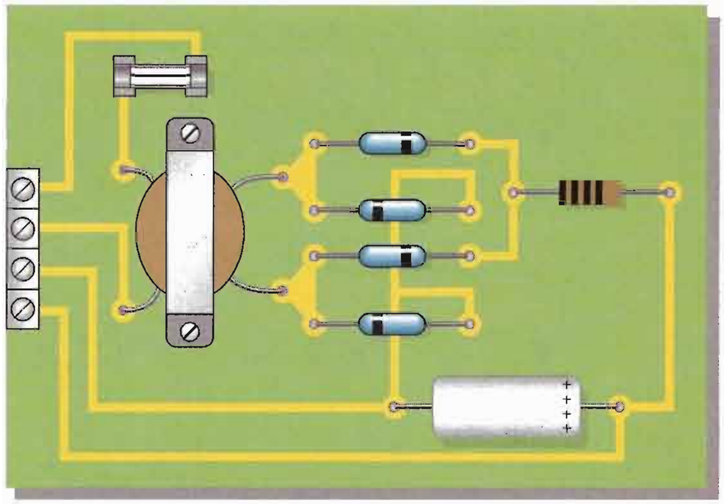


FIGURE 2–65

Power supply printed circuit board.

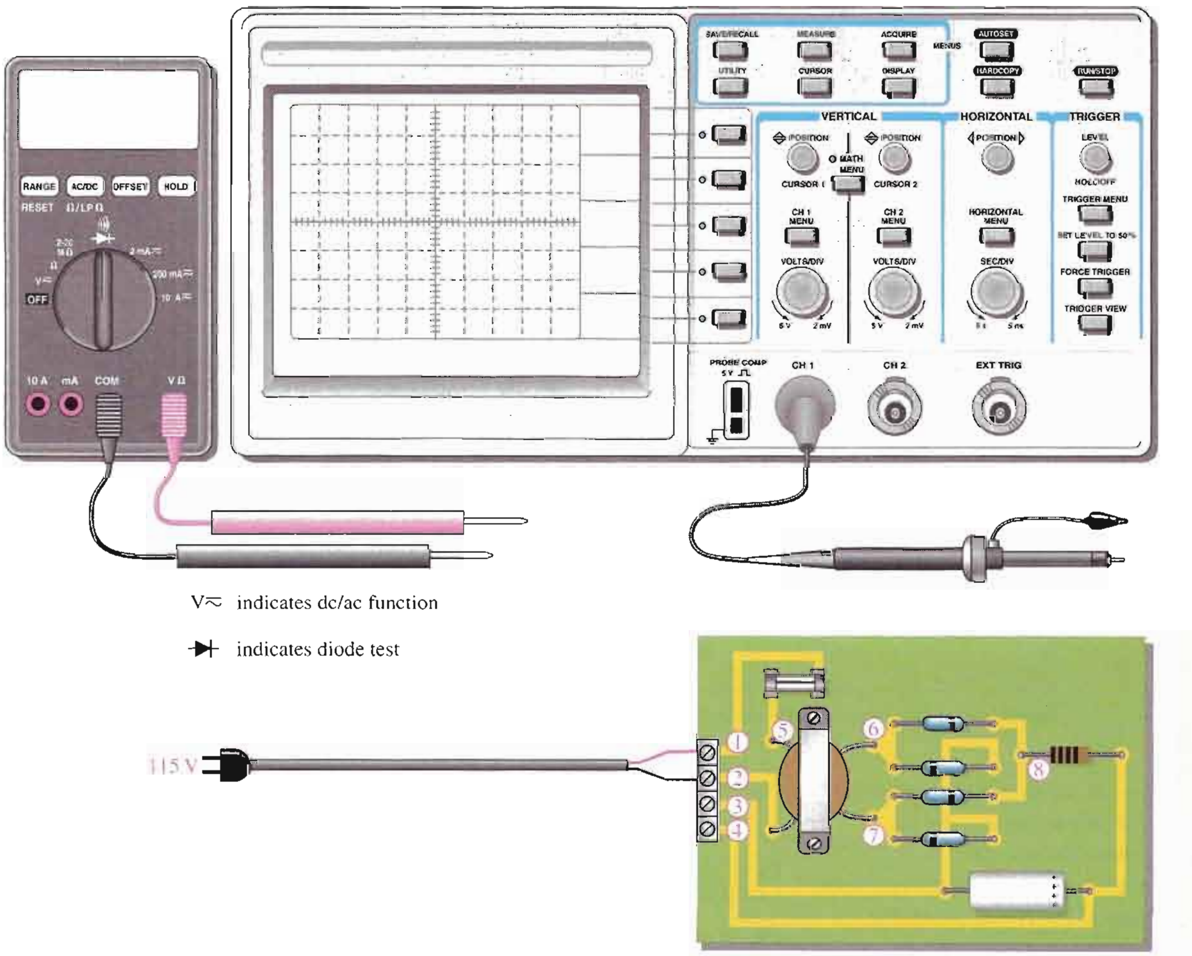
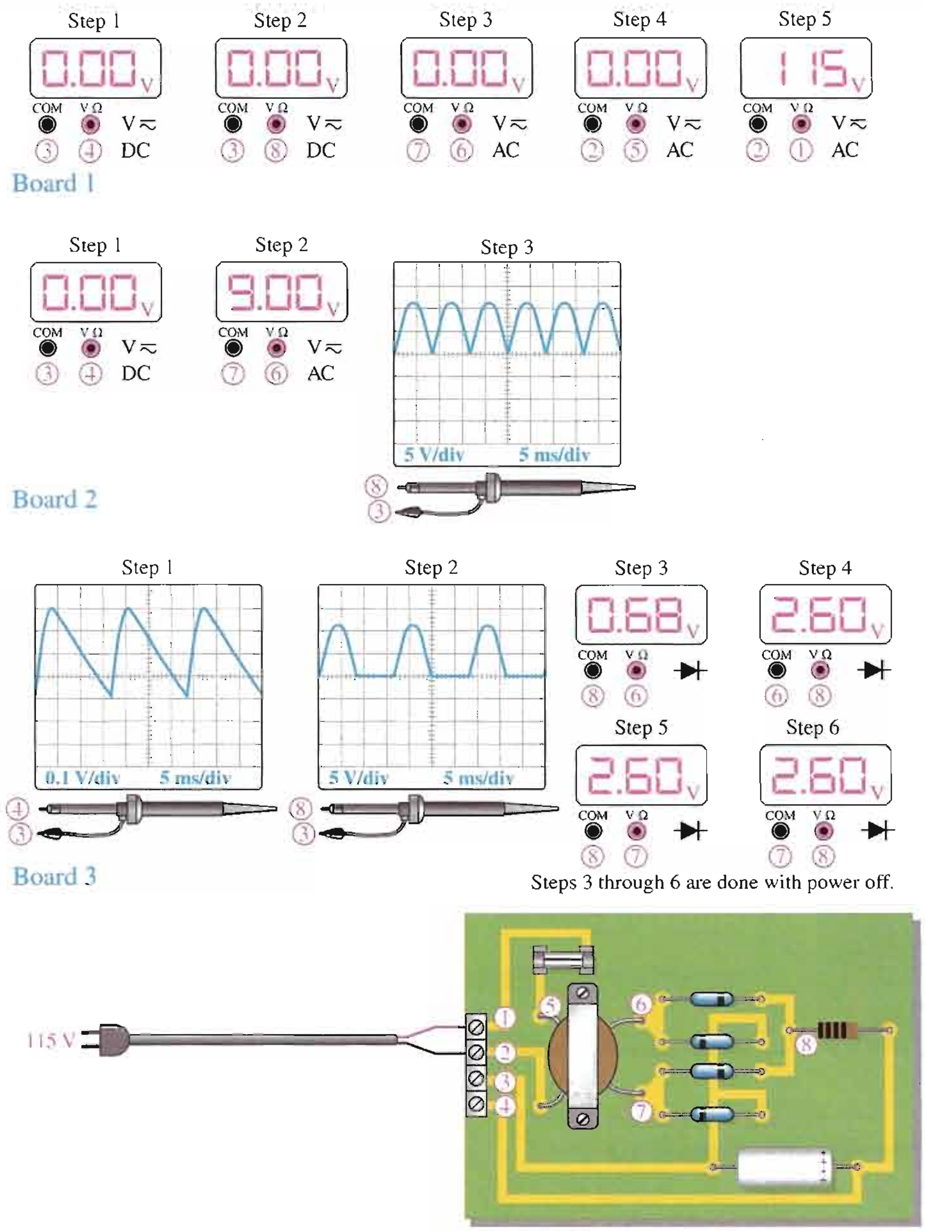


