Diode Circuits

張大中
中央大學 通訊工程系
dcchang@ce.ncu.edu.tw

Rectifier Circuits

- A diode rectifier forms the first stage of a dc power supply. Rectification is the process of converting an alternating (ac) voltage into one that is limited to one polarity.
- Rectification: half-wave rectification and full-wave rectification

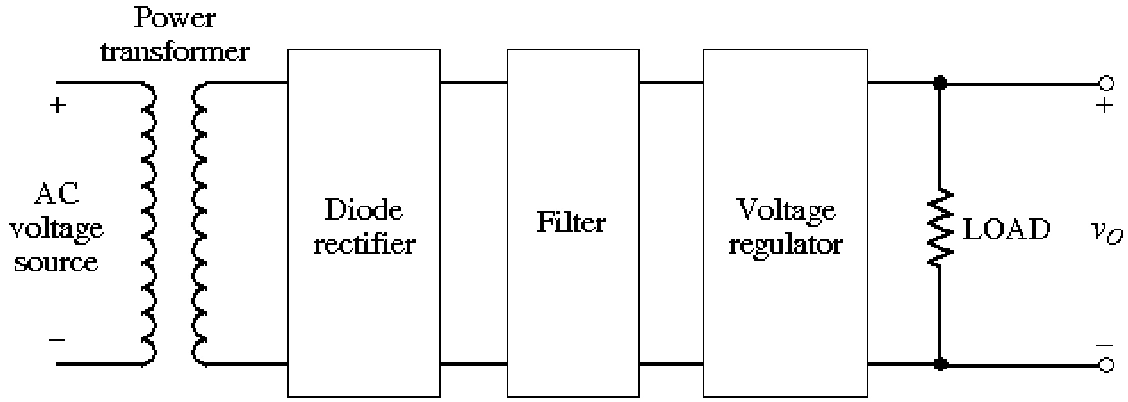
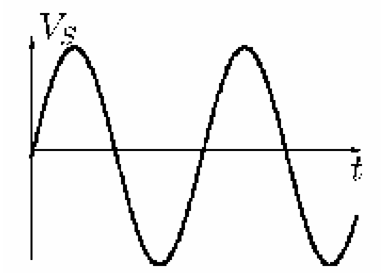
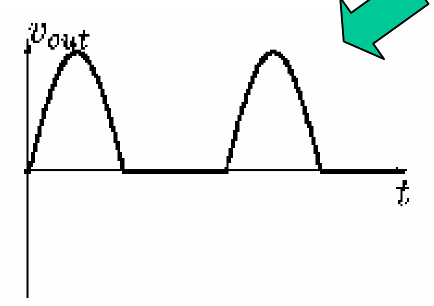


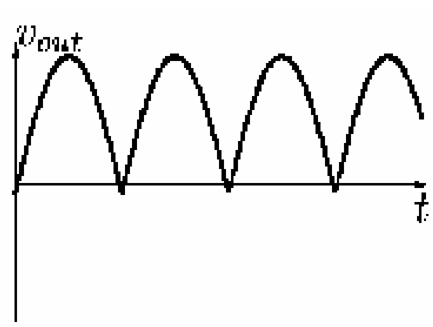
Figure 2.1 Block diagram of an electronic power supply



half-wave rectification



full-wave rectification



Half-Wave Rectification

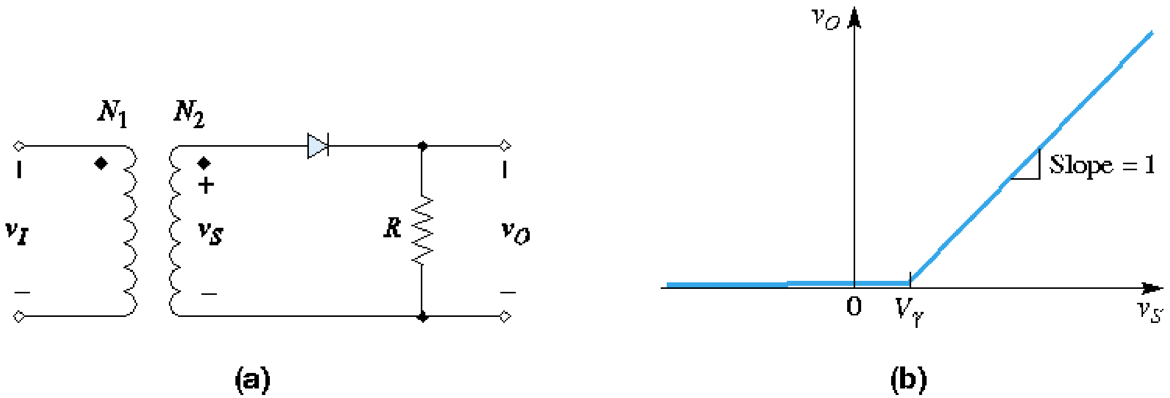


Figure 2.2 Diode in series with ac power source: (a) circuit and (b) voltage transfer characteristics

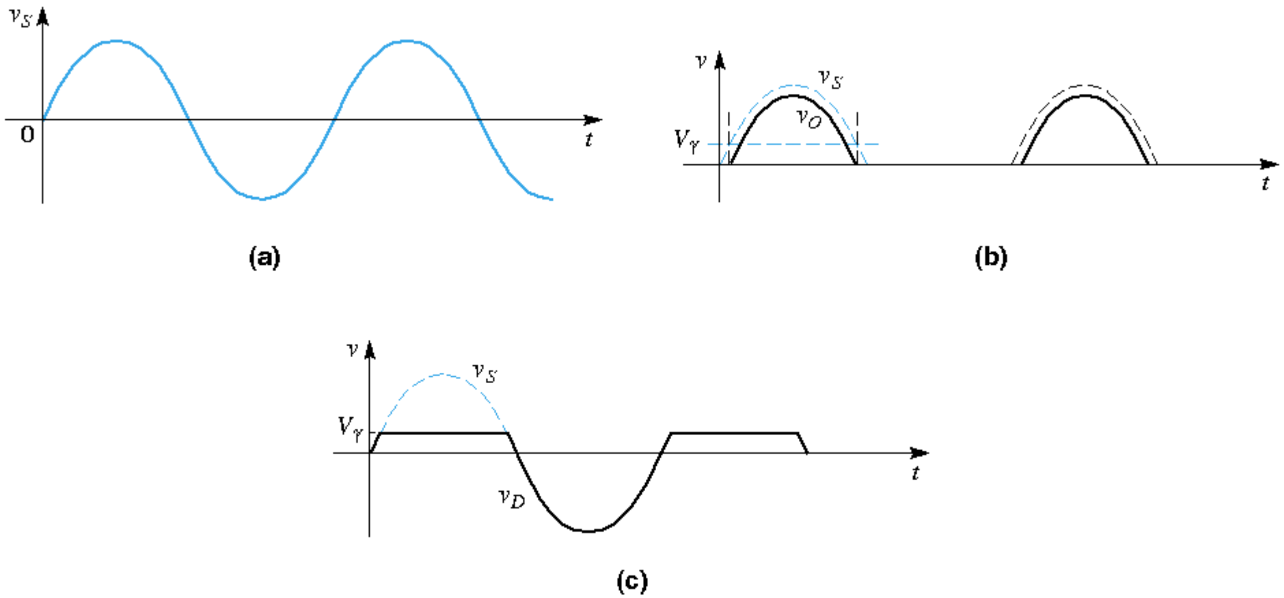


Figure 2.3 Half-wave rectifier circuit: (a) sinusoidal input voltage, (b) output voltage, and (c) diode voltage

Q-point Analysis of Half-Wave Rectification

- Load line Concept for Q-point

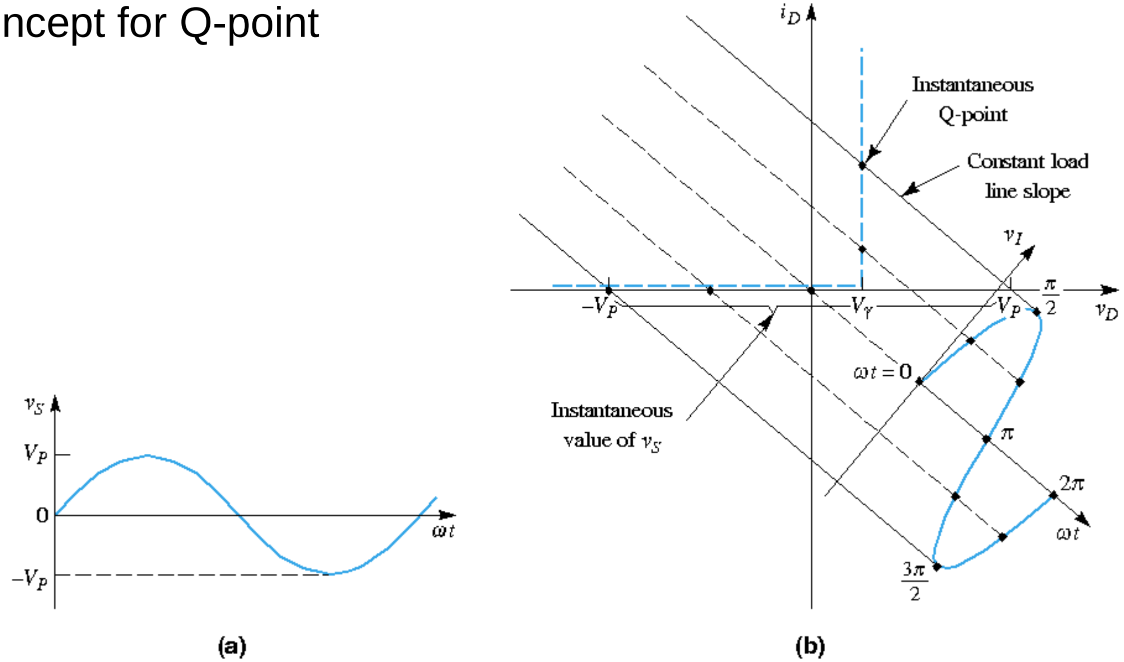


Figure 2.4 Operation of half-wave rectifier circuit: (a) sinusoidal input voltage and (b) diode piecewise linear characteristics and circuit load line at various times

