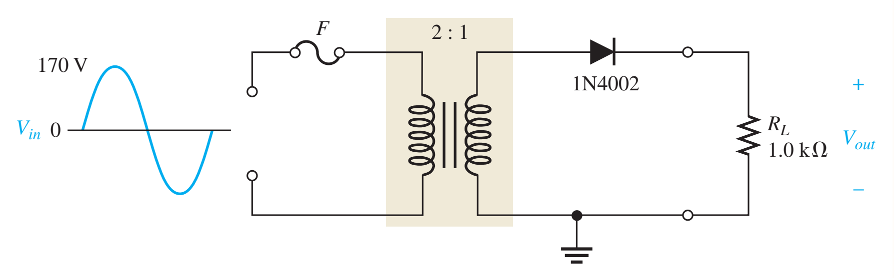
EXAMPLE 2–4

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

▶ FIGURE 2–28



Solution

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

The peak secondary voltage is

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

The rectified peak output voltage is

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

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

Related Problem

(a) Determine the peak value of the output voltage for Figure 2–28 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 E02-04 in the Examples folder on the companion website. For the specified input, measure the peak output voltage. Compare your measured result with the calculated value.

SECTION 2–4 CHECKUP

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?

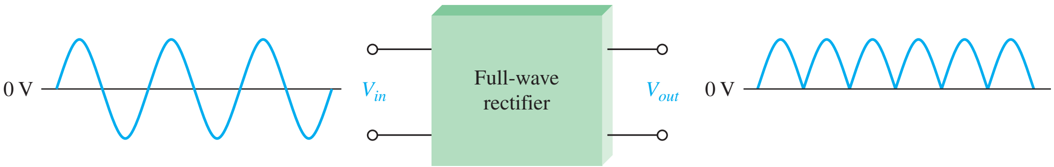
2–5 FULL-WAVE RECTIFIERS

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

After completing this section, you should be able to

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

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



▲ FIGURE 2–29

Full-wave rectification.

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

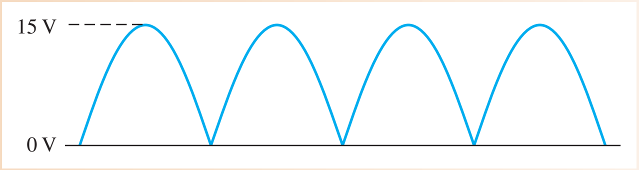
$$V_{AVG} = \frac{2V_p}{\pi}$$ **Equation 2–6**

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

EXAMPLE 2–5

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

► FIGURE 2–30



Solution

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

V_{AVG} is 63.7% of V_p.

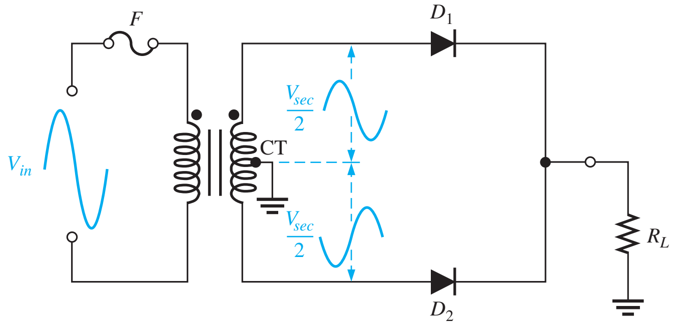
Related Problem Find the average value of the full-wave rectified voltage if its peak is 155 V.

Center-Tapped Full-Wave Rectifier Operation

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

▶ FIGURE 2–31

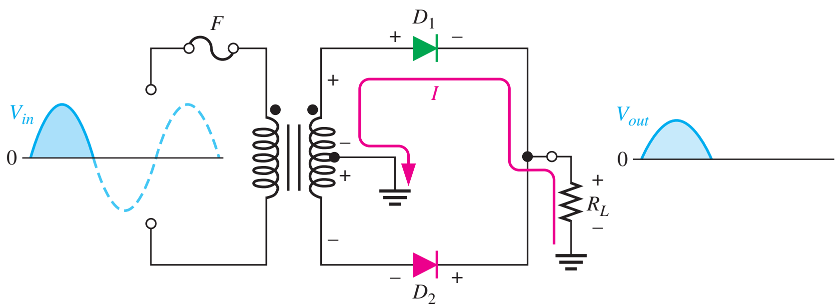
A center-tapped full-wave rectifier.