FIGURE 2–66

Power supply test bench.



▲ **FIGURE 2-67**

Signal tracing sequences for three faulty power supply boards.

measurements for each board indicated in Figure 2–67, determine the most likely fault(s) in each case.

The circled numbers indicate test point connections to the circuit board. The DMM function setting is indicated below the display, and the volt/div and sec/div for the oscilloscope are shown on the screen in each case.

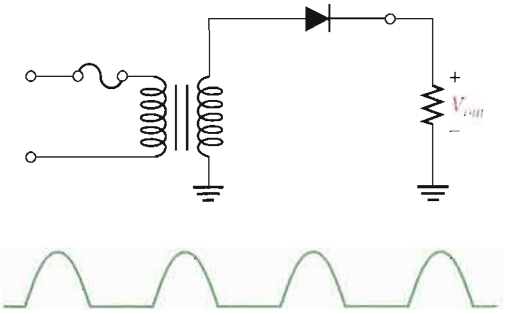
Final Report (Optional)

Submit a final written report on the power supply circuit board using an organized format that includes the following:

1. A physical description of the power supply circuit.
2. A discussion of the operation of the power supply.
3. A list of the specifications.
4. A list of parts with part numbers if available.
5. A list of the types of problems on the three faulty circuit boards.
6. A complete description of how you determined the problem on each of the three faulty circuit boards.

SUMMARY OF POWER SUPPLY RECTIFIERS

HALF-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

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

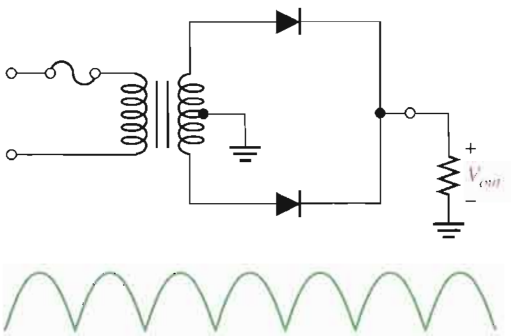
- Average value of output:

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

- Diode peak inverse voltage:

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

CENTER-TAPPED FULL-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

  $V_{p(out)} = \dfrac{V_{p(sec)}}{2} - 0.7\text{ V}$

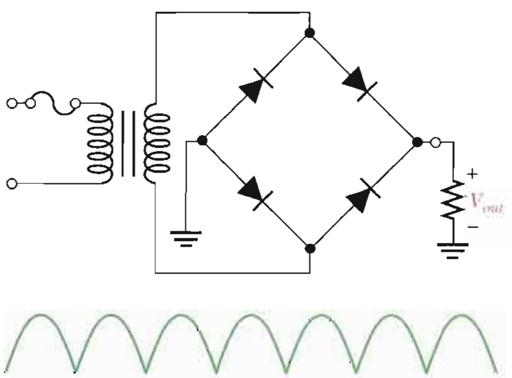
- Average value of output:

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

- Diode peak inverse voltage:

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

BRIDGE FULL-WAVE RECTIFIER



Output voltage waveform

- Peak value of output:

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

- Average value of output:

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

- Diode peak inverse voltage:

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

CHAPTER SUMMARY

- 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.
- 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.
- 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.*
- 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.
- A dc power supply typically consists of an input transformer, a diode rectifier, a filter, and a regulator.

