CHAPTER 3 DC Power Supply

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CHAPTER 3 DC Power Supply

3.1 Half-Wave Rectifier

3.2 Full-Wave Rectifier

3.3 Power Supply Filter And Regulators

3.1 Half-Wave Rectifier

- All active electronic devices require a source of constant dc that can be supplied by a battery or a dc power supply. The output dc voltage is used to power most electronic circuits. The dc voltage level required depends on the application, but most applications require relatively low dc voltages.
- Generally the ac input line voltage is stepped down to a lower ac voltage with a transformer (although it may be stepped up when higher voltages are needed or there may be no transformer at all in rare instances).

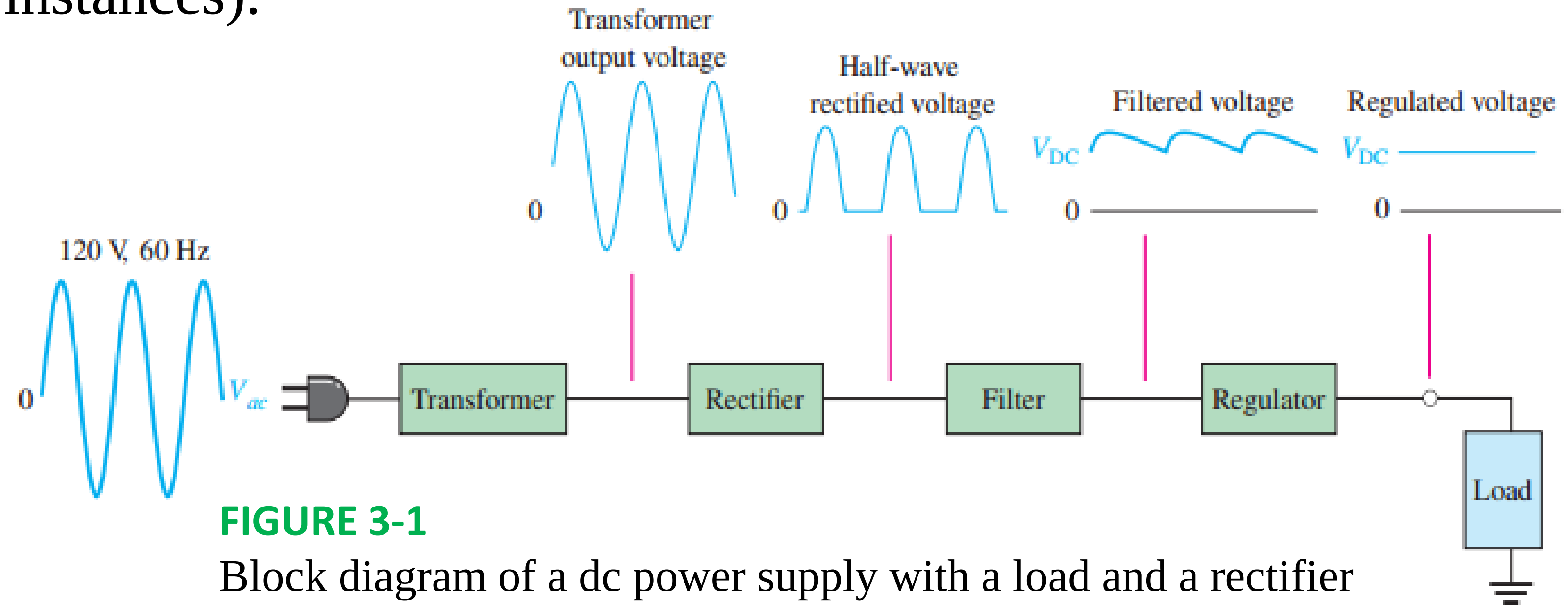


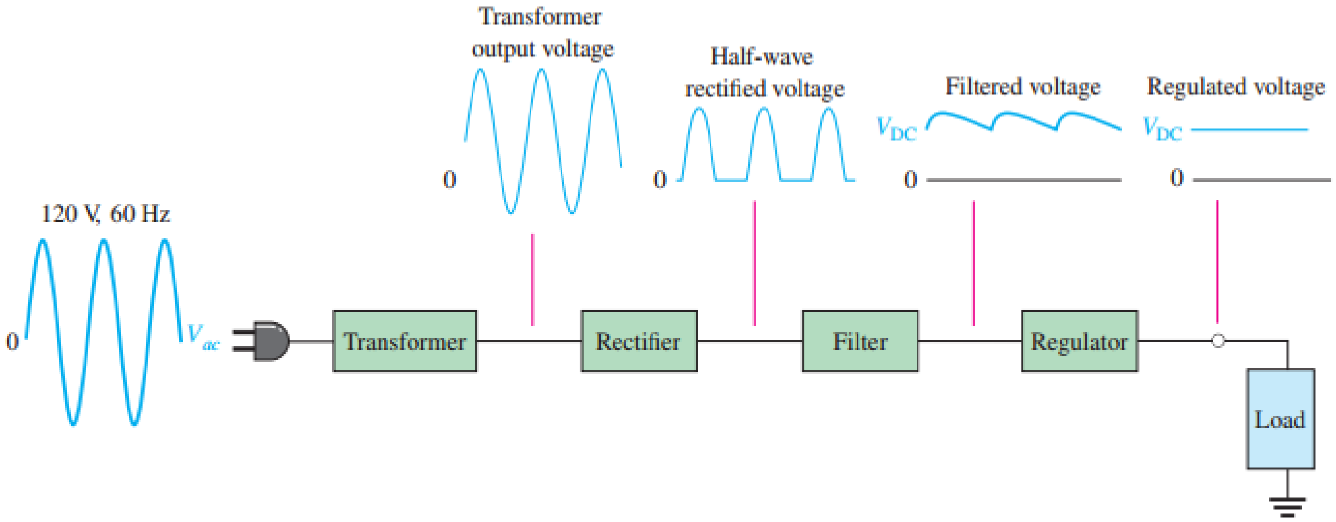
FIGURE 3-1

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

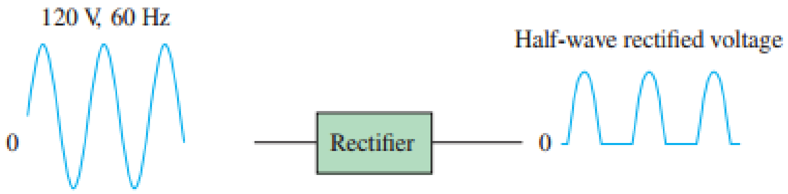
(a) Complete power supply with transformer, rectifier, filter, and regulator

The Basic DC Power Supply

- The rectifier can be either a half-wave rectifier or a full-wave rectifier . The rectifier converts the ac input voltage to a pulsating dc voltage, called a half-wave rectified voltage, as shown in Figure 3–1(b).
- The filter eliminates the fluctuations in the rectified voltage and produces a relatively smooth dc voltage.
- The regulator is a circuit that maintains a constant dc voltage for variations in the input line voltage or in the load. Regulators vary from a single semiconductor device to more complex integrated circuits.



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



(b) Half-wave rectifier

FIGURE 3-1
Block diagram of a dc power supply with a load and a rectifier

Half-Wave Rectifier Operation

- Figure 3-2 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.
- 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.

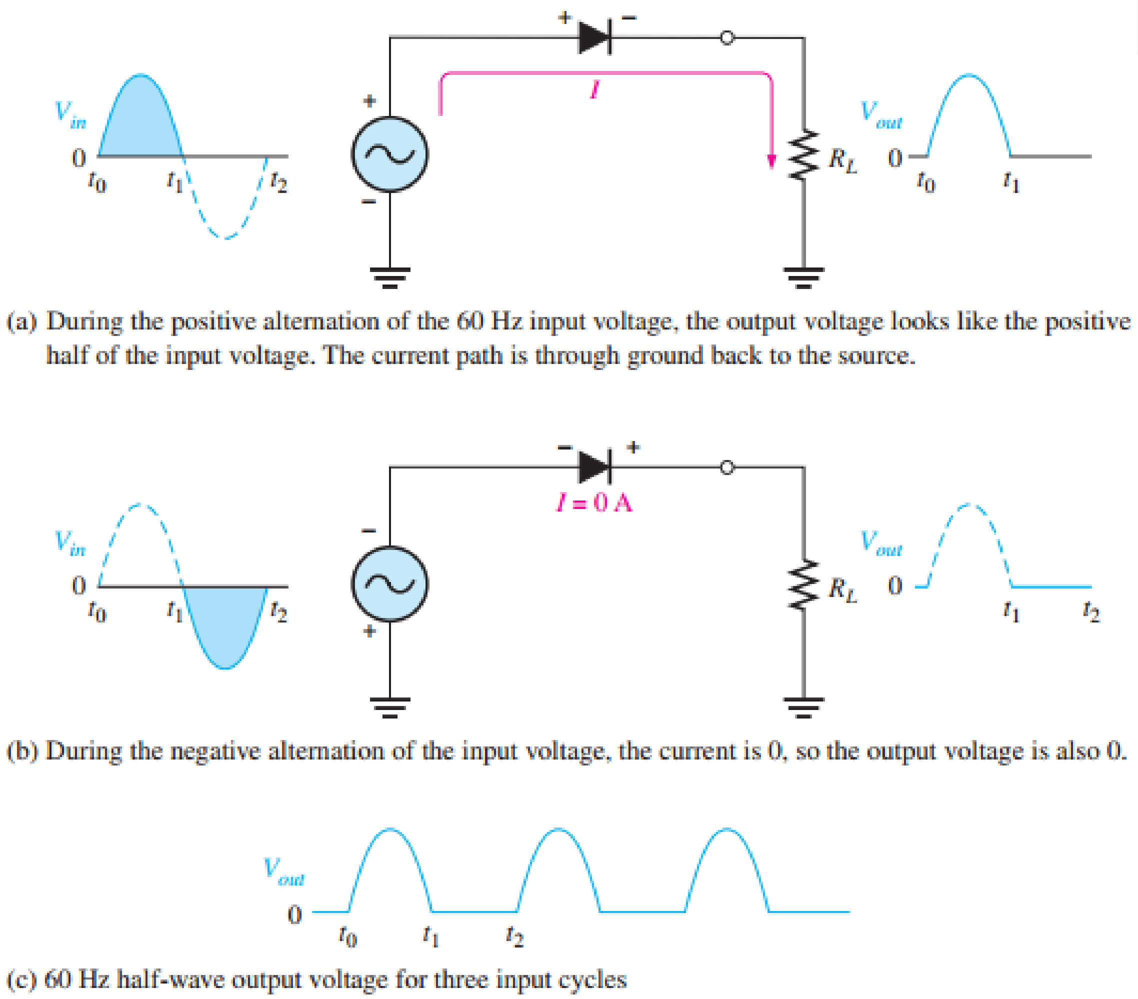


FIGURE 3-2 Half-wave rectifier operation. The diode is considered to be ideal.