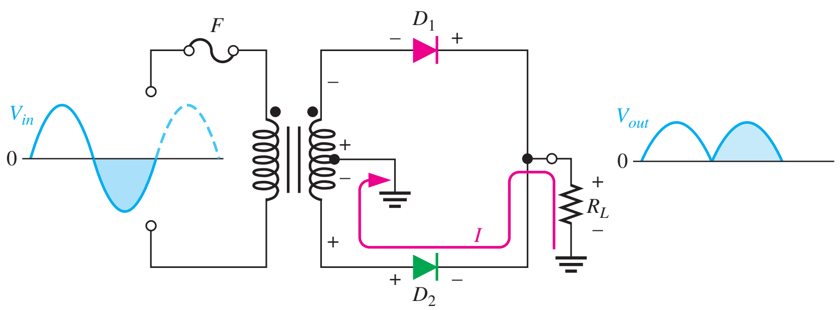
For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown in Figure 2–32(a). This condition forward-biases diode D_1 and reverse-biases diode D_2. The current path is through D_1 and the load resistor R_L, as indicated. For a negative half-cycle of the input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

▶ FIGURE 2–32

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



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



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

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

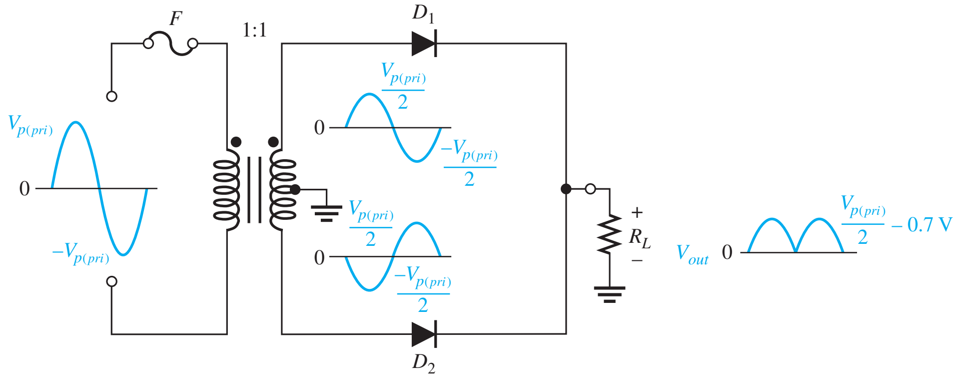


FIGURE 2–33

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

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.**

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

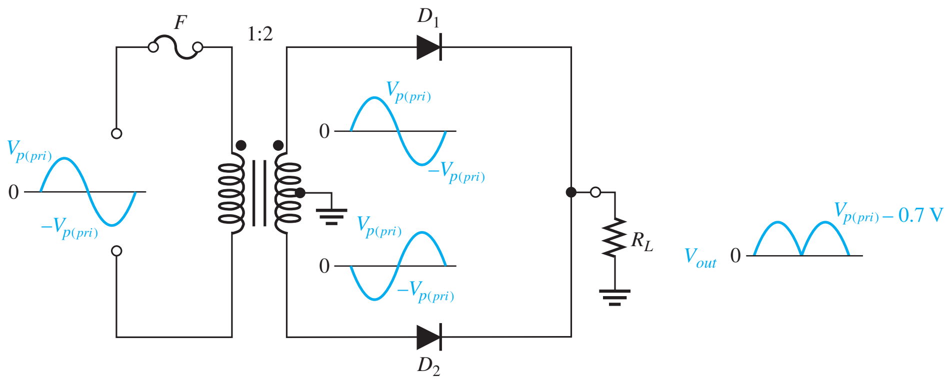


FIGURE 2–34

Center-tapped full-wave rectifier with a transformer turns ratio of 2.

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

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

Equation 2–7

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

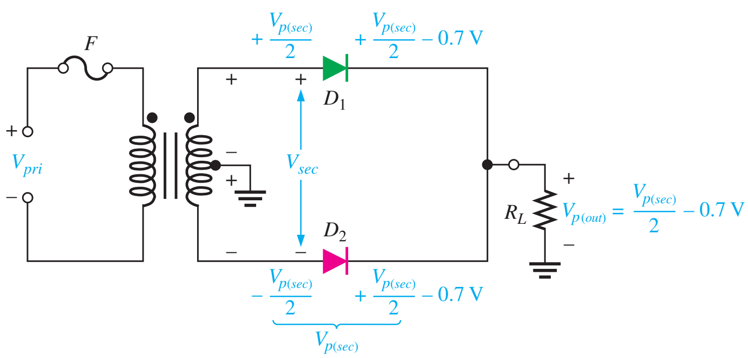


FIGURE 2–35

Diode reverse voltage (D_2 shown reverse-biased and D_1 shown forward-biased).