KEY TERMS

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

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

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

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 which occurs at the peak of the input cycle when the diode is reverse-biased.

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

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.

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.

KEY FORMULAS

2–1	$V_{AVG} = \frac{V_p}{\pi}$	Half-wave average value
2–2	$V_{p(out)} = V_{p(in)} - 0.7\ \text{V}$	Peak half-wave rectifier output (silicon)
2–3	$\text{PIV} = V_{p(in)}$	Peak inverse voltage, half-wave rectifier
2–4	$V_{sec} = nV_{pri}$	Transformer secondary voltage
2–5	$V_{AVG} = \frac{2V_p}{\pi}$	Full-wave average value
2–6	$V_{out} = \frac{V_{sec}}{2} - 0.7\ \text{V}$	Center-tapped full-wave output
2–7	$\text{PIV} = 2V_{p(out)} + 0.7\ \text{V}$	Peak inverse voltage, center-tapped rectifier
2–8	$V_{p(out)} = V_{p(sec)} - 1.4\ \text{V}$	Bridge full-wave output
2–9	$\text{PIV} = V_{p(out)} + 0.7\ \text{V}$	Peak inverse voltage, bridge rectifier
2–10	$r = \frac{V_{r(pp)}}{V_{DC}}$	Ripple factor
2–11	$V_{r(pp)} \cong \left(\frac{1}{fR_LC}\right)V_{p(rect)}$	Peak-to-peak ripple voltage, capacitor-input filter
2–12	$V_{DC} = \left(1 - \frac{1}{2fR_LC}\right)V_{p(rect)}$	DC output voltage, capacitor-input filter
2–13	$R_{surge} = \frac{V_{p(sec)} - 1.4\ \text{V}}{I_{FSM}}$	Surge resistance
2–14	$\text{Line regulation} = \left(\frac{\Delta V_{OUT}}{\Delta V_{IN}}\right)100\%$	
2–15	$\text{Load regulation} = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%$	

CIRCUIT-ACTION QUIZ

Answers are at the end of the chapter.

1. If the input voltage in Figure 2–10 is increased, the peak inverse voltage across the diode will
   (a) increase (b) decrease (c) not change
2. If the turns ratio of the transformer in Figure 2–10 is decreased, the forward current through the diode will
   (a) increase (b) decrease (c) not change
3. If the frequency of the input voltage in Figure 2–18 is increased, the output voltage will
   (a) increase (b) decrease (c) not change
4. If the PIV rating of the diodes in Figure 2–18 is increased, the current through R_L will
   (a) increase (b) decrease (c) not change
5. If one of the diodes in Figure 2–23 opens, the average voltage to the load will
   (a) increase (b) decrease (c) not change
6. If the value of R_L in Figure 2–23 is decreased, the current through each diode will
   (a) increase (b) decrease (c) not change
7. If the capacitor value in Figure 2–30 is decreased, the output ripple voltage will
   (a) increase (b) decrease (c) not change
8. If the line voltage in Figure 2–33 is increased, ideally the +5 V output will
   (a) increase (b) decrease (c) not change

9. If the bias voltage in Figure 2–37 is decreased, the positive portion of the output voltage will
   (a) increase (b) decrease (c) not change
10. If the bias voltage in Figure 2–37 is increased, the negative portion of the output voltage will
   (a) increase (b) decrease (c) not change
11. If the value of R_3 in Figure 2–43 is decreased, the positive output voltage will
   (a) increase (b) decrease (c) not change
12. If the input voltage in Figure 2–47 is increased, the peak negative value of the output voltage will
   (a) increase (b) decrease (c) not change

SELF-TEST

Answers are at the end of the chapter.

1. The average value of a half-wave rectified voltage with a peak value of 200 V is
   (a) 63.7 V (b) 127.3 V (c) 141 V (d) 0 V
2. 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
3. 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
4. For the circuit in Question 3, the diode must be able to withstand a reverse voltage of
   (a) 10 V (b) 5 V (c) 20 V (d) 3.18 V
5. 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
6. 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
7. 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
8. 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
9. 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
10. 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
11. 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
12. A 60 V peak full-wave rectified voltage is applied to a capacitor-input filter. If $f = 120$ Hz, $R_L = 10\ k\Omega$, and $C = 10\ \mu F$, the ripple voltage is
   (a) 0.6 V (b) 6 mV (c) 5.0 V (d) 2.88 V
13. 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
14. 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

15. 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

16. 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

17. 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

18. 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

19. 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

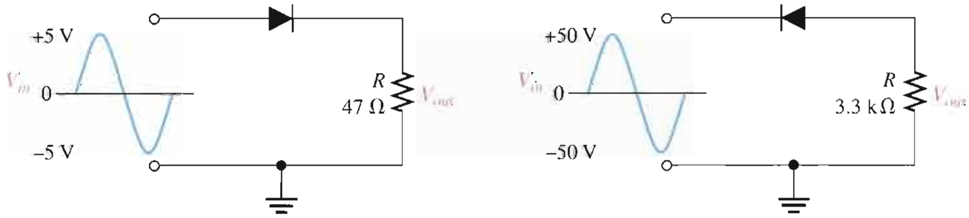
PROBLEMS

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

BASIC PROBLEMS

SECTION 2–1 Half-Wave Rectifiers

1. Draw the output voltage waveform for each circuit in Figure 2–68 and include the voltage values.



(a) (b)