- Battery Charger

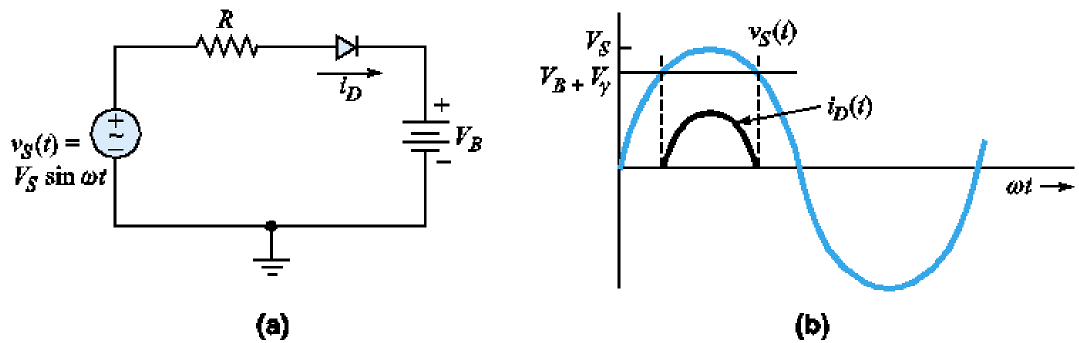


Figure 2.5 (a) Half-wave rectifier used as a battery charger; (b) input voltage and diode current waveforms

EXAMPLE 2.1

Objective: Determine the currents and voltages in a half-wave rectifier circuit.

Consider the circuit shown in Figure 2.6. Assume $V_B = 12$ V, $R = 100\ \Omega$, and $V_\gamma = 0.6$ V. Also assume $v_S(t) = 24 \sin \omega t$. Determine the peak diode current, maximum reverse-bias diode voltage, and the fraction of the cycle over which the diode is conducting.

Solution: Peak diode current:

$$i_D(peak) = \frac{V_S - V_B - V_\gamma}{R} = \frac{24 - 12 - 0.6}{0.10} = 114 \text{ mA}$$

Maximum reverse-bias diode voltage:

$$v_R(\max) = V_S + V_B = 24 + 12 = 36 \text{ V}$$

Diode conduction cycle:

$$v_I = 24 \sin \omega t_1 = 12.6$$

or

$$\omega t_1 = \sin^{-1}\left(\frac{12.6}{24}\right) \Rightarrow 31.7^\circ$$

By symmetry,

$$\omega t_2 = 180 - 31.7 = 148.3^\circ$$

Then

$$\text{Percent time} = \frac{148.3 - 31.7}{360} \times 100\% = 32.4\%$$

Full-Wave Center- Tapped Transformer Rectification

- The full-wave rectifier inverts the negative portions of the sine wave so that a unipolar output signal is generated during both halves of the input sinusoid.

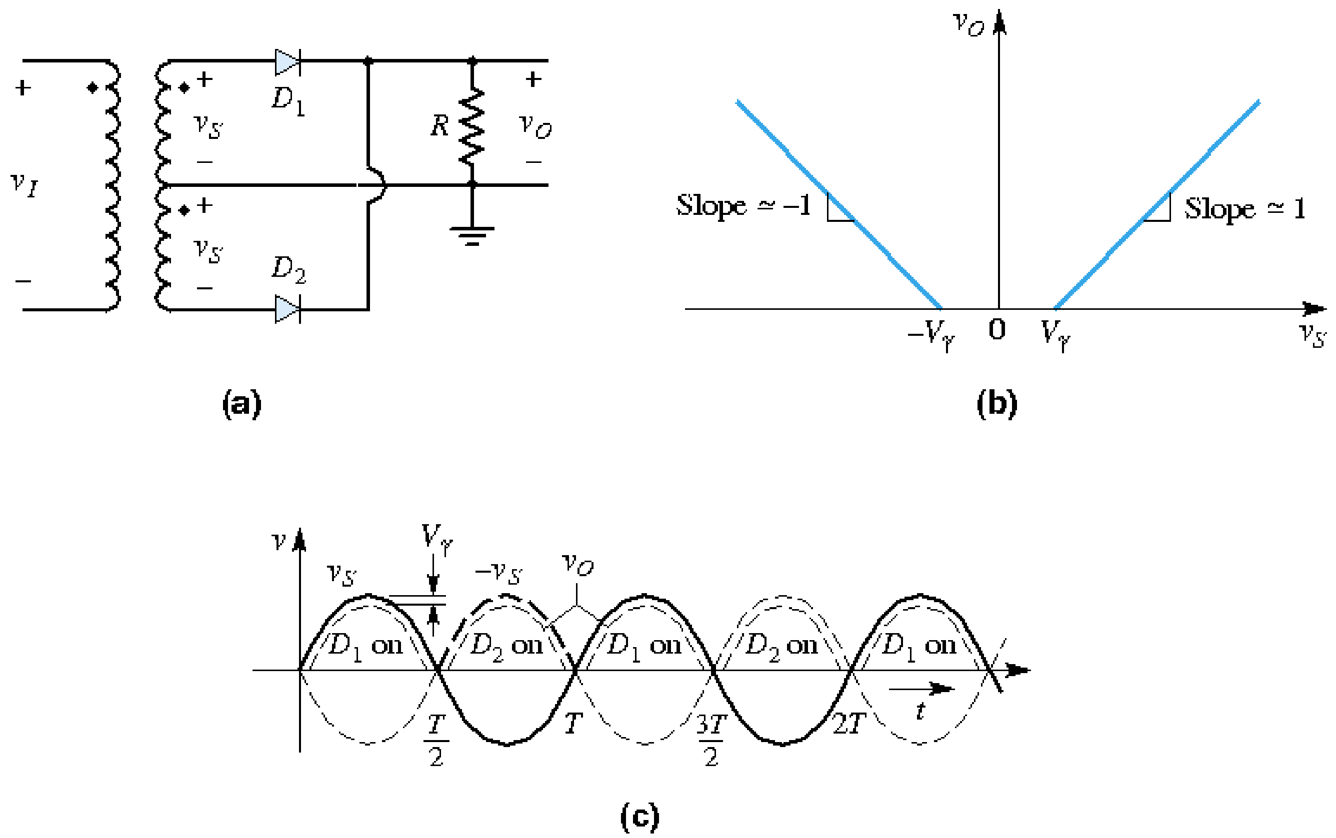


Figure 2.6 Full-wave rectifier: (a) circuit with center-tapped transformer, (b) voltage transfer characteristics, and (c) input and output waveforms