Half-Wave Rectifier Operation

- When the input voltage goes negative during the second half of its cycle, the diode is reverse-biased and the source voltage appears across the diode. There is no current, so the voltage across the load resistor is 0 V, as shown in Figure 3–2(b).
- The net result is that <u>only the positive half-cycles of the ac input voltage appear across the load</u>. Since the output does not change polarity, it is a pulsating dc voltage with a frequency of 60 Hz (China 50Hz) , as shown in part (c).

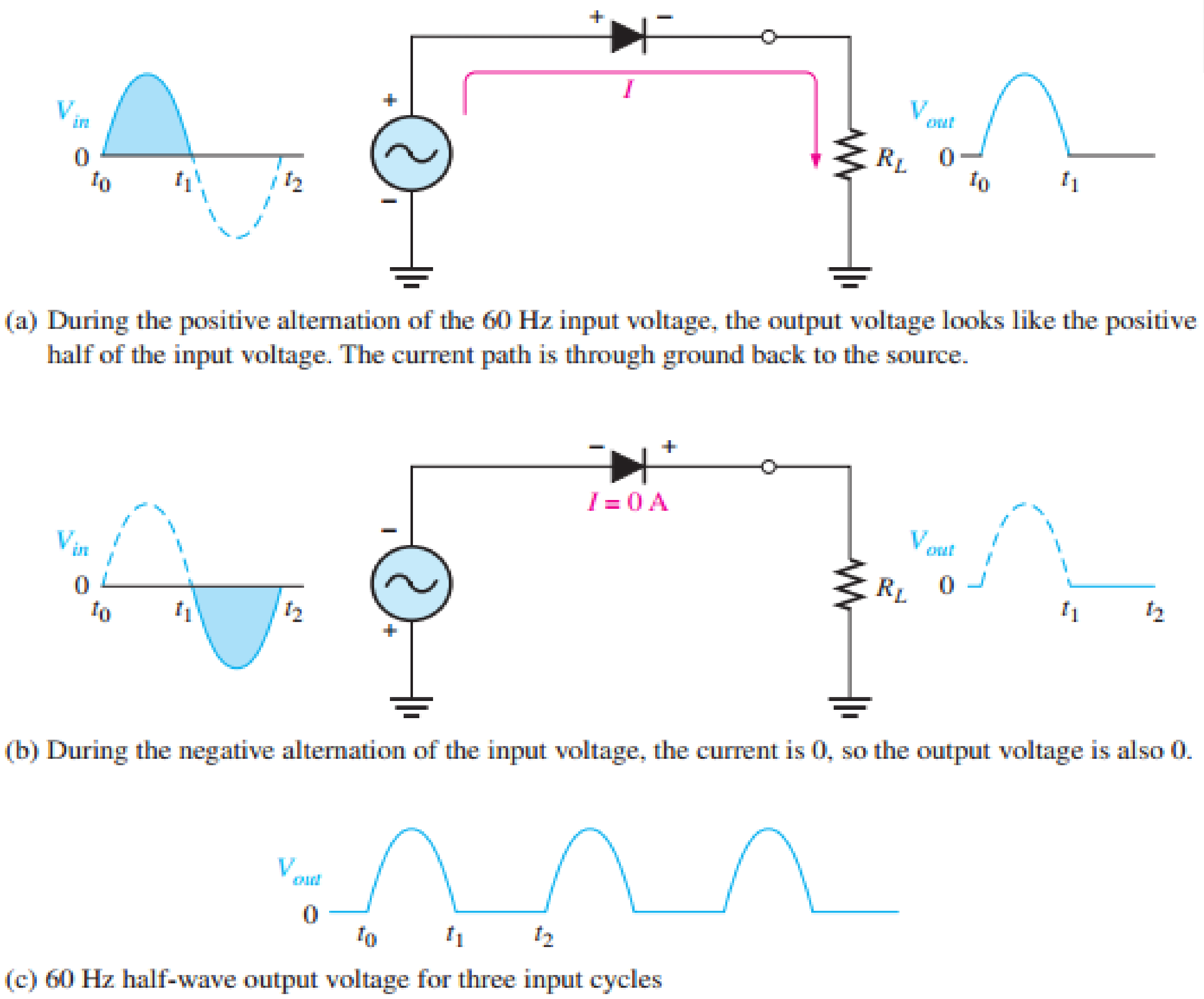


FIGURE 3-2 Half-wave rectifier operation. The diode is considered to be ideal.

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 3–3, and then dividing by 2π, the number of radians in a full cycle.
- The result of this is expressed in right Equation , 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.

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

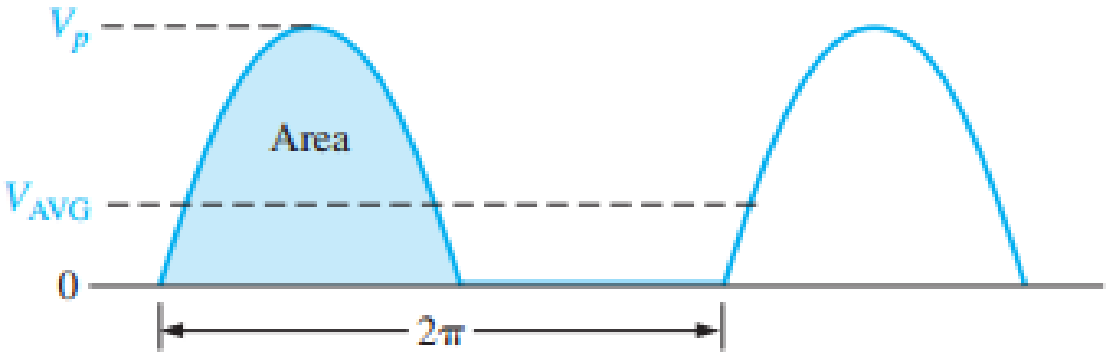
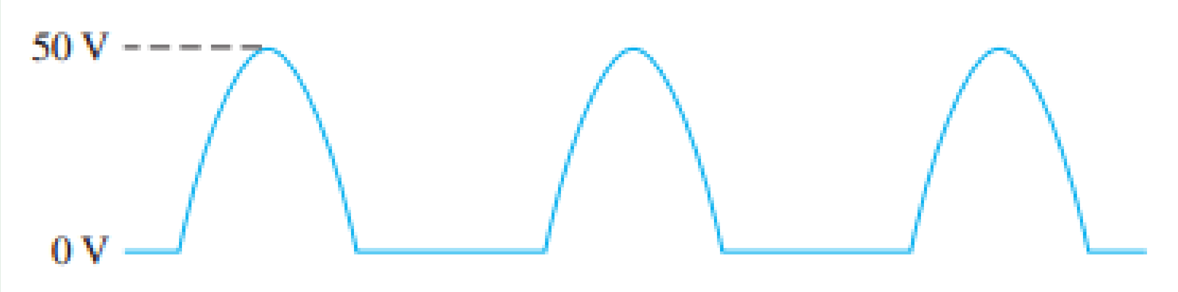


FIGURE 3-3 Average value of the half-wave rectified signal.

Example

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

▶ FIGURE 2–22



Example

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

FIGURE 2–22

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.

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.

- 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.

The expression for the peak output voltage is

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

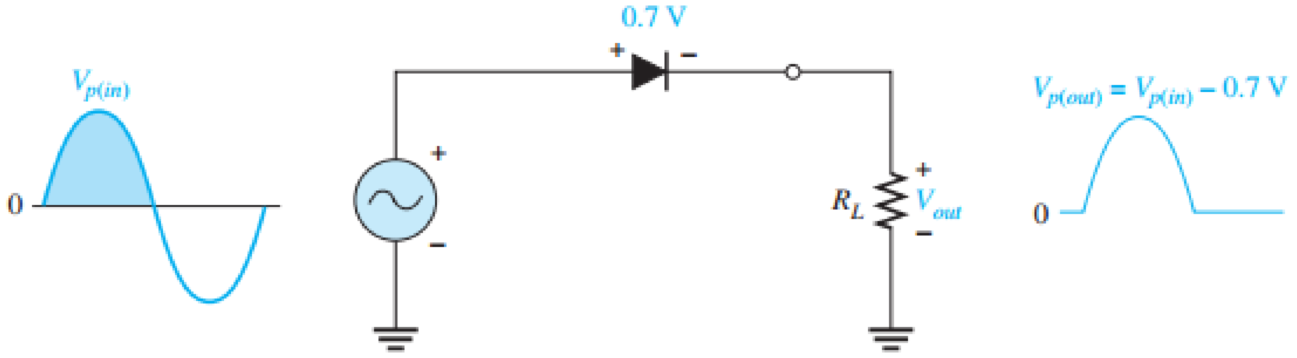
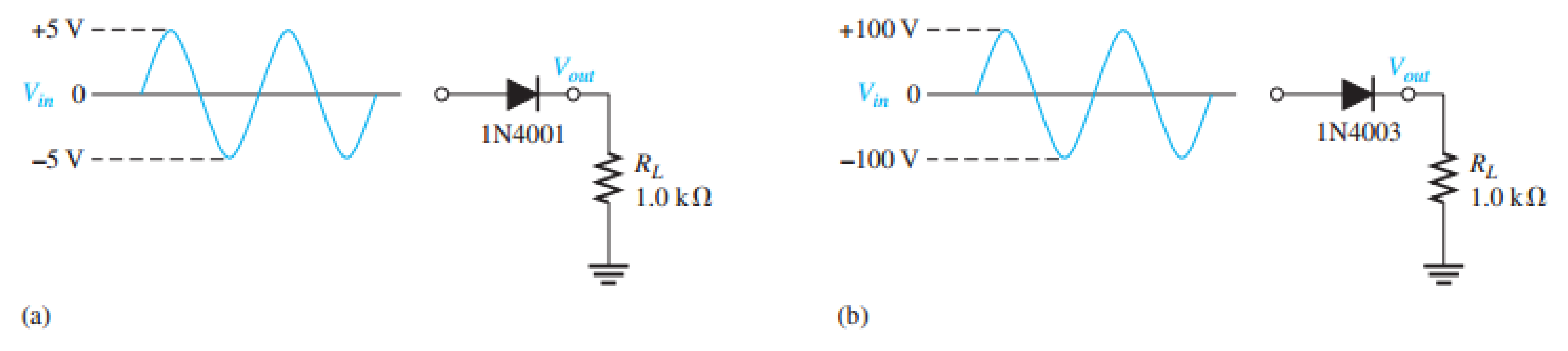


FIGURE 3-4

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.