▲ FIGURE 2–68

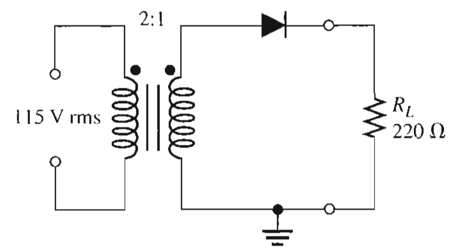
Multisim file circuits are identified with a CD logo and are in the Problems folder on your CD-ROM. Filenames correspond to figure numbers (e.g., F02–68).

2. What is the peak forward current through each diode in Figure 2–68?

3. A power-supply transformer has a turns ratio of 5:1. What is the secondary voltage if the primary is connected to a 115 V rms source?

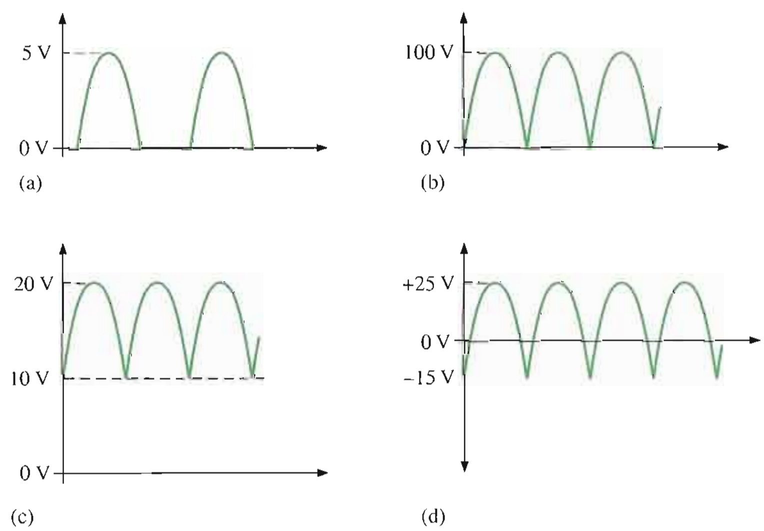
4. Determine the peak and average power delivered to R_L in Figure 2–69.

▶ FIGURE 2–69



SECTION 2–2 Full-Wave Rectifiers

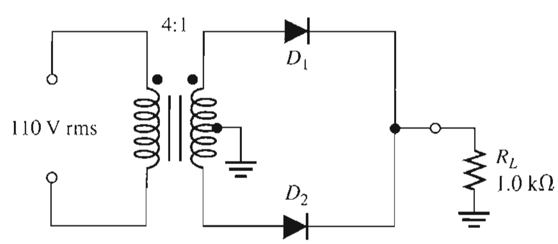
5. Find the average value of each voltage in Figure 2–70.



▲ FIGURE 2–70

6. Consider the circuit in Figure 2–71.
   (a) What type of circuit is this?
   (b) What is the total peak secondary voltage?
   (c) Find the peak voltage across each half of the secondary.
   (d) Sketch the voltage waveform across R_L.
   (e) What is the peak current through each diode?
   (f) What is the PIV for each diode?

▶ FIGURE 2–71



7. 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 110 V.

8. 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.
9. What PIV rating is required for the diodes in a bridge rectifier that produces an average output voltage of 50 V?
10. The rms output voltage of a bridge rectifier is 20 V. What is the peak inverse voltage across the diodes?
11. Draw the output voltage of the bridge rectifier in Figure 2–72. Notice that all the diodes are reversed from previous circuits.

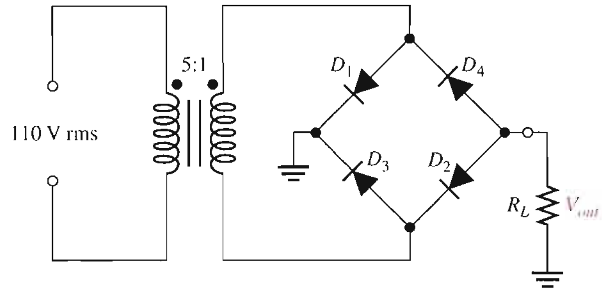


FIGURE 2–72

SECTION 2–3 Power Supply Filters and Regulators

12. 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.
13. 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.
14. What is the percentage of ripple for the rectifier filter in Problem 13?
15. 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 kΩ? Assume the rectifier produces a peak output of 18 V.
16. 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 kΩ.
17. Determine the peak-to-peak ripple and dc output voltages in Figure 2–73. The transformer has a 36 V rms secondary voltage rating, and the line voltage has a frequency of 60 Hz.