Full-Wave Bridge Rectifier

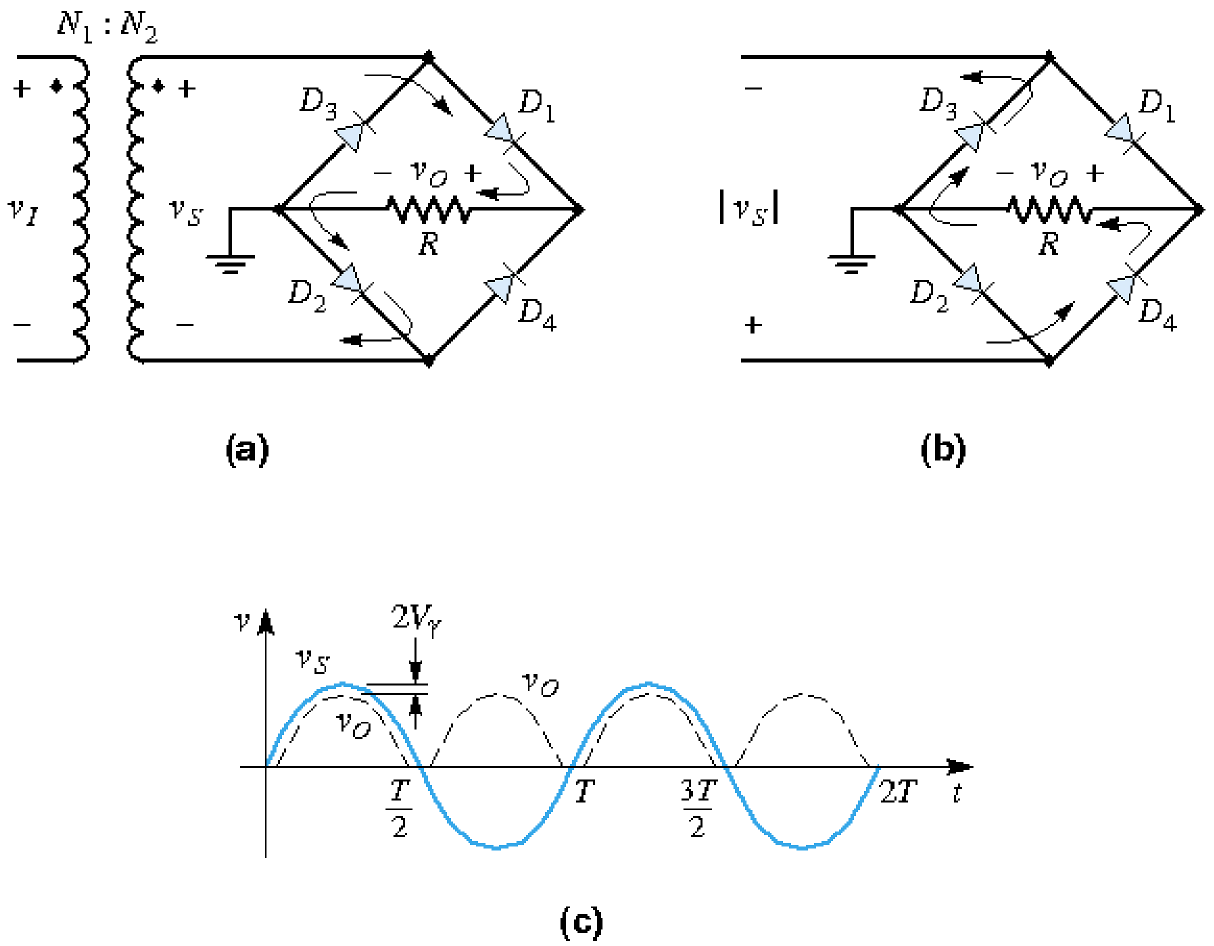
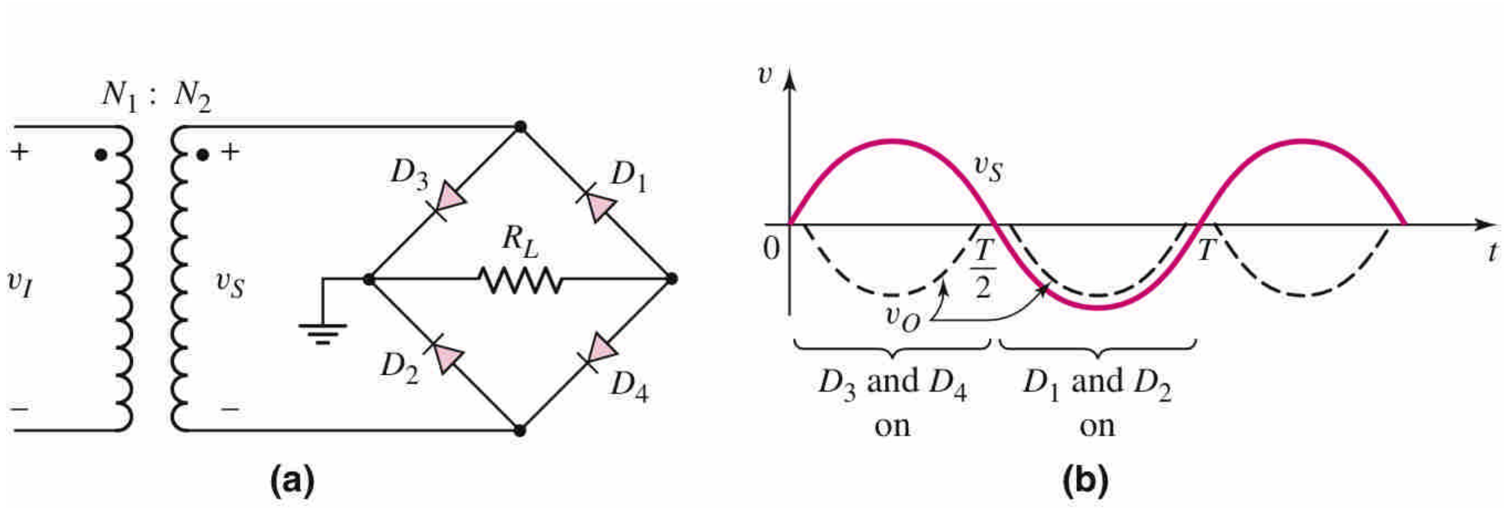


Figure 2.7 A full-wave bridge rectifier: (a) circuit showing the current direction for a positive input cycle, (b) current direction for a negative input cycle, and (c) input and output voltage waveforms

Full-Wave Bridge Rectifier

- Full-wave bridge rectifier circuit to produce negative output voltages

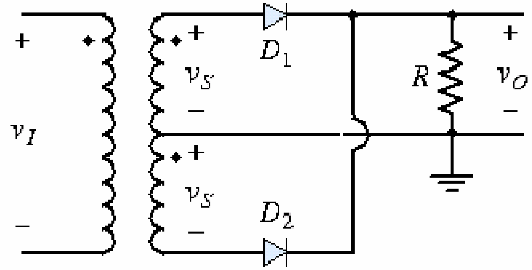


Example 2.1 **Objective:** Compare voltages and the transformer turns ratio in two full-wave rectifier circuits.

Consider the rectifier circuits shown in Figures 2.6(a) and 2.7(a). Assume the input voltage is from a 120 V (rms), 60 Hz ac source. The desired peak output voltage v_O is 9 V, and the diode cut-in voltage is assumed to be $V_\gamma = 0.7$ V.

Solution: For the center-tapped transformer circuit shown in Figure 2.6(a), a peak voltage of $v_O(\max) = 9$ V means that the peak value of v_S is

$$v_S(\max) = v_O(\max) + V_\gamma = 9 + 0.7 = 9.7\text{ V}$$



For a sinusoidal signal, this produces an rms value of

$$v_{S,\text{rms}} = \frac{9.7}{\sqrt{2}} = 6.86\text{ V}$$

The turns ratio of the primary to each secondary winding must then be

$$\frac{N_1}{N_2} = \frac{120}{6.86} \cong 17.5$$

For the center-tapped rectifier, the peak inverse voltage (PIV) of a diode is

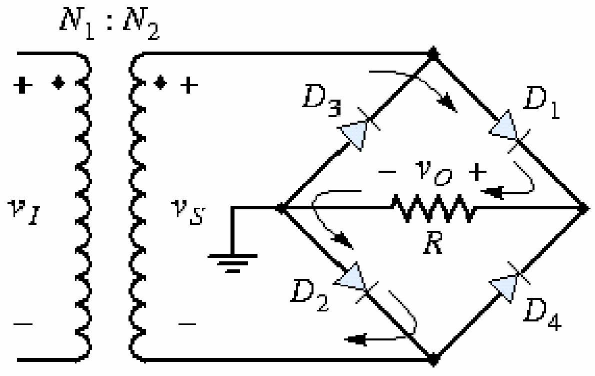
$$\text{PIV} = v_R(\max) = 2v_S(\max) - V_\gamma = 2(9.7) - 0.7 = 18.7\text{ V}$$

For the bridge circuit shown in Figure 2.7(a), a peak voltage of $v_O(\max) = 9\text{ V}$ means that the peak value of v_S is

$$v_S(\max) = v_O(\max) + 2V_\gamma = 9 + 2(0.7) = 10.4\text{ V}$$

For the bridge circuit shown in Figure 2.7(a), a peak voltage of $v_O(\max) = 9\text{ V}$ means that the peak value of v_S is

$$v_S(\max) = v_O(\max) + 2V_\gamma = 9 + 2(0.7) = 10.4\text{ V}$$



For a sinusoidal signal, this produces an rms value of

$$v_{S,\text{rms}} = \frac{10.4}{\sqrt{2}} = 7.35\text{ V}$$

The turns ratio should then be

$$\frac{N_1}{N_2} = \frac{120}{7.35} \cong 16.3$$

For the bridge rectifier, the peak inverse voltage of a diode is

$$\text{PIV} = v_R(\max) = v_S(\max) - V_\gamma = 10.4 - 0.7 = 9.7\text{ V}$$

Comment: These calculations demonstrate the advantages of the bridge rectifier over the center-tapped transformer circuit. First, only half as many turns are required for the secondary winding in the bridge rectifier. This is true because only half of the secondary winding of the center-tapped transformer is utilized at any one time. Second, for the bridge circuit, the peak inverse voltage that any diode must sustain without breakdown is only half that of the center-tapped transformer circuit.