Example

EXAMPLE 2–3 Draw the output voltages of each rectifier for the indicated input voltages, as shown in Figure 2–24. The 1N4001 and 1N4003 are specific rectifier diodes.



▲ FIGURE 2–24

Example

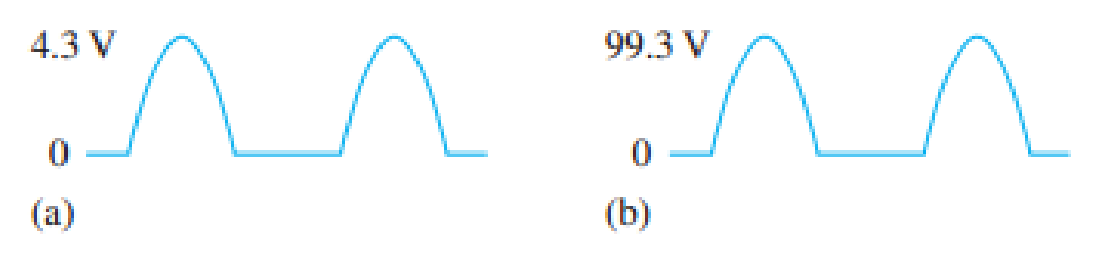
Solution The peak output voltage for circuit (a) is

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

The peak output voltage for circuit (b) is

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

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



截图(Alt + A)

▲ FIGURE 2–25

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

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

Peak Inverse Voltage (PIV) of diode

- The peak inverse voltage (PIV) equals the peak value of the input voltage, and the diode must be capable of withstanding at least this amount of repetitive reverse voltage.

- For the diode in Figure 3–5, the maximum value of reverse voltage, designated as PIV, occurs at the peak of each negative alternation of the input voltage when the diode is reverse-biased.

- A diode should be rated at least 20% higher than the PIV

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

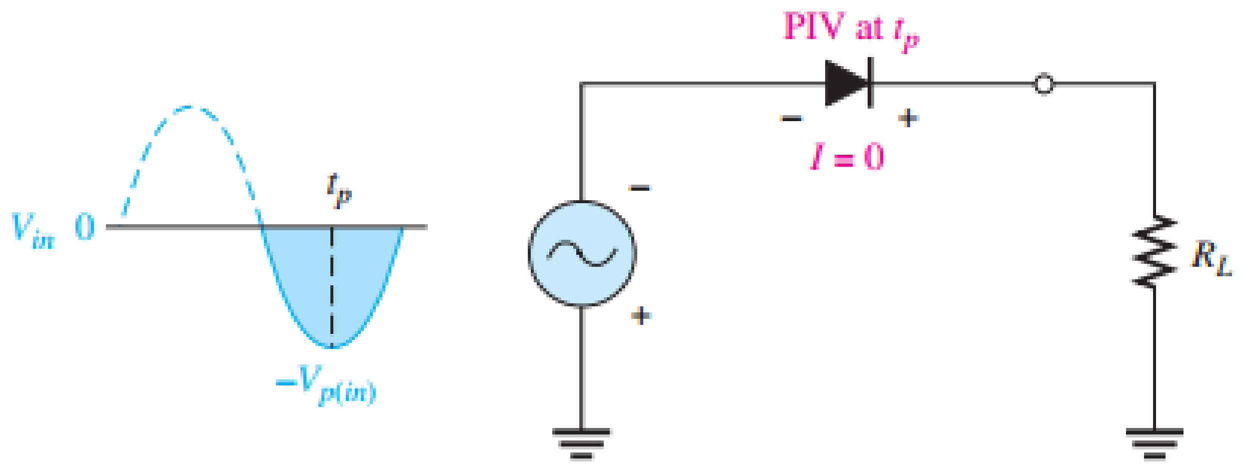


FIGURE 3-5
The PIV occurs at the peak of each half-cycle of the input voltage when the diode is reverse-biased. In this circuit, the PIV occurs at the peak of each negative half-cycle.

Transformer Coupling

- Transformer coupling provides two advantages. First, it allows the source voltage to be stepped up or down as needed. Second, the ac source is electrically isolated from the rectifier, thus avoiding a shock hazard in the secondary circuit for lower voltages

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

- 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 $V_{sec} = V_{pri}$, and the transformer is referred to as an isolation transformer.

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

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

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

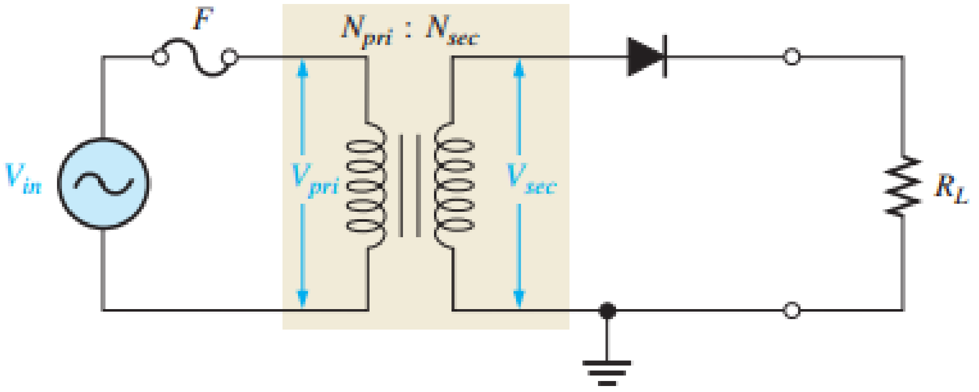
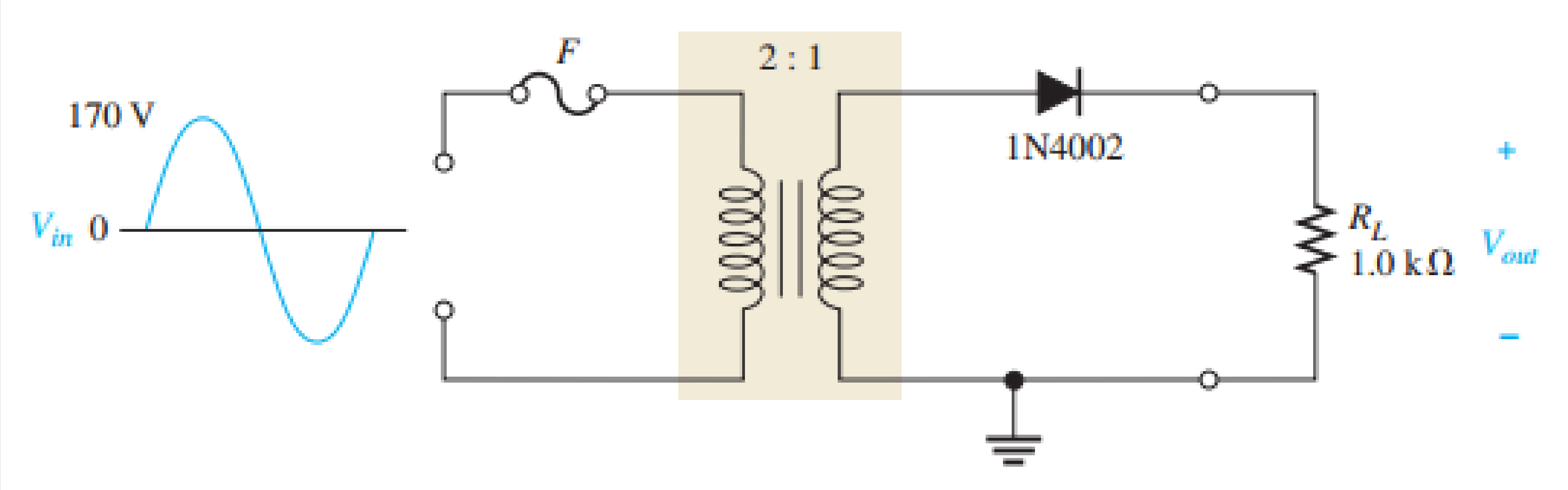


FIGURE 3-6 Half-wave rectifier with transformercoupled input voltage.

Example

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



Example

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.

3.2 Full-Wave Rectifier

- A full-wave rectifier allows unidirectional (one-way) current through the load during the entire 360° of the input cycle, where as 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 3–7.