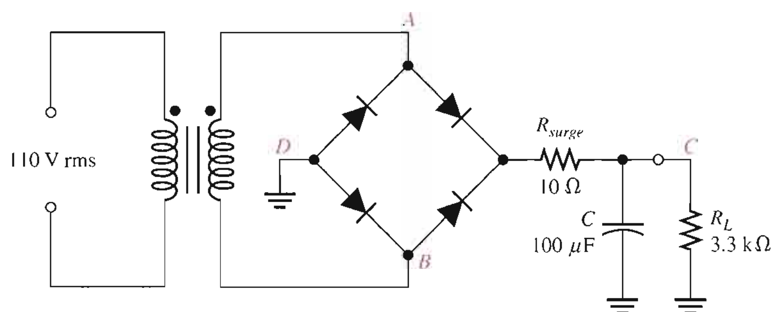


FIGURE 2–73

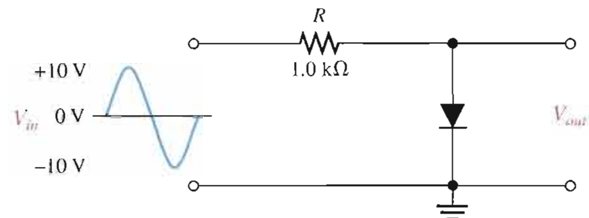
18. Refer to Figure 2–73 and draw the following voltage waveforms in relationship to the input waveforms: V_{AB}, V_{AD}, and V_{CD}. A double letter subscript indicates a voltage from one point to another.
19. If the no-load output voltage of a regulator is 15.5 V and the full-load output is 14.9 V, what is the percent load regulation?

20. Assume a regulator has a percent load regulation of 0.5%. What is output voltage at full-load if the unloaded output is 12.0 V?

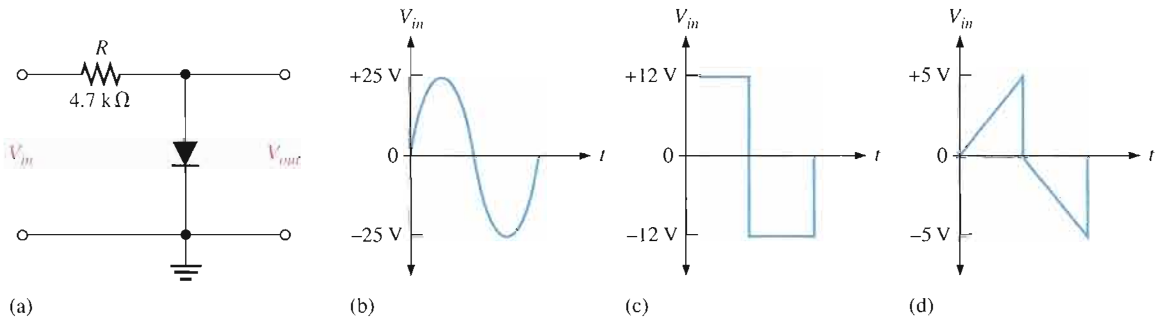
SECTION 2–4 Diode Limiting and Clamping Circuits