Filter Circuit for Diode Rectifier

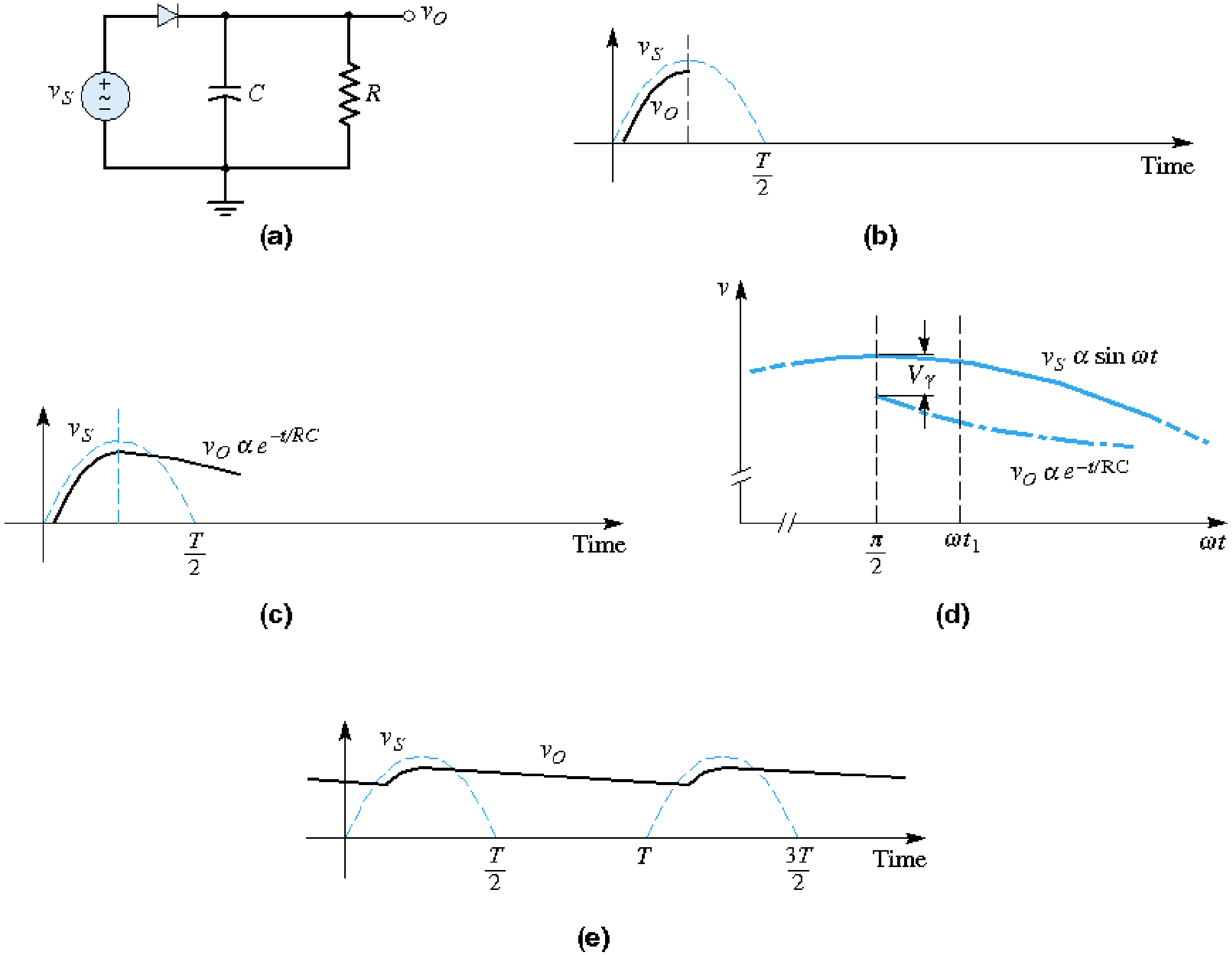


Figure 2.8 Simple filter circuit: (a) half-wave rectifier with an RC filter, (b) positive input voltage and initial portion of output voltage, (c) output voltage resulting from capacitor discharge, (d) expanded view of input and output voltages assuming capacitor discharge begins at $\omega t = \pi/2$, and (e) steady-state input and output voltages

Analysis of Filter Circuit for Diode Rectifier

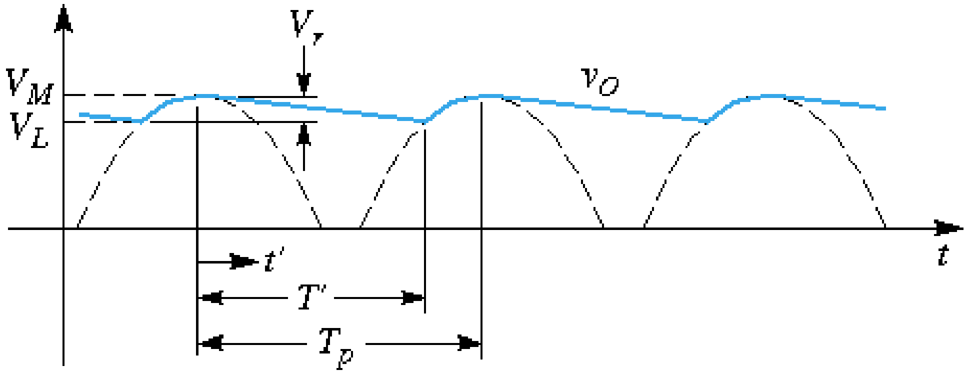


Figure 2.9 Output voltage of a full-wave rectifier with an *RC* filter

After the output has reached the peak value, $v_o(t) = V_M e^{-t'/RC}$

$$V_L = V_M e^{-T'/RC}$$

$$V_r = V_M - V_L = V_M (1 - e^{-T'/RC}) \approx V_M \left(\frac{T'}{RC} \right)$$

As $RC >> T'$, $T' \approx T_p$, and $V_r = V_M \left(\frac{T'}{RC} \right) \approx V_M \left(\frac{T_p}{RC} \right)$

$$T_p = \frac{1}{2f}, \quad V_r = \frac{V_M}{2fRC}$$

Example 2.2 **Objective:** Determine the capacitance required to yield a particular ripple voltage.

Consider a full-wave rectifier circuit with a 60 Hz input signal and a peak output voltage of $V_M = 10\,\text{V}$. Assume the output load resistance is $R = 10\,\text{k}\Omega$ and the ripple voltage is to be limited to $V_r = 0.2\,\text{V}$.

Solution: From Equation (2.9), we can write

$$C = \frac{V_M}{2fRV_r} = \frac{10}{2(60)(10 \times 10^3)(0.2)} \Rightarrow 41.7\,\mu\text{F}$$

Comment: If the ripple voltage is to be limited to a smaller value, a larger filter capacitor must be used.

Current in the Filter Circuit for Diode Rectifier

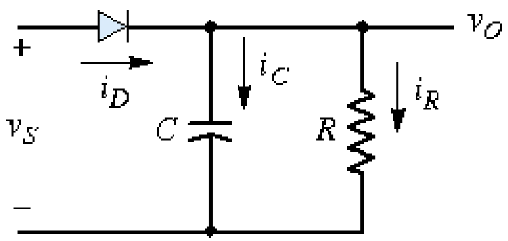


Figure 2.11 Equivalent circuit of a full-wave rectifier during capacitor charging cycle

$$i_D = i_C + i_R$$

$$i_D = C\frac{dv_o}{dt} + \frac{v_o}{R}$$

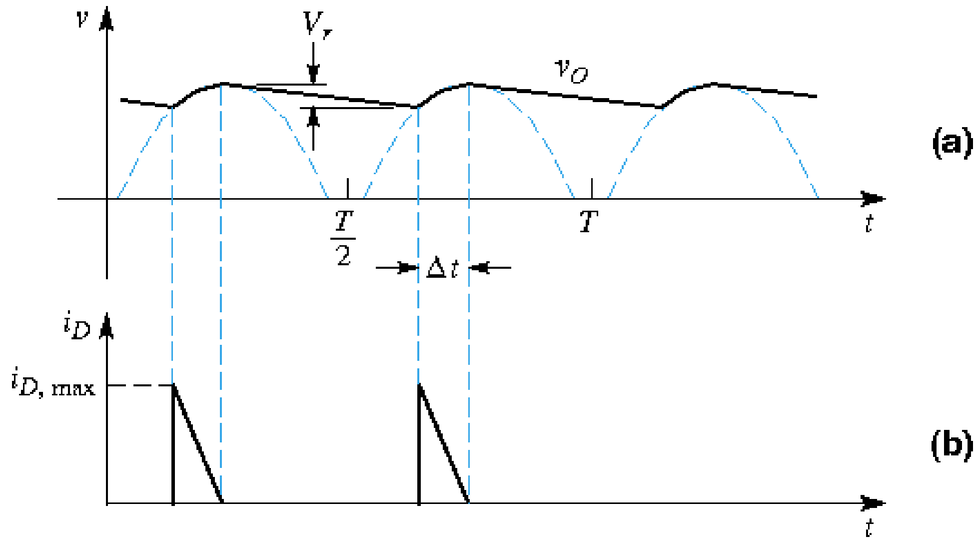
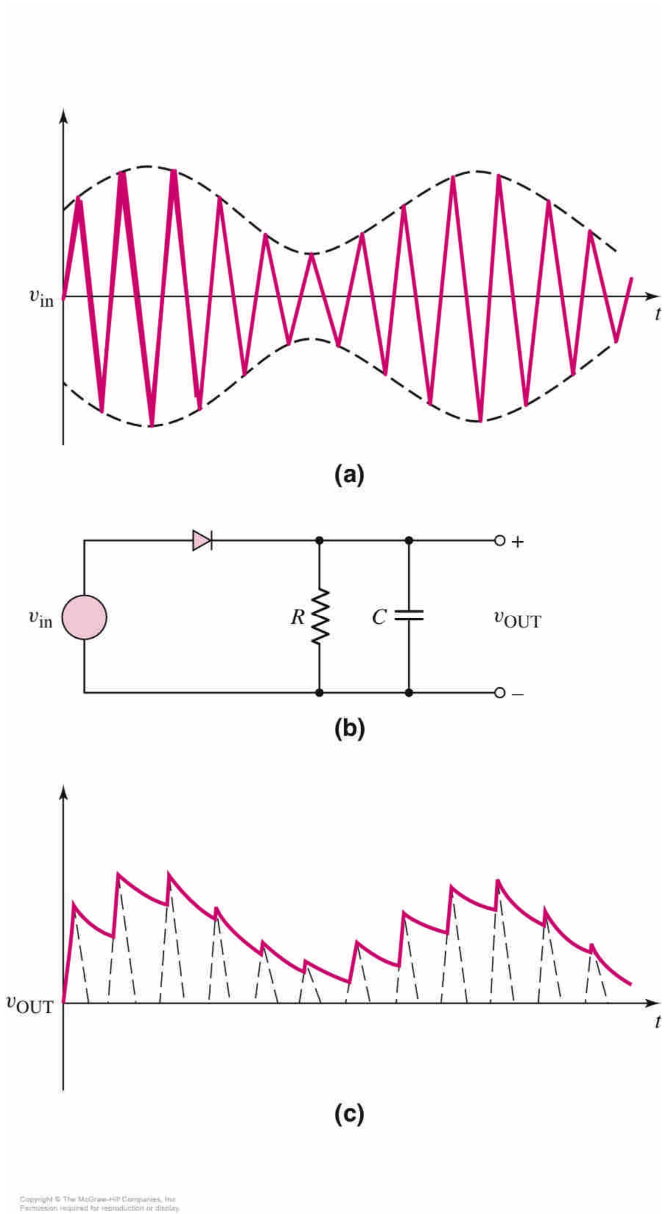