- 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 right formula:

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

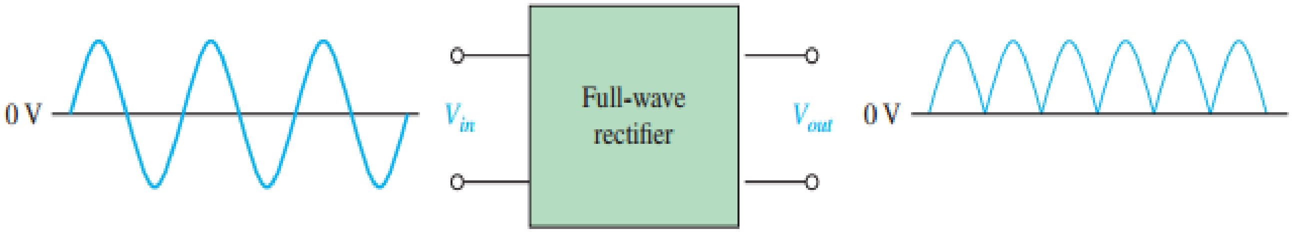


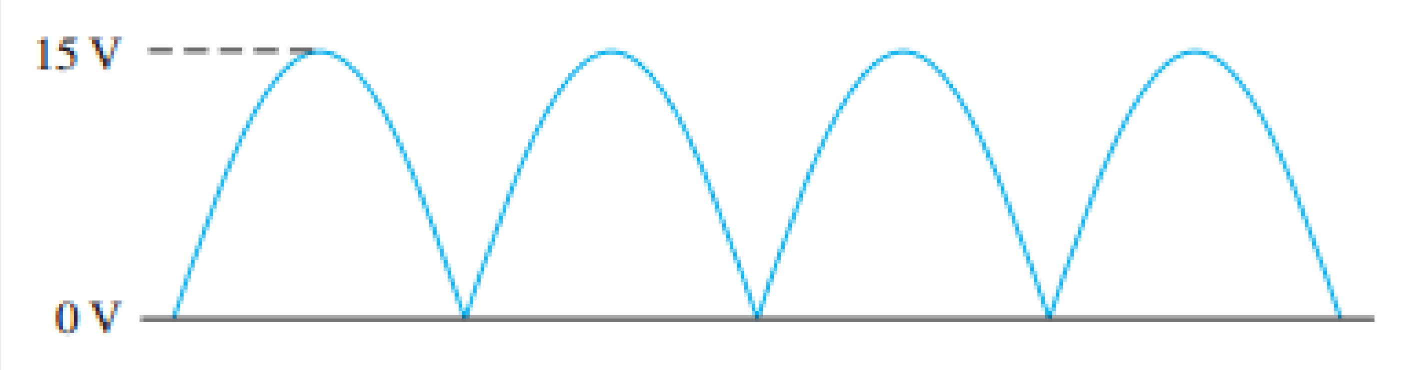
FIGURE 3-7 Full-wave rectification.

Example

EXAMPLE 2–5

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

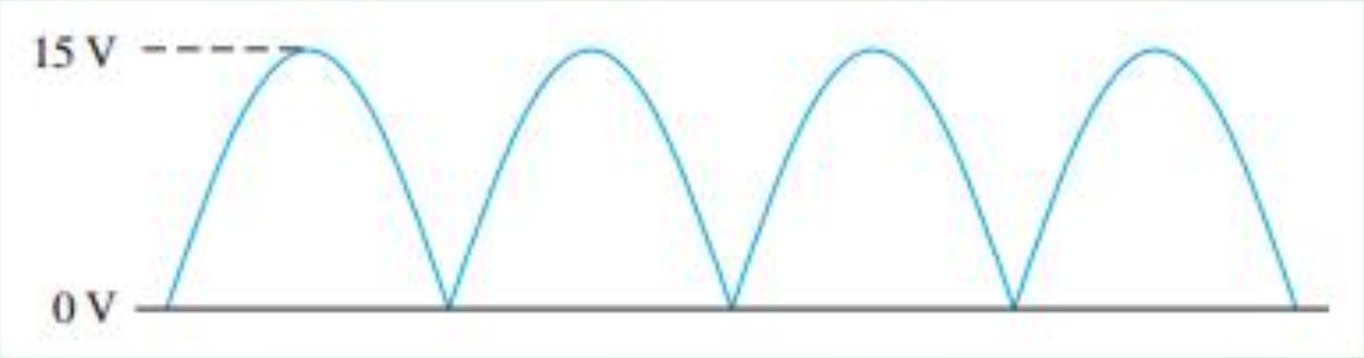
▶ FIGURE 2–30



Example

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 3–8.

- 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.

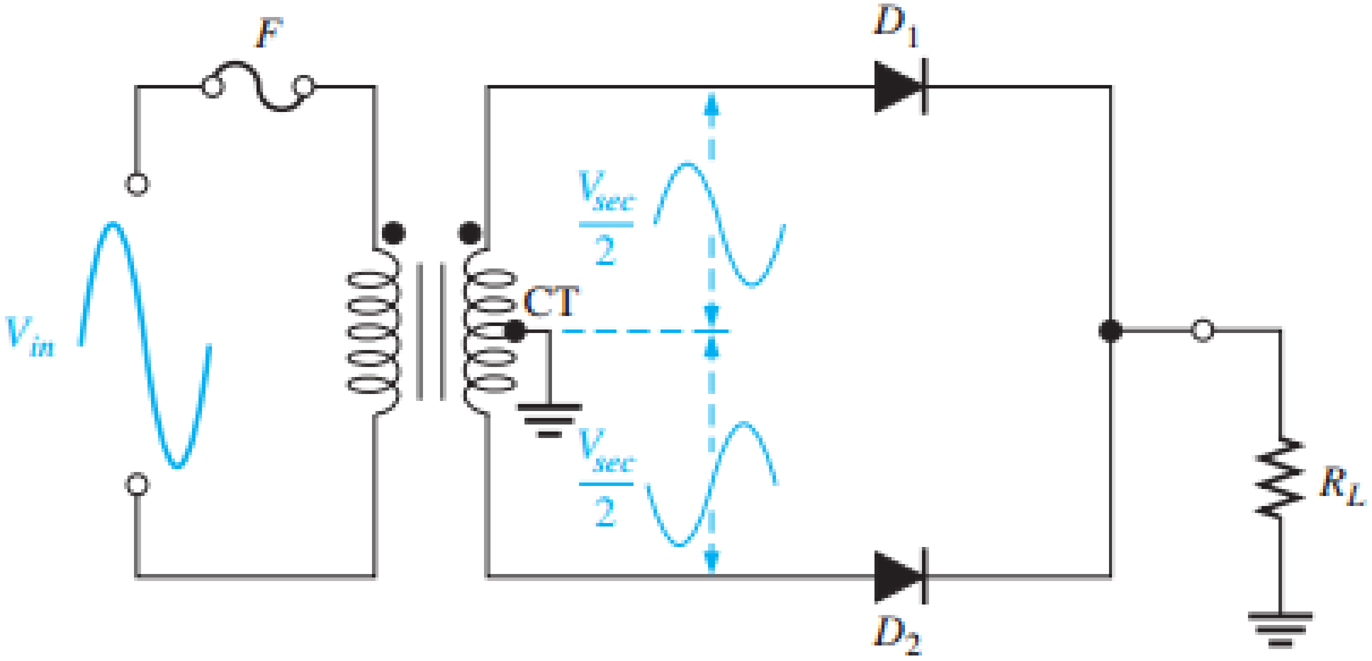


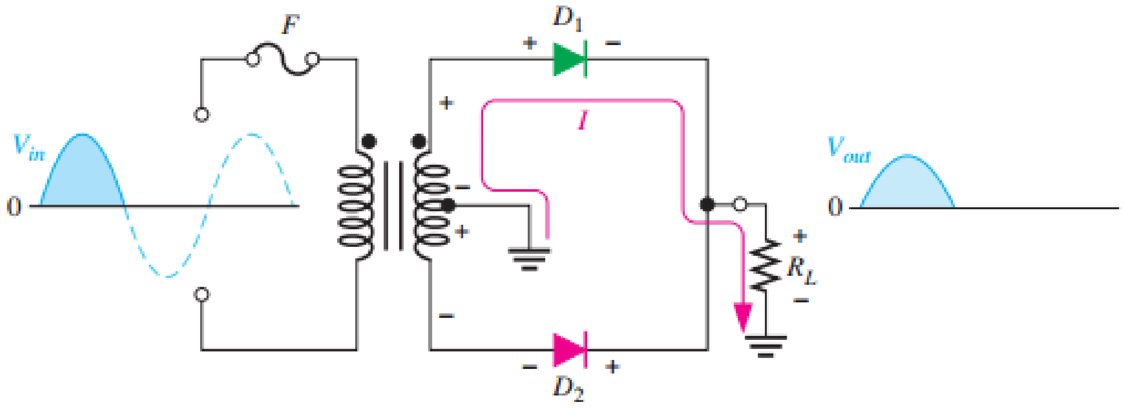
FIGURE 3-8 A center-tapped full-wave rectifier

Center-Tapped Full-Wave Rectifier Operation

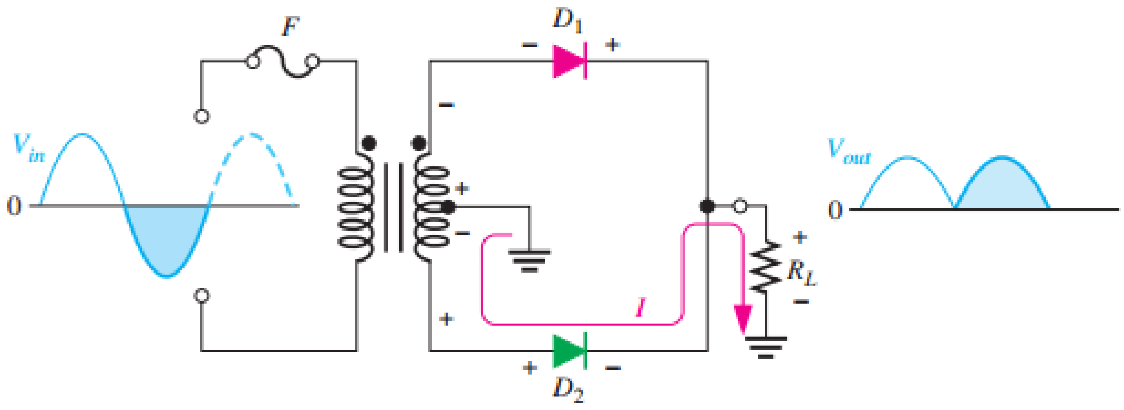
- For a positive half-cycle of the input voltage, the polarities of the secondary voltages are as shown in Figure 3–9(a). This condition forward-biases diode D1 and reverse-biases diode D2. The current path is through D1 and the load resistor R_L, as indicated.

- For a negative half-cycle of the input voltage, the voltage polarities on the secondary are as shown in Figure 3–9(b). This condition reverse-biases D1 and forward-biases D2. The current path is through D2 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.



(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 3-9 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 3–10. 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.
- 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 3–11. 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}.