21. Determine the output waveform for the circuit of Figure 2–74.

▶ FIGURE 2–74

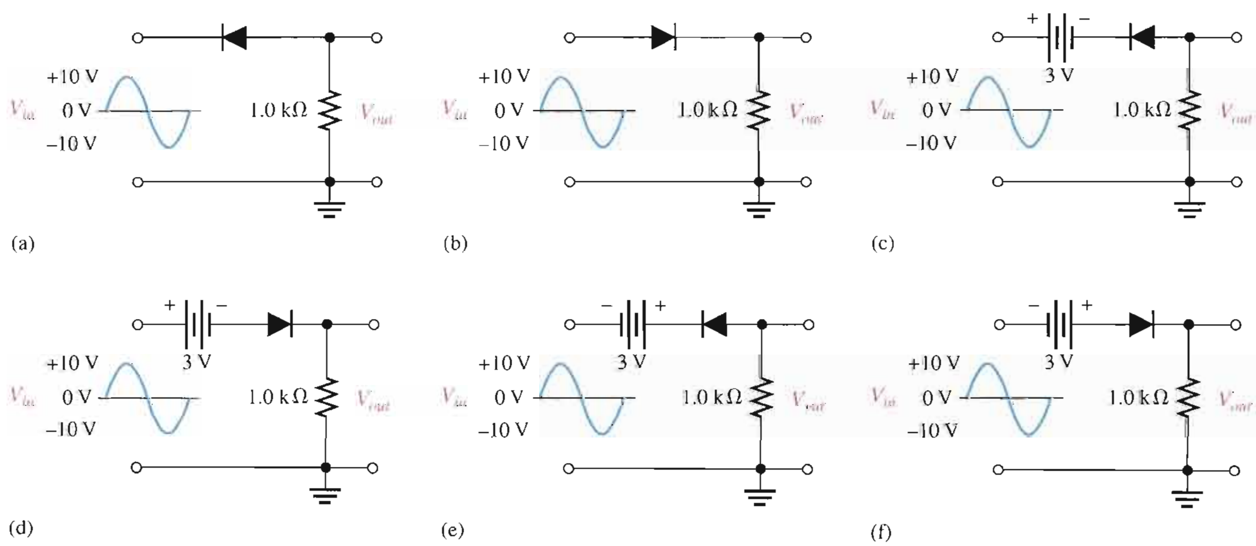


22. Determine the output voltage for the circuit in Figure 2–75(a) for each input voltage in (b), (c), and (d).



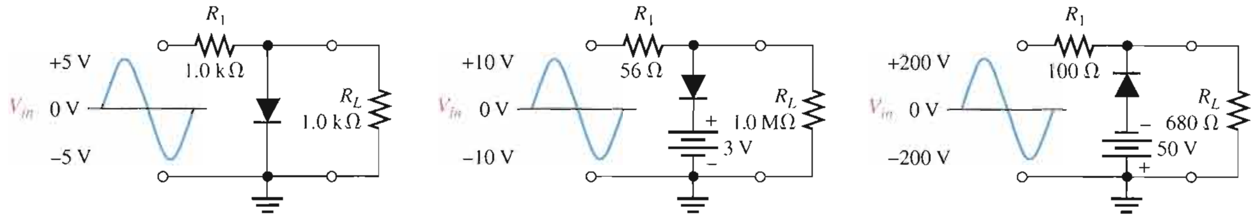
▲ FIGURE 2–75

23. Determine the output voltage waveform for each circuit in Figure 2–76.



▲ FIGURE 2–76

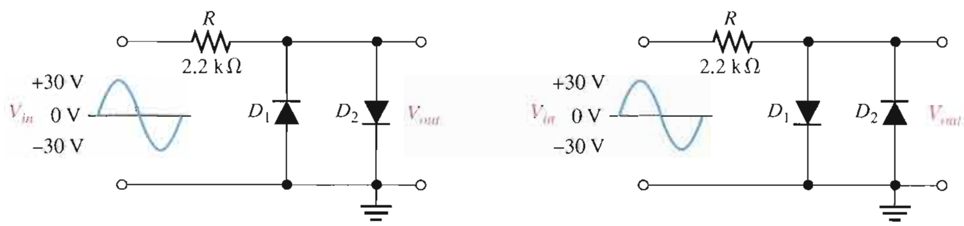
24. Determine the R_L voltage waveform for each circuit in Figure 2–77.



(a) (b) (c)

▲ FIGURE 2–77

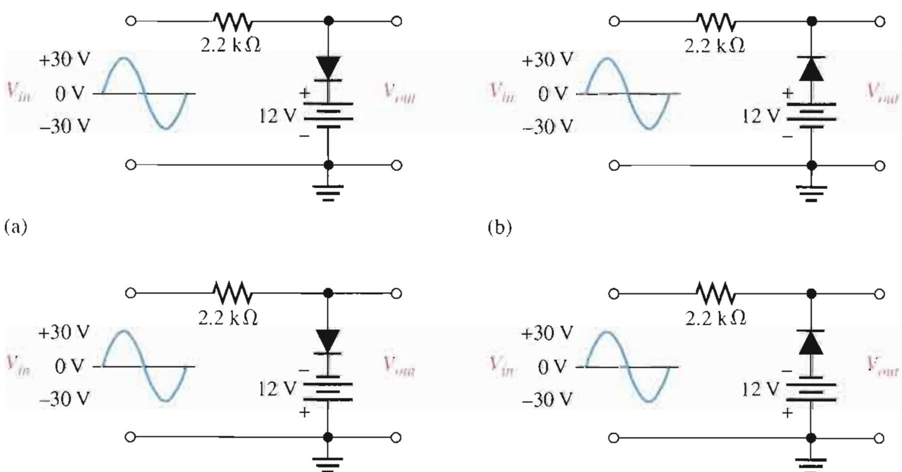
25. Draw the output voltage waveform for each circuit in Figure 2–78.



(a) (b)

▲ FIGURE 2–78

26. Determine the output voltage waveform for each circuit in Figure 2–79.



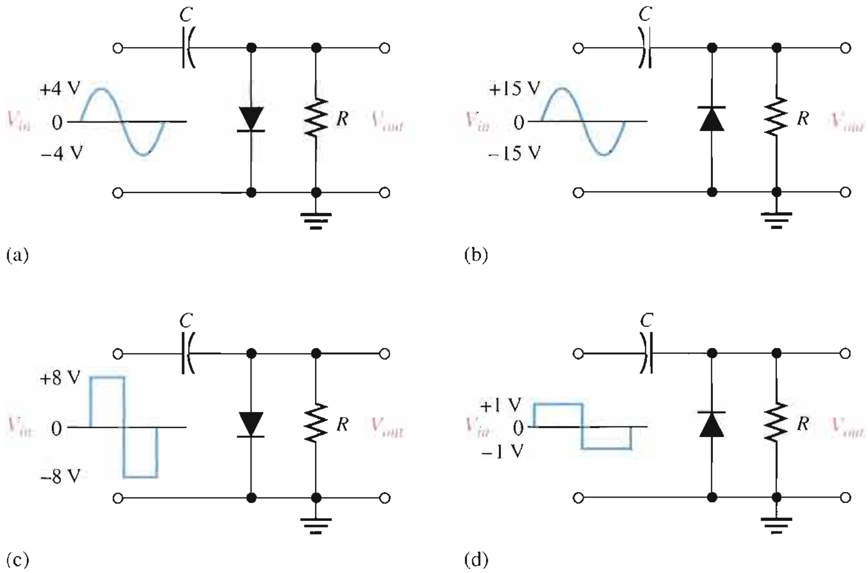
(a) (b) (c) (d)

▲ FIGURE 2–79

27. Describe the output waveform of each circuit in Figure 2–80. Assume the *RC* time constant is much greater than the period of the input.

28. Repeat Problem 27 with the diodes turned around.

▶ FIGURE 2–80



SECTION 2–5

Voltage Multipliers

29. 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.

30. Repeat Problem 29 for a voltage tripler and quadrupler.

SECTION 2–6

The Diode Data Sheet

31. From the data sheet in Figure 2–55, determine how much peak inverse voltage that a 1N1183A diode can withstand.

32. Repeat Problem 31 for a 1N1188A.

33. If the peak output voltage of a bridge full-wave rectifier is 50 V, determine the minimum value of the surge-limiting resistor required when INI183A diodes are used.