Figure 2.10 Output of a full-wave rectifier with an *RC* filter: (a) diode conduction time and (b) diode current

Detectors



Voltage Doubler Circuit

- There are also voltage tripler and voltage quadrupler circuits. These circuits provides a means by which multiple dc voltage can be generated from a single ac source and power transformer.

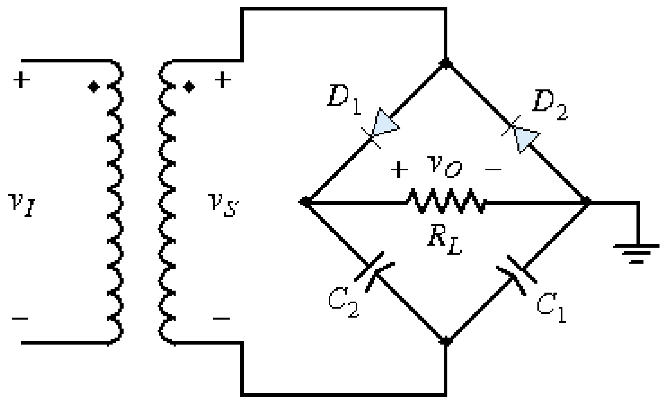


Figure 2.13 A voltage doubler circuit

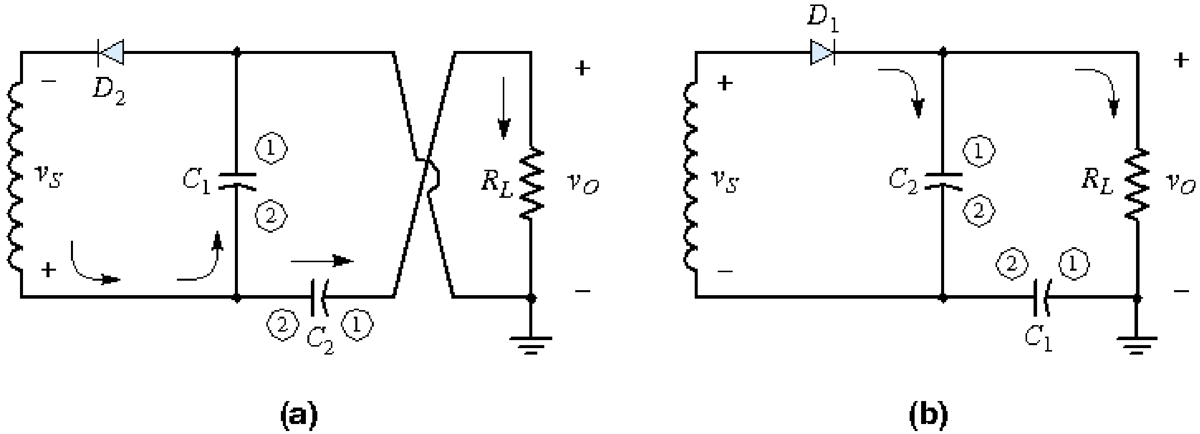


Figure 2.14 Equivalent circuit of the voltage doubler circuit: (a) negative input cycle and (b) positive input cycle

Zener Diode Circuits

- Zener Voltage Reference Circuit

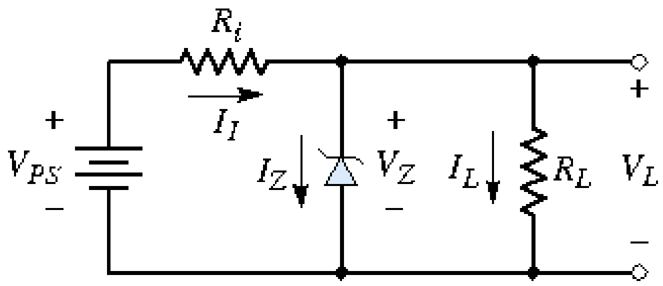


Figure 2.15 A Zener diode voltage regulator circuit

I_Z maximum : V_{PS} maximum and I_L minimum

$$R_i = \frac{V_{PS}(\max) - V_Z}{I_Z(\max) + I_L(\min)}$$

I_Z minimum : V_{PS} minimum and I_L maximum

$$R_i = \frac{V_{PS}(\min) - V_Z}{I_Z(\min) + I_L(\max)}$$

$$\begin{aligned}&[V_{PS}(\min) - V_Z]\cdot[I_Z(\max) + I_L(\min)] \\ &= [V_{PS}(\max) - V_Z]\cdot[I_Z(\min) + I_L(\max)]\end{aligned}$$

Choose $I_Z(\min) = 0.1 I_Z(\max)$, we have

$$I_Z(\max) = \frac{I_L(\max)[V_{PS}(\max) - V_Z] - I_L(\min)[V_{PS}(\min) - V_Z]}{V_{PS}(\min) - 0.9V_Z - 0.1V_{PS}(\max)}$$

Design Example 2.4 **Objective:** Design a voltage regulator using the circuit in Figure 2.15.

The voltage regulator is to power a car radio at $V_L = 9\,\text{V}$ from an automobile battery whose voltage may vary between 11 and 13.6 V. The current in the radio will vary between 0 (off) to 100 mA (full volume).

The equivalent circuit is shown in Figure 2.16.

Solution: The maximum Zener diode current can be determined from Equation (2.23) as

$$I_Z(\max) = \frac{(100)[13.6 - 9] - 0}{11 - (0.9)(9) - (0.1)(13.6)} \cong 300\,\text{mA}$$

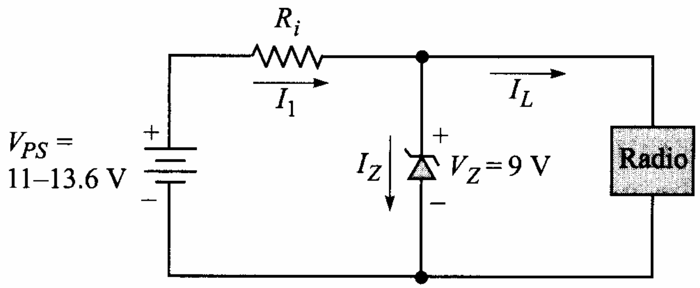


Figure 2.16 Circuit for Design Example 2.4

The maximum power dissipated in the Zener diode is then

$$P_Z(\max) = I_Z(\max) \cdot V_Z = (300)(9) \Rightarrow 2.7\,\text{W}$$

The value of the current-limiting resistor R_i, from Equation (2.21(b)), is

$$R_i = \frac{13.6 - 9}{0.3} = 15.3\,\Omega$$

The maximum power dissipated in this resistor is

$$P_{Ri}(\max) = \frac{(V_{PS}(\max) - V_Z)^2}{R_i} = \frac{(13.6 - 9)^2}{15.3} \cong 1.4\,\text{W}$$

Comment: From this design, we see that the minimum power ratings of the Zener diode and input resistor are 2.7 W and 1.4 W, respectively. The minimum Zener diode current occurs for $V_{PS}(\min)$ and $I_L(\max)$. We find $I_Z(\min) = 30.7\,\text{mA}$, which is approximately 10 percent of $I_Z(\max)$ as specified by the design equations.

Design Pointer: (1) The variable input in this example was due to a variable battery voltage. However, referring back to Example 2.3, the variable input could also be a function of using a standard transformer with a given turns ratio as opposed to a custom design with a particular turns ratio and/or having a 120 V (rms) input voltage that is not exactly constant.

(2) The 9 V output is a result of using a 9 V Zener diode. However, a Zener diode with exactly a 9 V breakdown voltage may also not be available. We will again see later how more sophisticated designs can solve this problem.