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

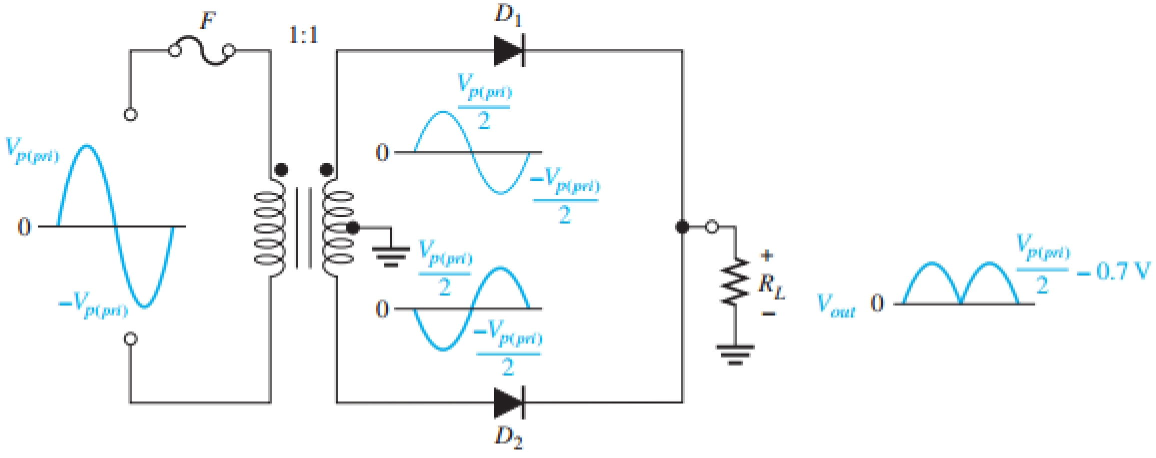


FIGURE 3-10 Center-tapped full-wave rectifier with a transformer turns ratio of 1.

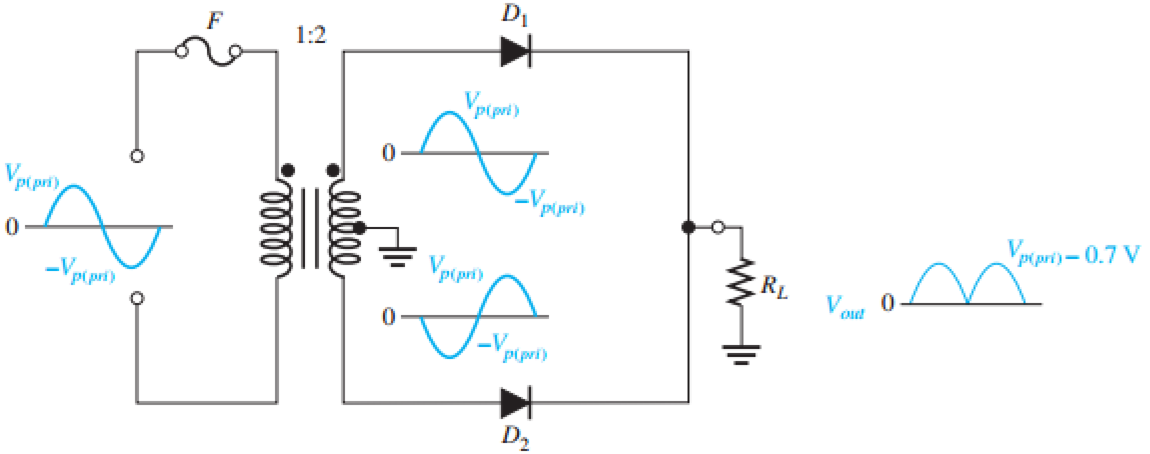


FIGURE 3-11 Center-tapped full-wave rectifier with a transformer turns ratio of 2.

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 $V_{p(sec)}$-0.7V.
- This is shown in Figure 3–12 where D_2 is assumed to be reverse-biased (red) and D_1 is assumed to be forward-biased (green) to illustrate the concept.

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

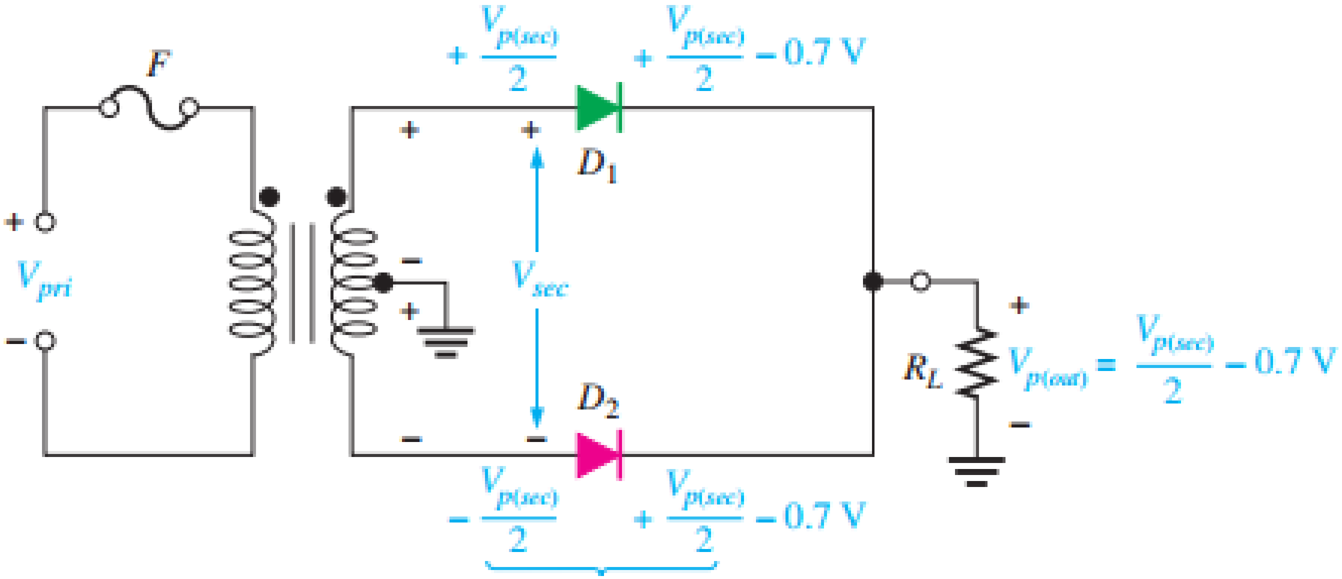


FIGURE 3-12 Diode reverse voltage (D2 shown reverse-biased and D1 shown forward-biased).

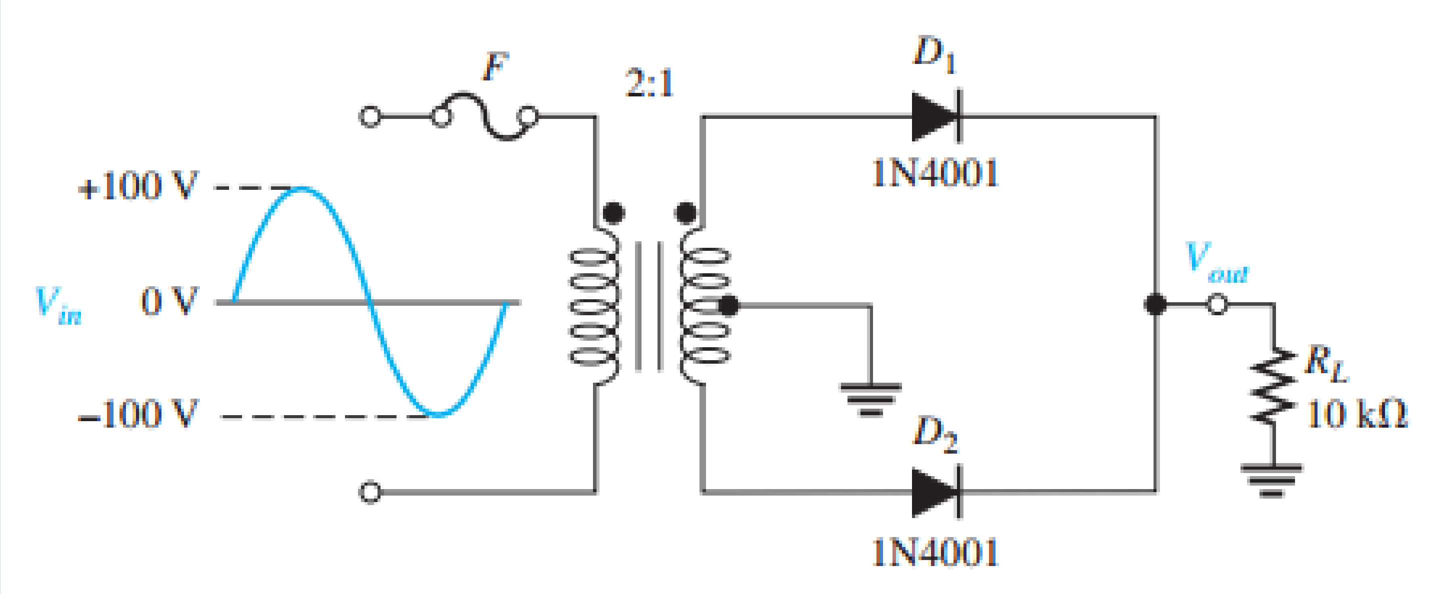
Example

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) Assuming a 20% margin, what minimum PIV rating must the diodes have?