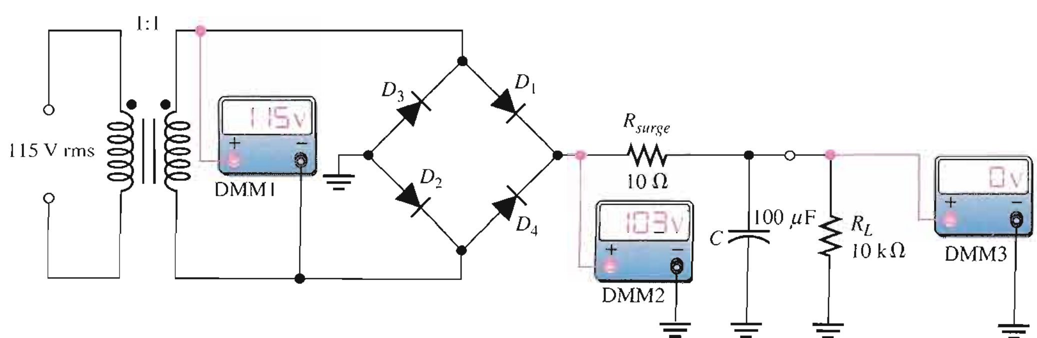
TROUBLESHOOTING PROBLEMS

SECTION 2–7

Troubleshooting

34. If one of the diodes in a bridge rectifier opens, what happens to the output?

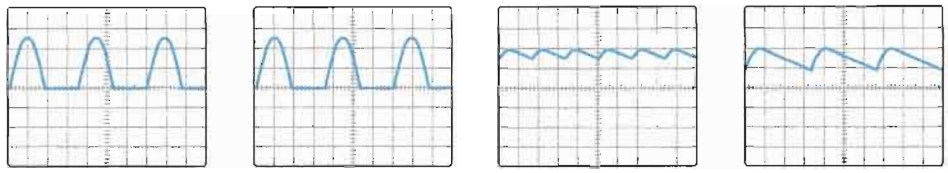
35. From the meter readings in Figure 2–81, determine if the rectifier is functioning properly. If it is not, determine the most likely failure(s).



▲ FIGURE 2–81

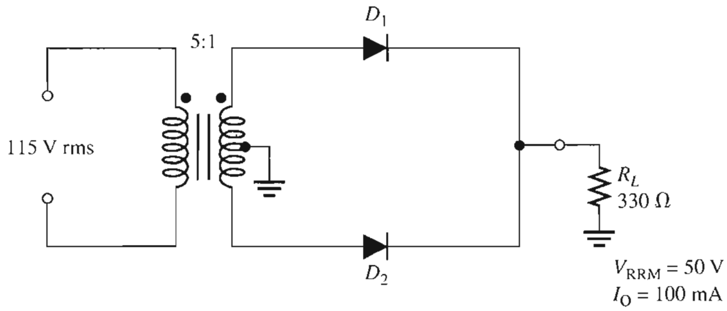
36. Each part of Figure 2–82 shows oscilloscope displays of various rectifier output voltages. In each case, determine whether or not the rectifier is functioning properly and if it is not, determine the most likely failure(s).

37. Based on the values given, would you expect the circuit in Figure 2–83 to fail? If so, why?



(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)

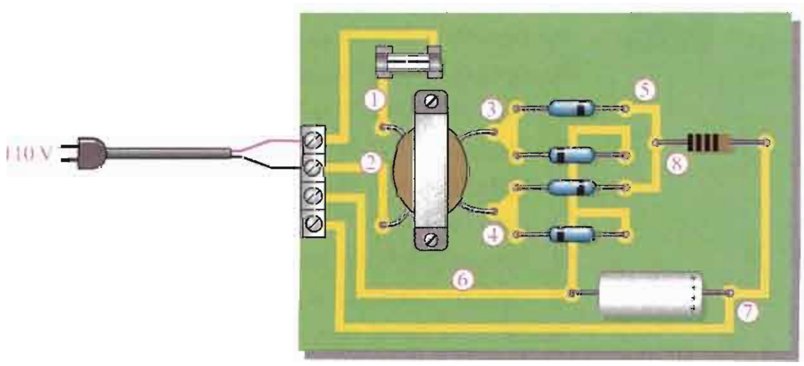
▲ FIGURE 2–82



▲ FIGURE 2–83

SYSTEM APPLICATION PROBLEMS

38. Determine the most likely failure in the circuit board of Figure 2–84 for each of the following symptoms. State the corrective action you would take in each case. The transformer has a rated output of 36 V.
   - **(a)** No voltage measured from test point 1 to test point 2.
   - **(b)** No voltage from test point 3 to test point 4, 110 V rms from test point 1 to test point 2.
   - **(c)** 50 V rms from test point 3 to test point 4. Input is correct at 110 V rms.
   - **(d)** 25 V rms from test point 3 to test point 4. Input is correct at 110 V rms.
   - **(e)** A full-wave rectified voltage with a peak of approximately 50 V at test point 7 with respect to ground.
   - **(f)** Excessive 120 Hz ripple voltage at test point 7.
   - **(g)** The ripple voltage has a frequency of 60 Hz at test point 7.
   - **(h)** No voltage at test point 7.



▲ FIGURE 2–84

39. In testing the power supply board in Figure 2–84 with a 10 kΩ load resistor connected, you find the voltage at the positive side of the filter capacitor to have a 60 Hz ripple voltage. You replace all the diodes, plug in the board, and check the point again to verify proper operation and it still has the 60 Hz ripple voltage. What now?

40. If the top diode on the circuit board in Figure 2–84 is incorrectly installed backwards, what voltage would you measure at test point 8?

ADVANCED PROBLEMS

41. A full-wave rectifier with a capacitor-input filter provides a dc output voltage of 35 V to a 3.3 kΩ load. Determine the minimum value of filter capacitor if the maximum peak-to-peak ripple voltage is to be 0.5 V.