Zener Resistance and Percentage Regulation

- Because of the Zener resistance, the output voltage will not remain constant.
- Source regulation: a measure of the change in output voltage with a change in source voltage.

$$\text{Source regulation (\%)} = \frac{\Delta v_L}{\Delta v_{PS}} \times 100\%$$

- Load regulation: a measure of the change in output voltage with a change in load current.

$$\text{Load regulation (\%)} = \frac{v_{L,\text{no load}} - v_{L,\text{full load}}}{v_{L,\text{ full load}}} \times 100\%$$

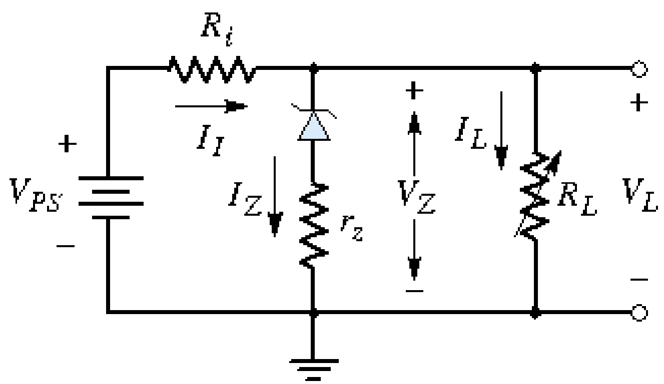


Figure 2.17 A Zener diode voltage regulator circuit with a nonzero Zener resistance

EXAMPLE 2.6

Objective: Determine the source regulation and load regulation of a voltage regulator circuit.

Consider the circuit described in Example 2.5 and assume a Zener resistance of $r_z = 2\ \Omega$.

Solution: Consider the effect of a change in input voltage for a no-load condition ($R_L = \infty$). For $v_{PS} = 13.6$ V, we find

$$I_Z = \frac{13.6 - 9}{15.3 + 2} = 0.2659 \text{ A}$$

Then

$$v_{L,\max} = 9 + (2)(0.2659) = 9.532 \text{ V}$$

For $v_{PS} = 11$ V, we find

$$I_Z = \frac{11 - 9}{15.3 + 2} = 0.1156 \text{ A}$$

Then

$$v_{L,\min} = 9 + (2)(0.1156) = 9.231 \text{ V}$$

We obtain

$$\text{Source regulation} = \frac{\Delta v_L}{\Delta v_{PS}} \times 100\% = \frac{9.532 - 9.231}{13.6 - 11} \times 100\% = 11.6\%$$

Now consider the effect of a change in load current for $v_{PS} = 13.6$ V. For $I_L = 0$, we find

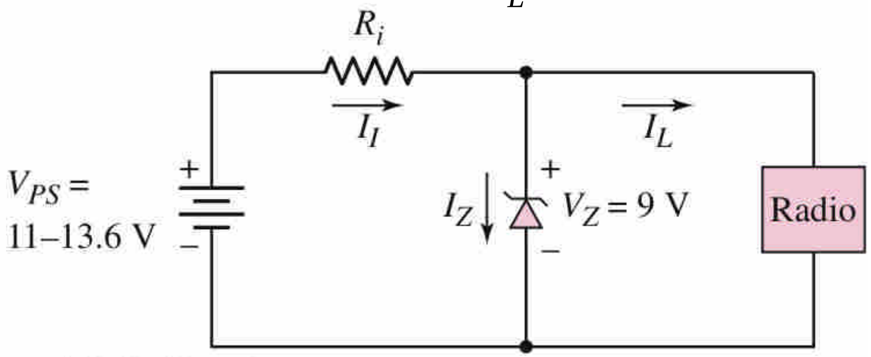
$$I_Z = \frac{13.6 - 9}{15.3 + 2} = 0.2659 \text{ A}$$

and

$$v_{L,\text{no load}} = 9 + (2)(0.2659) = 9.532 \text{ V}$$

$$R_i = 15.3\Omega$$

$$I_L = 0 \sim 100mA$$



For a load current of $I_L = 100$ mA, we find

$$I_Z = \frac{13.6 - [9 + I_Z(2)]}{15.3} - 0.10$$

which yields

$$I_Z = 0.1775 \text{ A}$$

Then

$$v_{L,\text{full load}} = 9 + (2)(0.1775) = 9.355 \text{ V}$$

We now obtain

$$\text{Load regulation} = \frac{v_{L,\text{no load}} - v_{L,\text{full load}}}{v_{L,\text{full load}}} \times 100\%$$
$$= \frac{9.532 - 9.355}{9.355} \times 100\% = 1.89\%$$

Comment: The ripple voltage on the input of 2.6 V is reduced by approximately a factor of 10. The change in output load results in a small percentage change in the output voltage.

Clipper Circuits

- Clipper circuits are used to eliminate portions of a signal that are above or/and below a specified level.
- Transfer characteristics of a limiter circuits

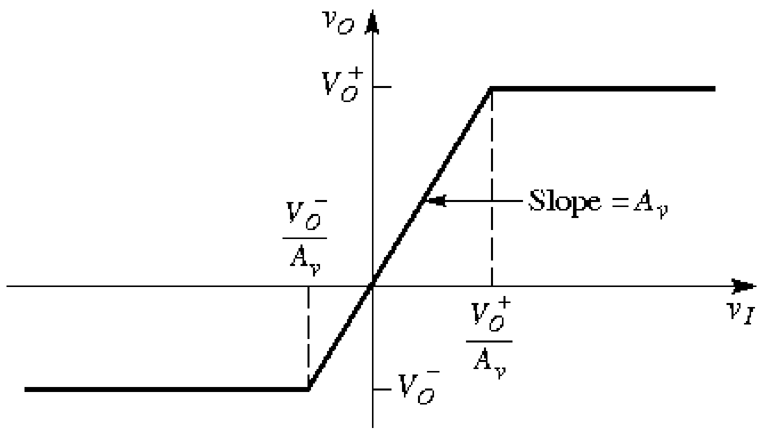


Figure 2.18 General voltage transfer characteristics of a limiter circuit

- Single diode clipper

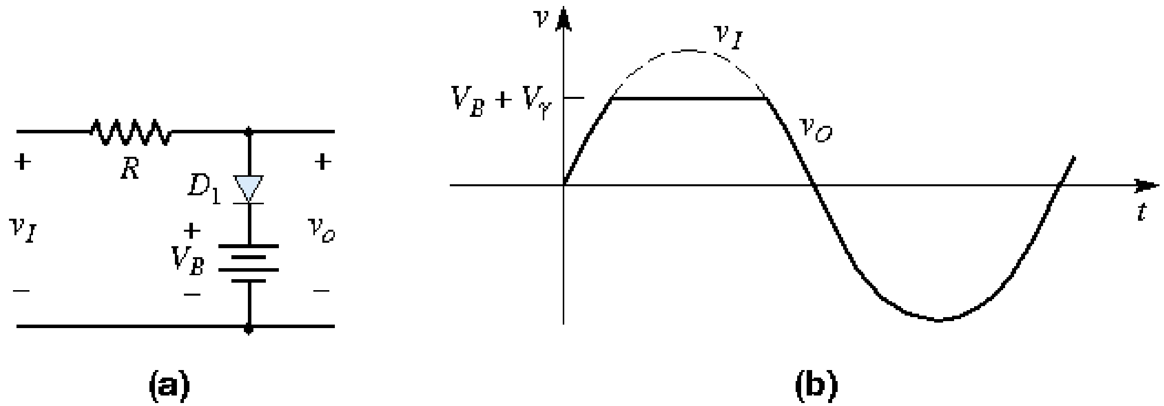


Figure 2.19 Single-diode clipper: (a) circuit and (b) output response

Parallel-Based Clipper

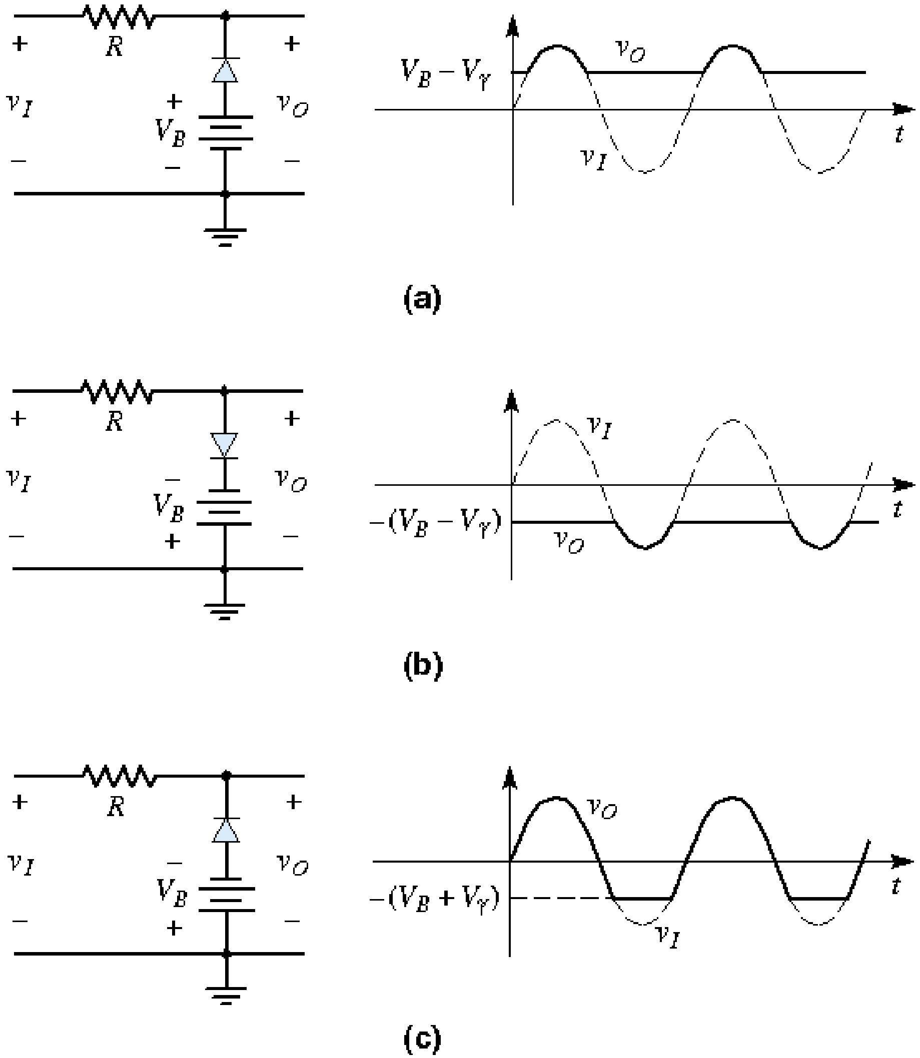


Figure 2.20 Additional diode clipper circuits and their corresponding output responses