▶ FIGURE 2–36



Example

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

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

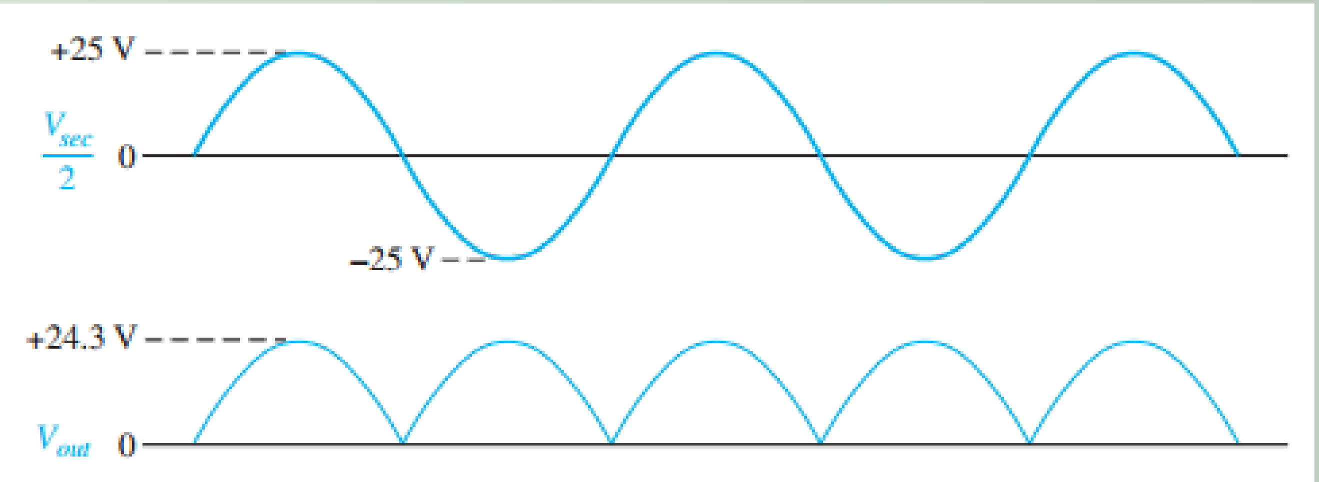
There is a 25 V peak across each half of the secondary with respect to ground. The output load voltage has a peak value of 25 V, less the 0.7 V drop across the diode. The waveforms are shown in Figure 2–37.

(b) The PIV for each diode is

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

The PIV rating should be at least 20% higher, or **60 V**.

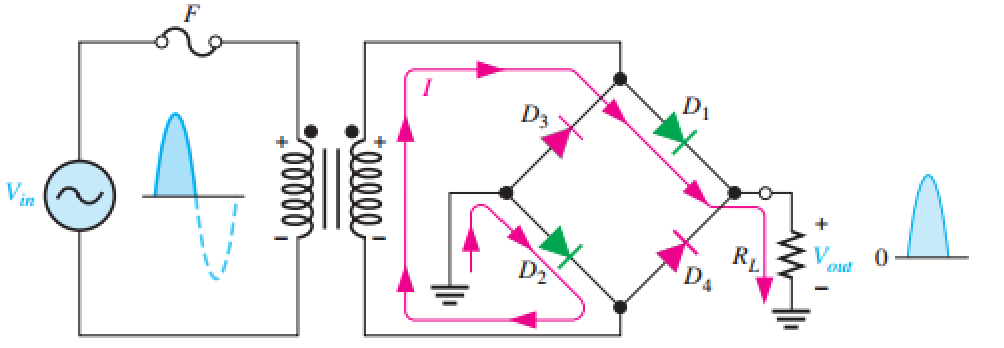
FIGURE 2–37



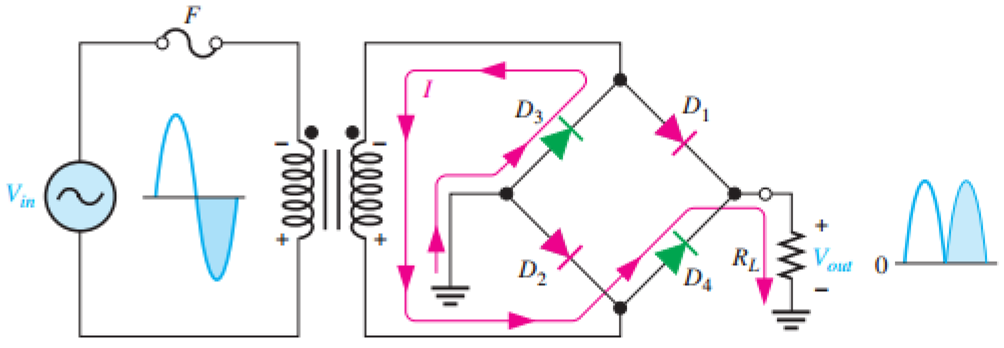
Related Problem What diode PIV rating is required to handle a peak input of 160 V in Figure 2–36?

Bridge Full-Wave Rectifier Operation

- The bridge rectifier uses four diodes connected as shown in Figure 3–13. When the input cycle is positive as in part (a), diodes D1 and D2 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 D3 and D4 are reverse-biased.
- When the input cycle is negative as in Figure 3–13(b), diodes D3 and D4 are forward biased and conduct current in the same direction through R_L as during the positive half cycle. During the negative half-cycle, D1 and D2 are reverse-biased. A full-wave rectified output voltage appears across R_L as a result of this action.



(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.

FIGURE 3-13 Operation of a bridge rectifier.

Bridge Output Voltage

- A bridge rectifier with a transformer-coupled input is shown in Figure 3–14(a).
- During the positive half-cycle of the total secondary voltage, diodes D1 and D2 are forward-biased. Neglecting the diode drops, the secondary voltage appears across the load resistor. The same is true when D3 and D4 are forward-biased during the negative half-cycle
- As you can see in Figure 3–14(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

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

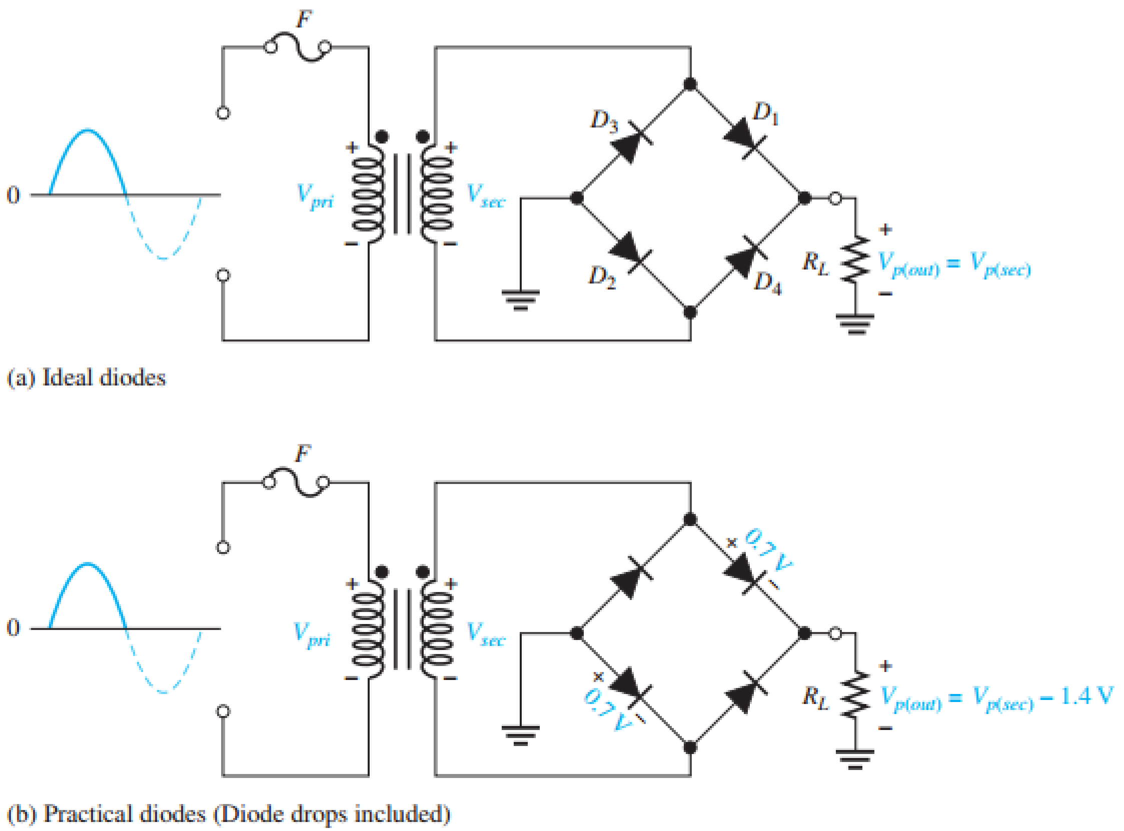
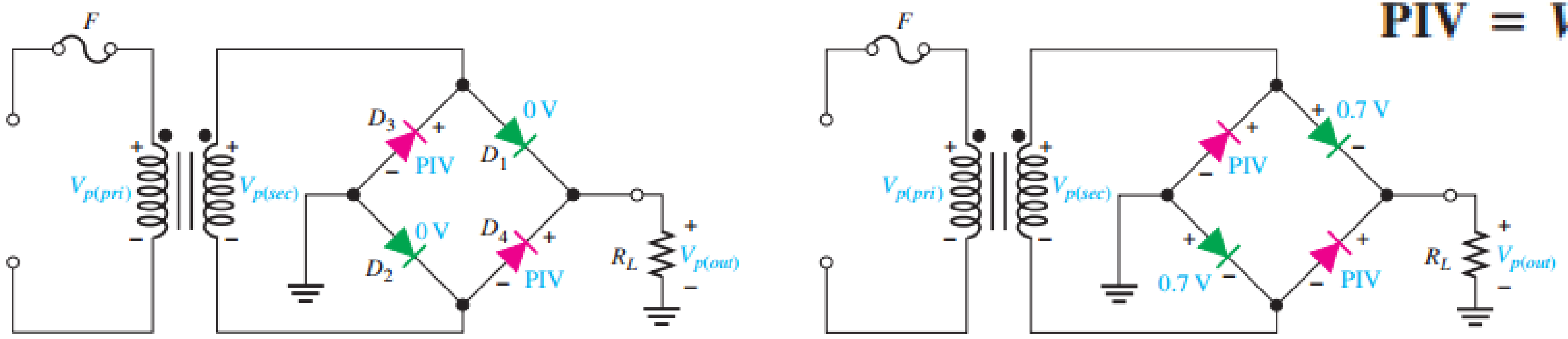


FIGURE 3-14 Bridge operation during a positive half-cycle of the primary and secondary voltages.