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

The peak inverse voltage across D_2 is

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

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

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

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

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

Equation 2–8

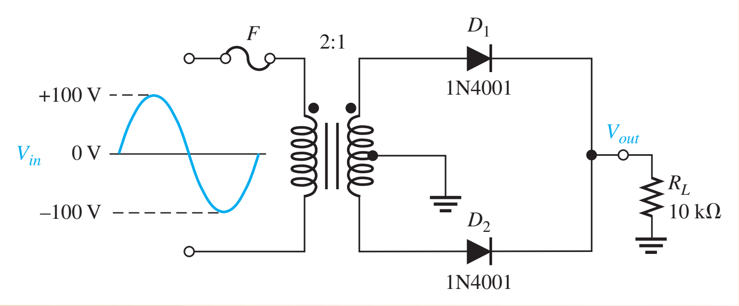
$$\mathbf{PIV = 2V_{p(out)} + 0.7\text{ V}}$$

EXAMPLE 2–6

(a) Show the voltage waveforms across each half of the secondary winding and across R_L when a 100 V peak sine wave is applied to the primary winding in Figure 2–36.

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

▶ FIGURE 2–36



Solution

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

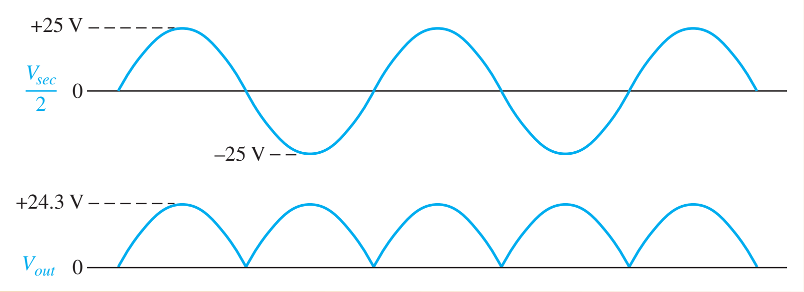
$$V_{p(sec)} = nV_{p(pri)} = 0.5(100\text{ V}) = 50\text{ V}$$

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 2–37.

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

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

▶ FIGURE 2–37



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

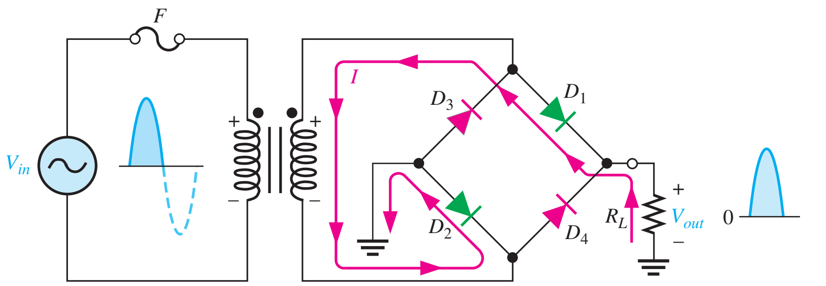
Open the Multisim file E02-06 in the Examples folder on the companion website. For the specified input voltage, measure the voltage waveforms across each half of the secondary and across the load resistor. Compare with the results shown in the example.

Bridge Full-Wave Rectifier Operation

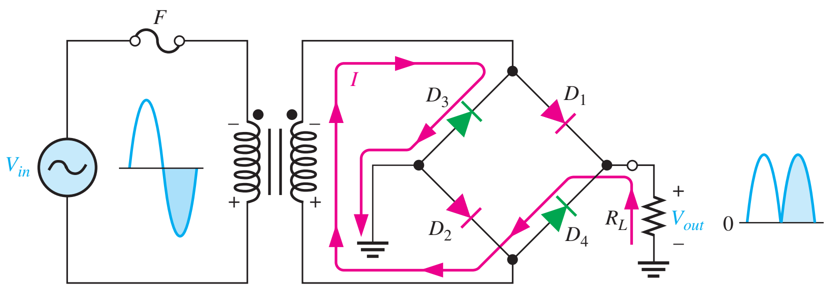
The **bridge rectifier** uses four diodes connected as shown in Figure 2–38. When the input cycle is positive as in part (a), diodes D_1 and D_2 are forward-biased and conduct current in the direction shown. A voltage is developed across R_L that looks like the positive half of the input cycle. During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

FIGURE 2–38

Operation of a bridge rectifier.