Parallel-Based Clipper

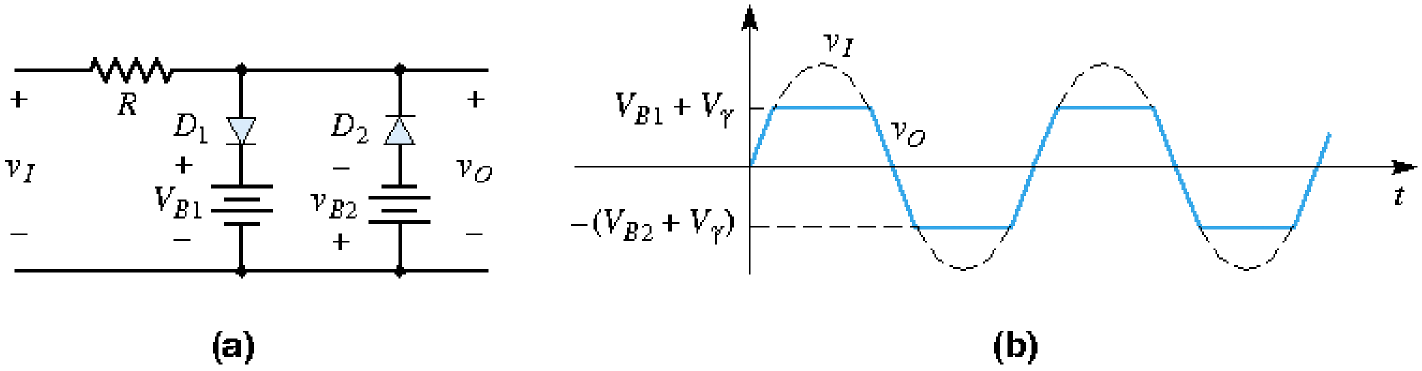
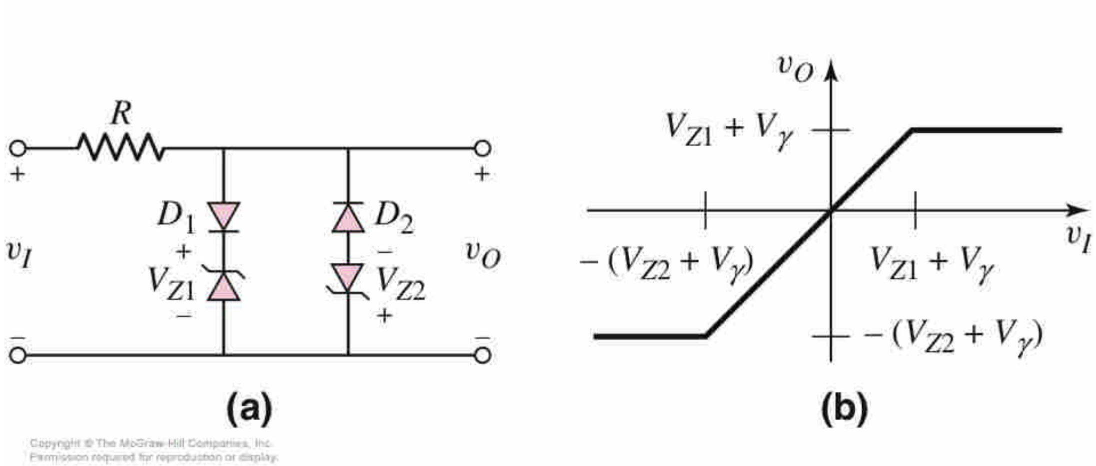


Figure 2.21 A parallel-based diode clipper circuit and its output response



Example 2.6 **Objective:** Find the output of the parallel-based clipper in Figure 2.22(a).

For simplicity, assume that $V_\gamma = 0$ and $r_f = 0$ for both diodes.

Solution: For $t = 0$, we see that $v_I = 0$ and both D_1 and D_2 are reverse biased. For $0 < v_I \le 2\,\text{V}$, D_1 and D_2 remain off; therefore, $v_O = v_I$. For $v_I > 2\,\text{V}$, D_1 turns on and

$$i_1 = \frac{v_I - 2}{10 + 10}$$

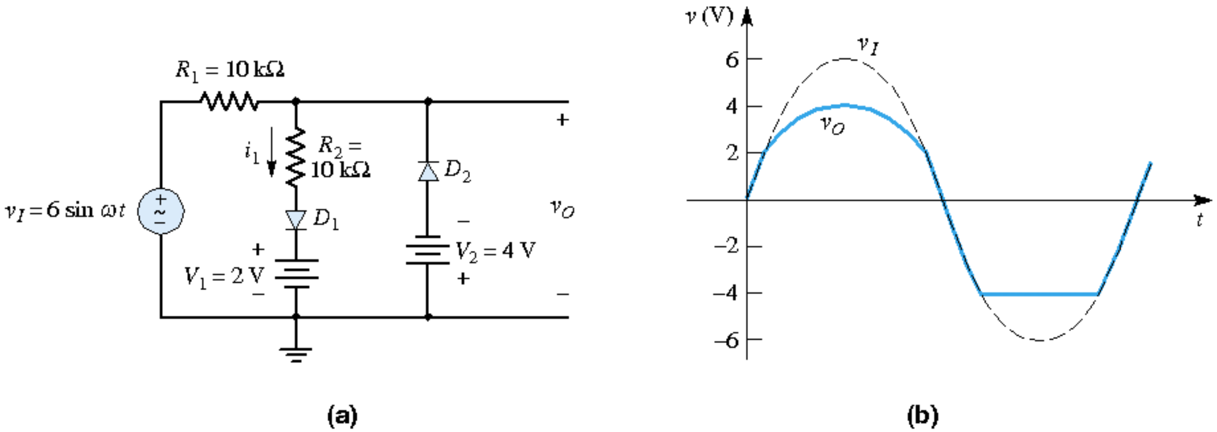


Figure 2.22 Figure for Example 2.6

Also,

$$v_O = i_1 R_2 + 2 = \tfrac{1}{2}(v_I - 2) + 2 = \tfrac{1}{2}v_I + 1$$

If $v_I = 6\,\text{V}$, then $v_O = 4\,\text{V}$.

For $-4 < v_I < 0\,\text{V}$, both D_1 and D_2 are off and $v_O = v_I$. For $v_I \le -4\,\text{V}$, D_2 turns on and the output is constant at $v_O = -4\,\text{V}$. The input and output waveforms are plotted in Figure 2.22(b).

Comment: If we assume that $V_\gamma \ne 0$, the output will be very similar to the results calculated here. The only difference will be the points at which the diodes turn on.