Bridge Output Voltage

- Let's assume that D1 and D2 are forward-biased and examine the reverse voltage across D3 and D4. Visualizing D1 and D2 as shorts (ideal model), as in Figure 3–15(a), you can see that D3 and D4 have a peak inverse voltage equal to the peak secondary voltage.
- Since the output voltage is ideally equal to the secondary voltage. If the diode drops of the forward-biased diodes are included as shown in Figure 3–15(b), the peak inverse voltage across each reverse-biased diode in terms of $V_{p(out)}$ is

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



(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 3-15

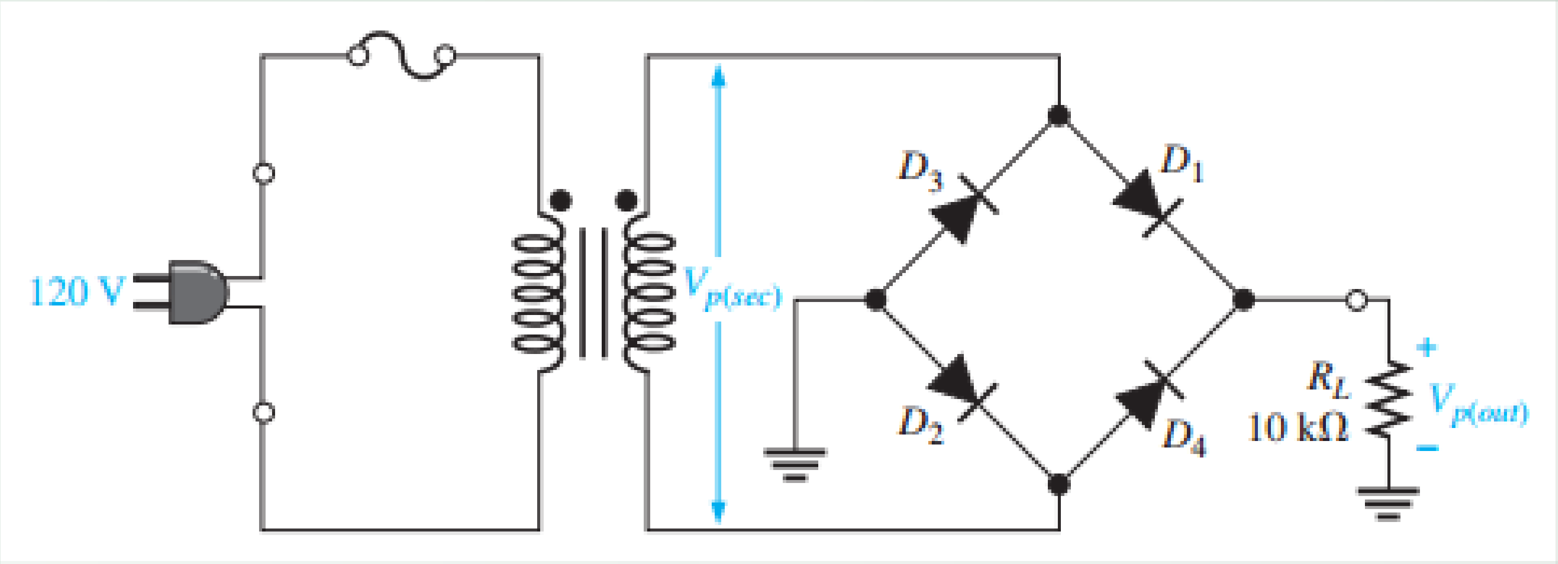
Peak inverse voltages across diodes D3 and D4 in a bridge rectifier during the positive half-cycle of the secondary voltage

Example

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**



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

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

Example

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 for each diode is

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

The PIV rating must exceed this value.

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 minimum PIV rating for the diodes?

3.3 Power Supply Filter And Regulators

- In most power supply applications, the standard 60 Hz (China 50 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 3–16 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.

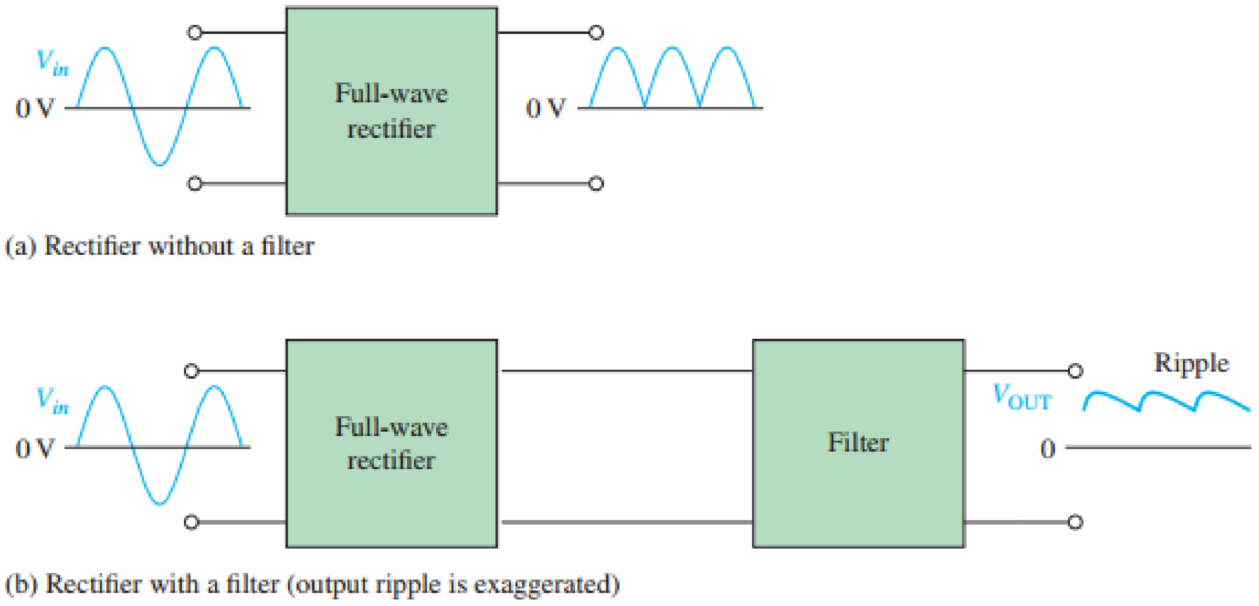


FIGURE 3-16 Power supply filtering.

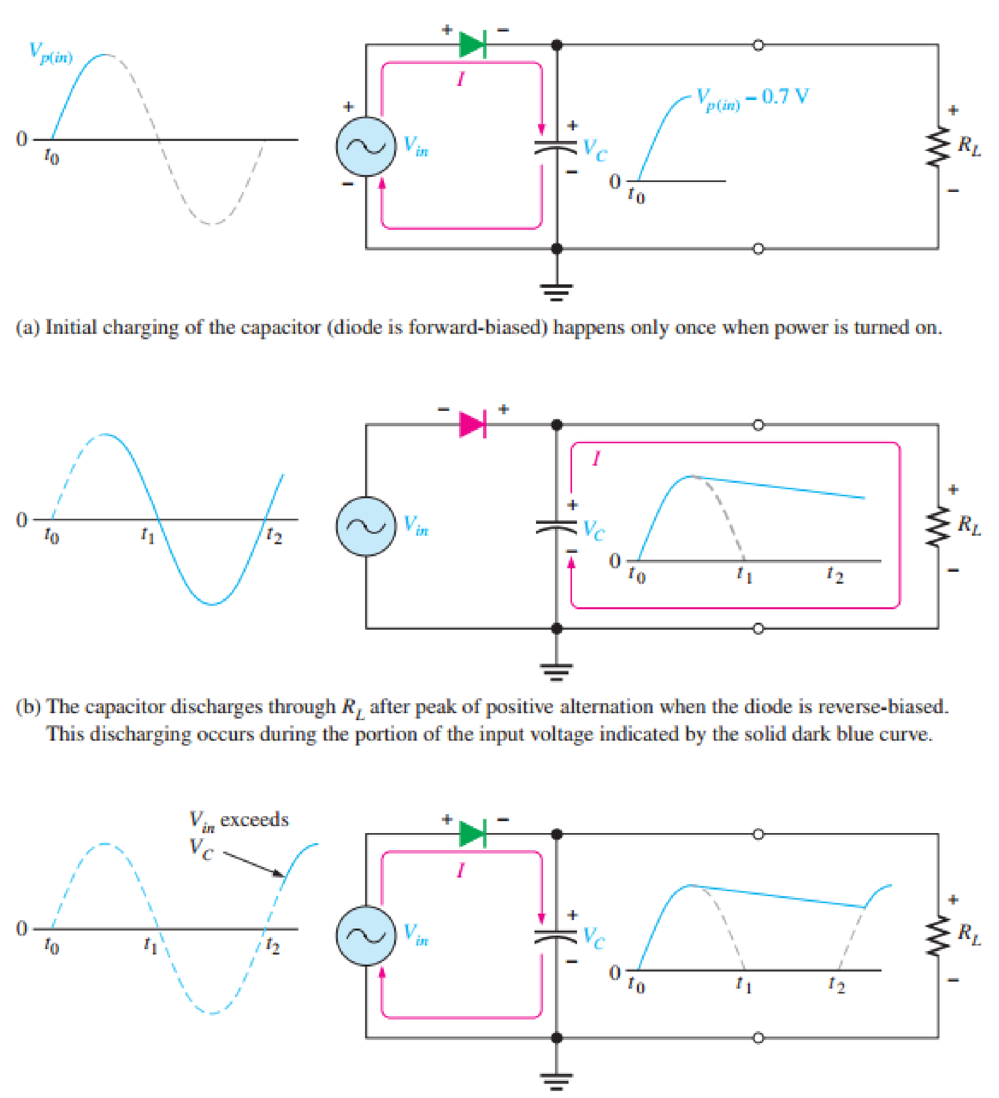
Capacitor-Input Filter

- A half-wave rectifier with a capacitor-input filter is shown in Figure 3–17. The filter is simply a capacitor connected from the rectifier output to ground. R_L represents the equivalent resistance of a load.

- 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 3–17(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. Then the capacitor discharges through the load resistor.

- 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.



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

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

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

FIGURE 3-17 Operation of a half-wave rectifier with a capacitor-input filter. The current indicates charging or discharging of the capacitor.

Ripple Voltage

- 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 3–18.