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

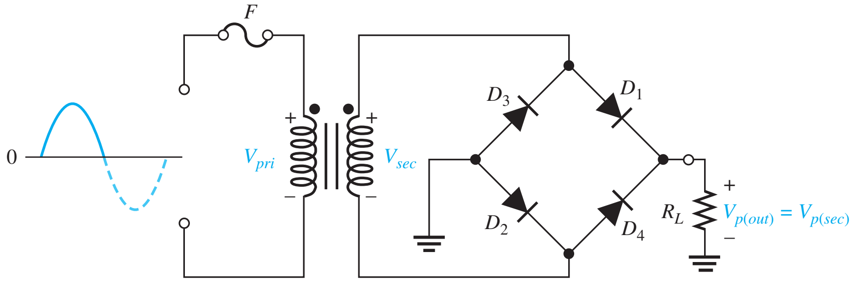
Bridge Output Voltage A bridge rectifier with a transformer-coupled input is shown in Figure 2–39(a). During the positive half-cycle of the total secondary voltage, diodes D_1 and D_2 are forward-biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true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

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

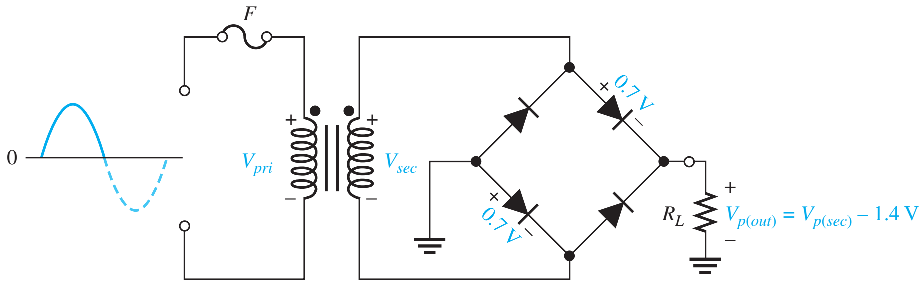
As you can see in Figure 2–39(b), two diodes are always in series with the load resistor during both the positive and negative half-cycles. If these diode drops are taken into account, the output voltage is

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

Equation 2–9



(a) Ideal diodes



(b) Practical diodes (Diode drops included)

▲ **FIGURE 2–39**

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

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

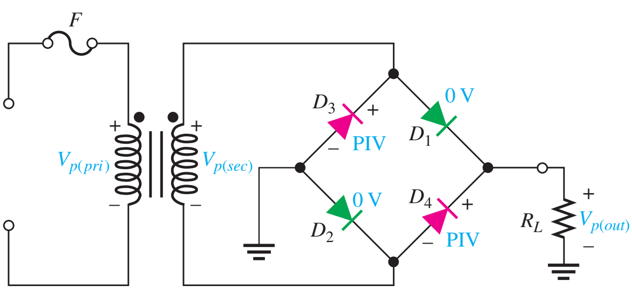
$$\text{PIV} = V_{p(out)}$$

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

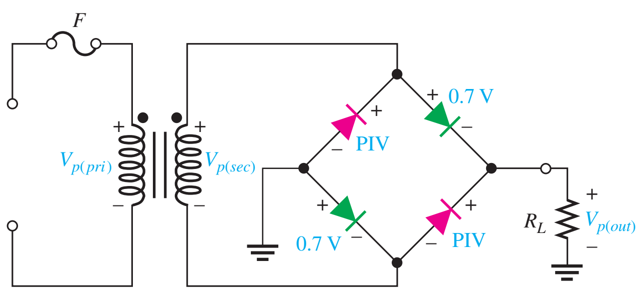
Equation 2–10

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

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



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



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

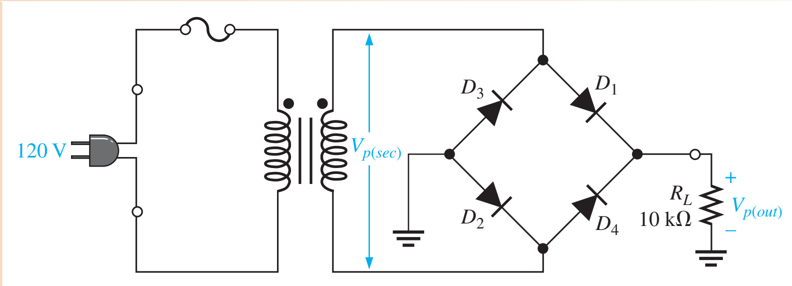
▲ **FIGURE 2–40**

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

EXAMPLE 2–7

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

▶ **FIGURE 2–41**



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

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

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

The PIV rating for each diode is

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

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

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

SECTION 2–5 CHECKUP

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

2–6 POWER SUPPLY FILTERS AND REGULATORS

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