42. A certain unfiltered full-wave rectifier with 115 V, 60 Hz input produces an output with a peak of 15 V. When a capacitor-input filter and a 1.0 kΩ load are connected, the dc output voltage is 14 V. What is the peak-to-peak ripple voltage?

43. 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 110 V, 60 Hz input. Determine the value of the surge resistor in this circuit.

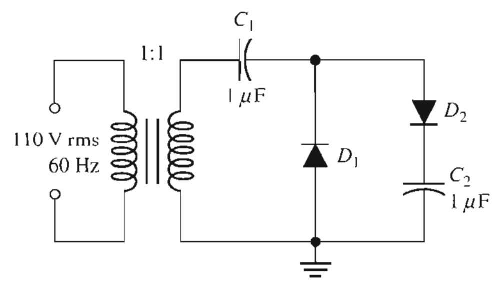
44. Design a full-wave rectifier using an 18 V center-tapped transformer. The output ripple is not to exceed 5% of the output voltage with a load resistance of 680 Ω. Specify the I_O and PIV ratings of the diodes and select an appropriate diode from Figure 2–55.

45. Design a filtered power supply that can produce dc output voltages of +9 V ± 10% and −9 V ±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.

46. Design a circuit to limit a 20 V rms sinusoidal voltage to a maximum positive amplitude of 18 V and a maximum negative amplitude of 10 V using a single 24 V dc voltage source.

47. Determine the voltage across each capacitor in the circuit of Figure 2–85.

▶ FIGURE 2–85



MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on your CD-ROM.

48. Open file TSP02-48 and determine the fault.
49. Open file TSP02-49 and determine the fault.
50. Open file TSP02-50 and determine the fault.
51. Open file TSP02-51 and determine the fault.
52. Open file TSP02-52 and determine the fault.
53. Open file TSP02-53 and determine the fault.
54. Open file TSP02-54 and determine the fault.
55. Open file TSP02-55 and determine the fault.
56. Open file TSP02-56 and determine the fault.

ANSWERS

SECTION REVIEWS

SECTION 2–1 Half-Wave Rectifiers

1. PIV across the diode occurs at the peak of the input when the diode is reversed biased.
2. There is current through the load for approximately half (50%) of the input cycle.
3. The average value is $10\text{ V}/\pi = 3.18\text{ V}$.
4. The peak output voltage is $25\text{ V} - 0.7\text{ V} = 24.3\text{ V}$.
5. The PIV must be at least 50 V.

SECTION 2–2 Full-Wave Rectifiers

1. A full-wave voltage occurs on each half of the input cycle and has a frequency of twice the input frequency. A half-wave voltage occurs once each input cycle and has a frequency equal to the input frequency.
2. The average value of $2(60\text{ V})/\pi = 38.12\text{ V}$
3. The bridge rectifier has the greater output voltage.
4. The 50 V diodes must be used in the bridge rectifier.
5. In the center-tapped rectifier, diodes with a PIV rating of at least 90 V would be required.

SECTION 2–3 Power Supply Filters and Regulators

1. The output frequency is 60 Hz.
2. The output frequency is 120 Hz.
3. The ripple voltage is caused by the slight charging and discharging of the capacitor through the load resistor.
4. The ripple voltage amplitude increases when the load resistance decreases.
5. Ripple factor is the ratio of the ripple voltage to the average or dc voltage.
6. Input regulation means that the output is constant over a range of input voltages. Load regulation means that the output voltage is constant over a range of load current values.

SECTION 2–4 Diode Limiting and Clamping Circuits

1. Limiters clip off or remove portions of a waveform. Clampers insert a dc level.
2. A positive limiter clips off positive voltages. A negative limiter clips off negative voltages.
3. 0.7 V appears across the diode.
4. The bias voltage must be $5\text{ V} - 0.7\text{ V} = 4.3\text{ V}$.
5. The capacitor acts as a battery.

SECTION 2–5 Voltage Multipliers

1. The peak voltage rating must be 100 V.
2. The PIV rating must be at least 310 V.

SECTION 2–6 The Diode Data Sheet

1. The three rating categories on a diode data sheet are maximum ratings, electrical characteristics, and mechanical data.
2. V_F is forward voltage, I_R is reverse current, and I_O is peak average forward current.
3. I_{FSM} is maximum forward surge current, V_{RRM} is maximum reverse peak repetitive voltage, and V_{RSM} is maximum reverse peak nonrepetitive voltage.
4. The 1N4720 has an $I_O = 3.0\text{ A}$, $I_{FSM} = 300\text{ A}$, and $V_{RRM} = 100\text{ V}$.

SECTION 2–7 Troubleshooting

1. An open diode results in no output voltage.
2. An open diode produces a half-wave output voltage.
3. The shorted diode may burn open. Transformer will be damaged. Fuse will blow.
4. The amplitude of the ripple voltage increases with a leaky filter capacitor.
5. There will be no output voltage when the primary opens.
6. The problem may be a partially shorted secondary winding.

RELATED PROBLEMS FOR EXAMPLES

2–1 3.82 V

2–2 (**a**) 2.3 V (**b**) 209.3 V

2–3 (**a**) 623.3 V (**b**) 624 V (**c**) negative half-cycles rather than positive half cycles

2–4 98.7 V

2–5 79.3 V including diode drop

2–6 41.0 V; 41.7 V

2–7 103 mV

2–8 3.7%

2–9 A positive peak of 8.72 V and clipped at −0.7 V

2–10 Limited at +10.7 V and − 10.7 V

2–11 Change R_3 to 1.0 kΩ or R_2 to 2.2 kΩ.

2–12 Same voltage waveform as Figure 2–48

2–13 Verify C is shorted and replace it.

CIRCUIT-ACTION QUIZ

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

SELF-TEST

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