- For a given input frequency, the output frequency of a full-wave rectifier is twice that of a half-wave rectifier.

- 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 fullwave pulses.

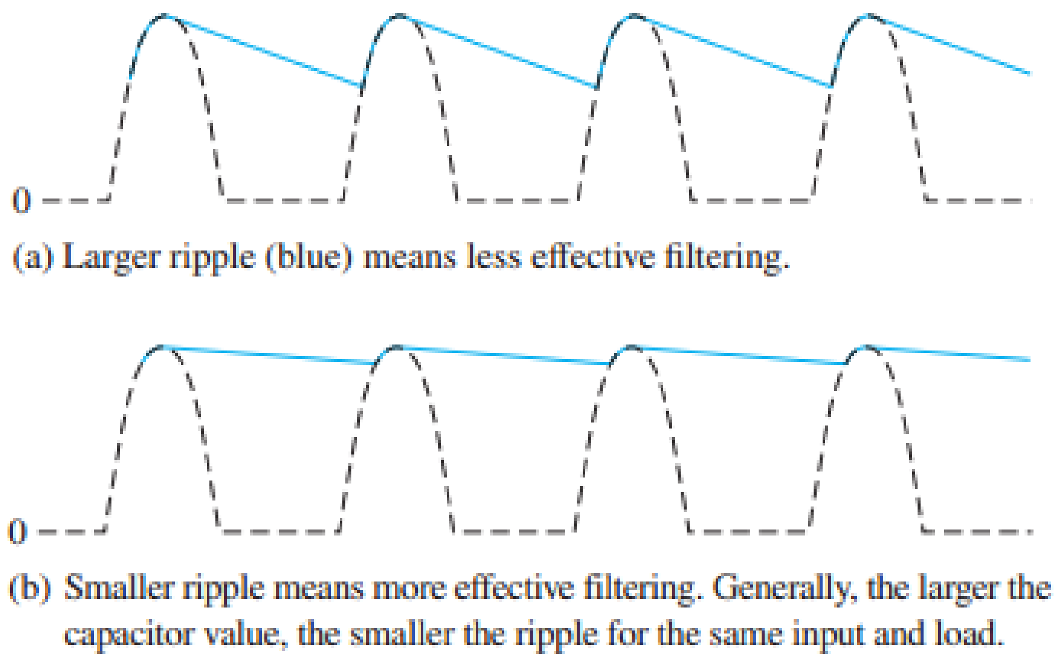


FIGURE 3-18 Half-wave ripple voltage (blue line).

Ripple Factor

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

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

- 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 3–19.

- 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.

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

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

The variable Vp(rect) is the unfiltered peak rectified voltage

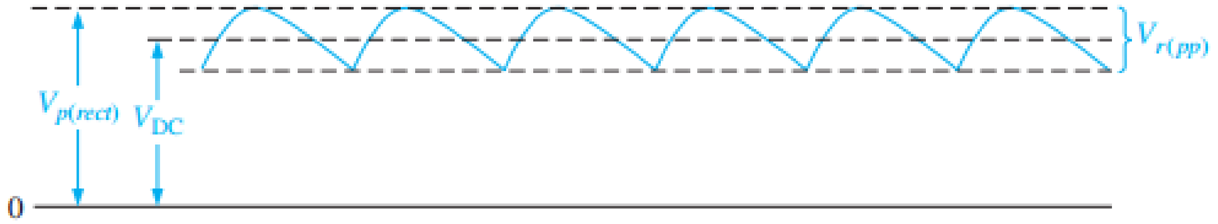


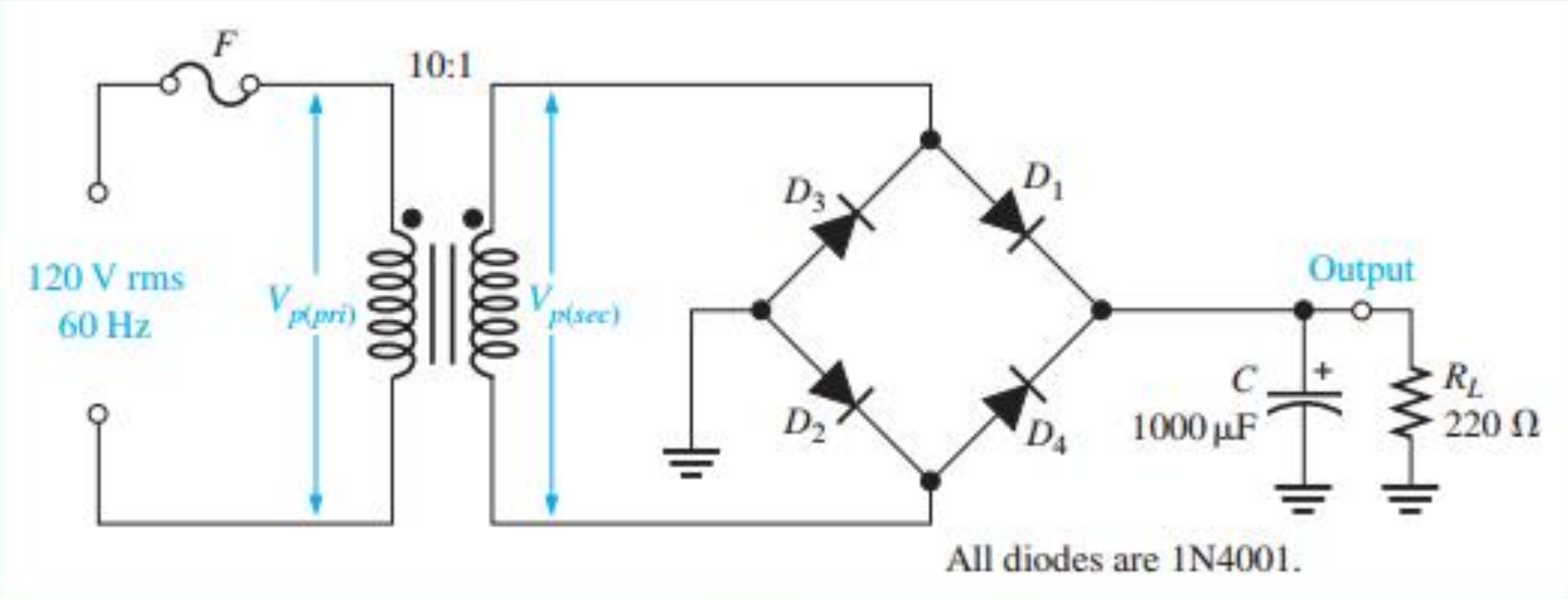
FIGURE 3-19 Vr and VDC determine the ripple factor.

Example

EXAMPLE 2–8

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

FIGURE 2–48



Example

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

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

The peak secondary voltage is

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

The unfiltered peak full-wave rectified voltage is

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

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

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

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

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

The resulting ripple factor is

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

The percent ripple is 3.9%.

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

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.
- 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 3–20.

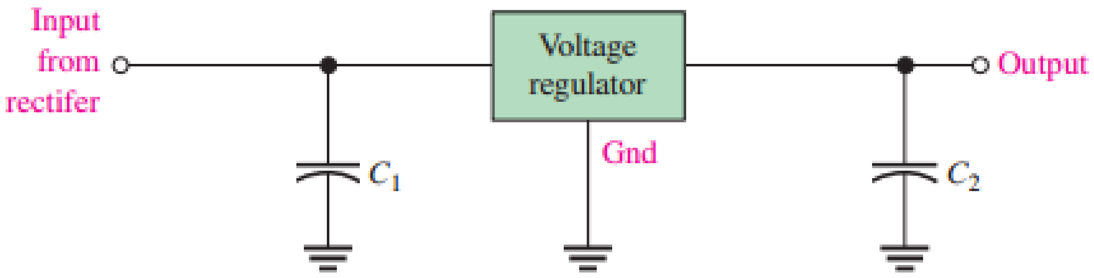


FIGURE 3-20
A voltage regulator with input and output capacitors.

Voltage Regulators

- A basic fixed power supply with a +5 V voltage regulator is shown in Figure 3–21.
- Specific integrated circuit three-terminal regulators with fixed output voltages

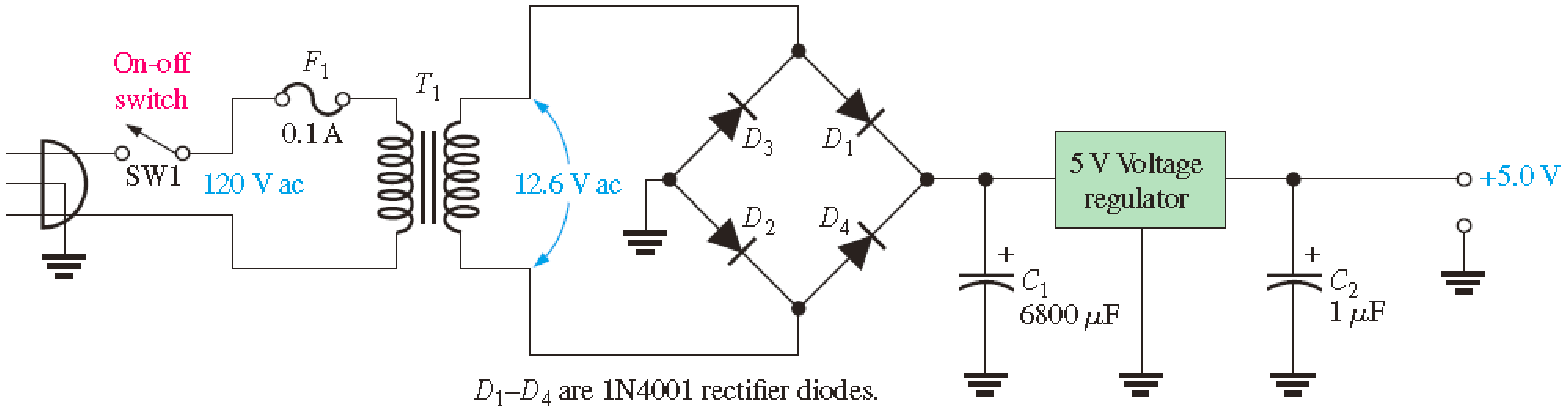


FIGURE 3-20
A basic +5.0 V regulated power supply.