Series-Based Clipper

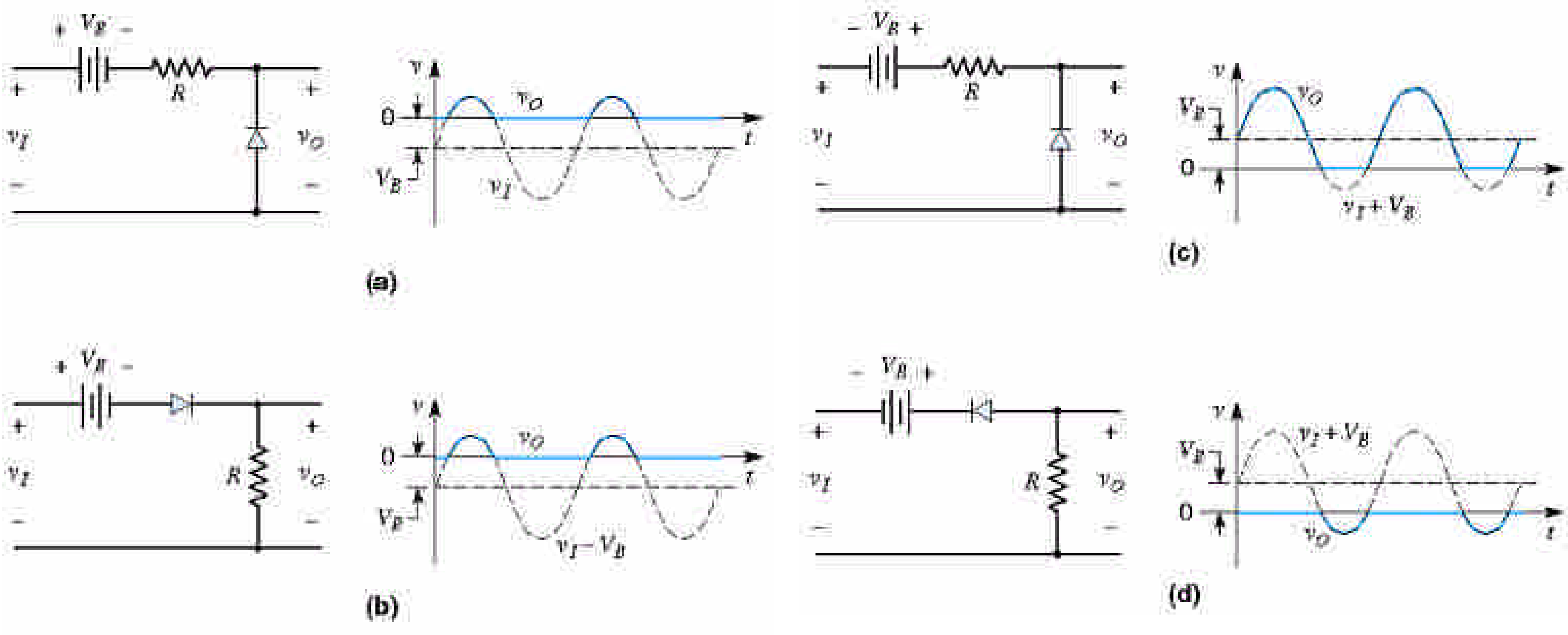


Figure 2.23 Series-based diode clipper circuits and their corresponding output responses

Clampers

- Clamping shifts the entire signal voltage by a dc level. The distinguishing feature of a clamper is that it adjusts the dc level without needing to know the exact waveform.

$$v_o(t) = -v_C + v_I = -(V_M - V_\gamma) + V_M \sin \omega t$$

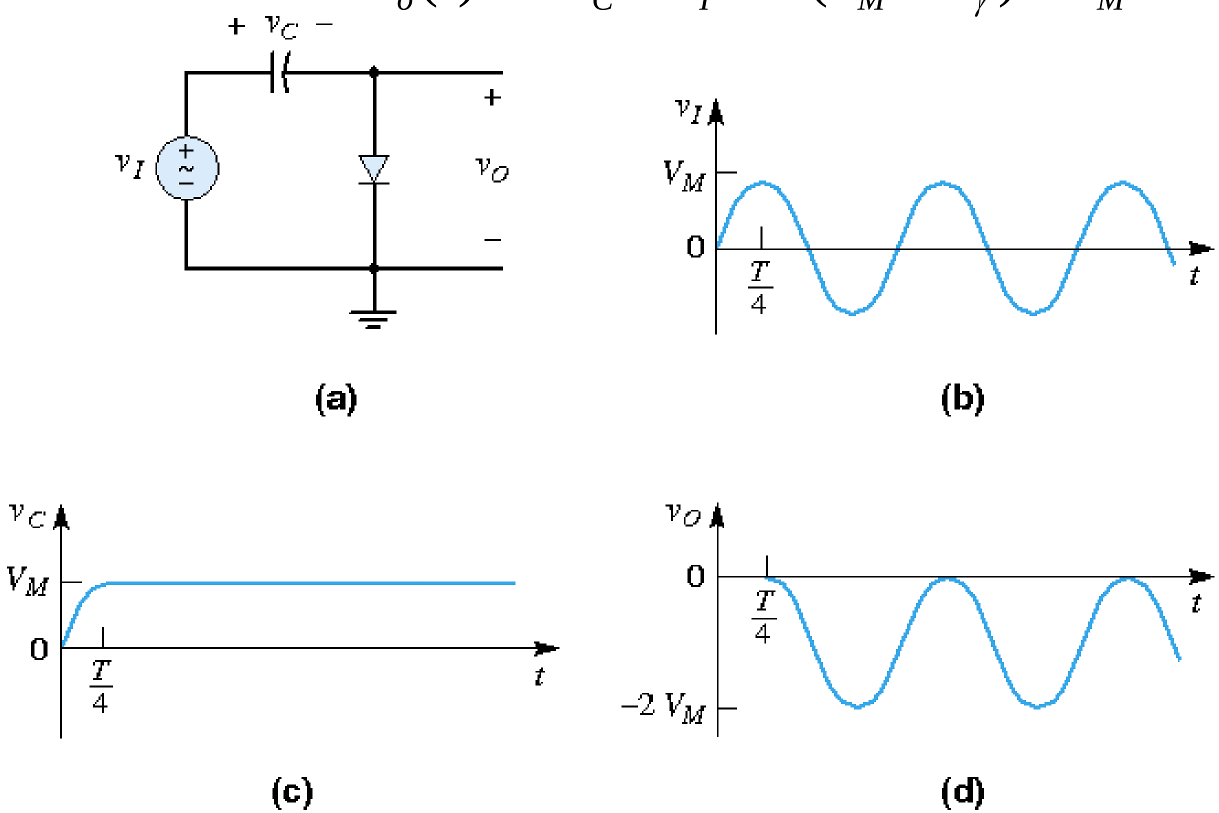


Figure 2.25 Action of a diode clamper circuit: (a) a typical diode clamper circuit, (b) the sinusoidal input signal, (c) the capacitor voltage, and (d) the output voltage

Clampers

- Clamping Circuit Including an Independent Voltage Source

$$v_o(t) = -v_C + v_I = -(V_M - V_B - V_\gamma) + V_M \sin \omega t$$
$$= V_B + V_\gamma + V_M(\sin \omega t - 1)$$

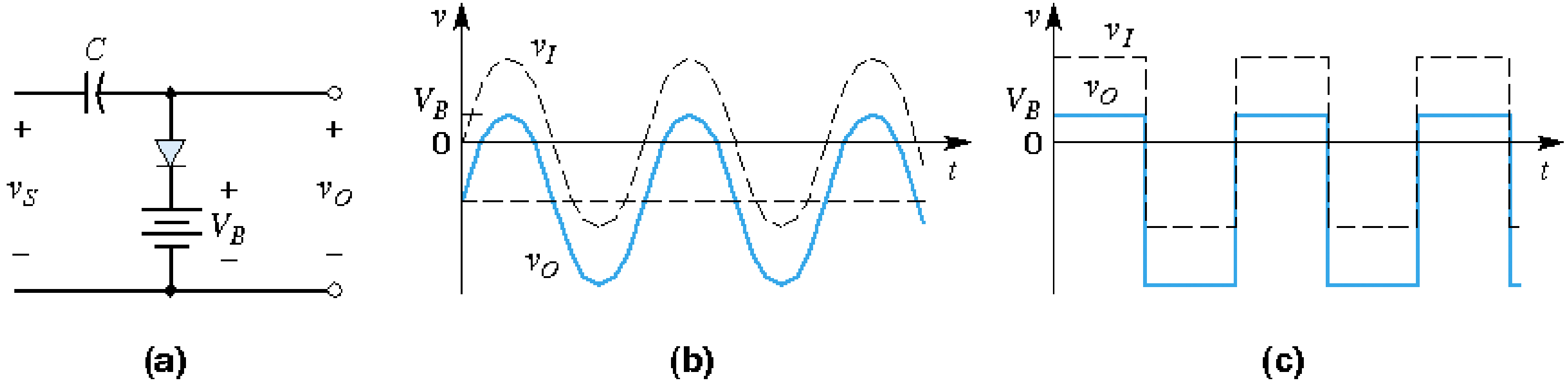


Figure 2.26 Action of a diode clamper circuit with a voltage source: (a) the circuit, (b) steady-state sinusoidal input and output signals, and (c) steady-state square-wave input and output signals

Example 2.7 **Objective:** Find the steady-state output of the diode-clamper circuit shown in Figure 2.27(a).

The input v_I is assumed to be a sinusoidal signal whose dc level has been shifted with respect to a receiver ground by a value V_B during transmission. Assume $V_\gamma = 0$ and $r_f = 0$ for the diode.

Solution: Figure 2.27(b) shows the sinusoidal input signal. If the capacitor is initially uncharged, then the output voltage is $v_O = V_B$ at $t = 0$ (diode reverse-biased). For $0 \le t \le t_1$, the effective RC time constant is infinite, the voltage across the capacitor does not change, and $v_O = v_I + V_B$.

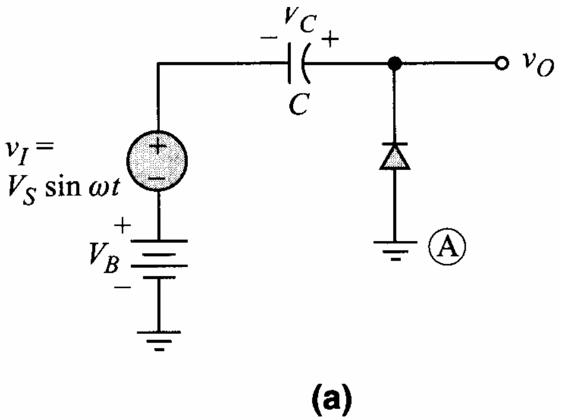
At $t = t_1$, the diode becomes forward biased; the output cannot go negative, so the voltage across the capacitor changes (the $r_f C$ time constant is zero).

At $t = (\frac{3}{4})T$, the input signal begins increasing and the diode becomes reverse biased, so the voltage across the capacitor now remains constant at $V_S - V_B$ with the polarity shown. The output voltage is now given by

$$v_O = (V_S - V_B) + v_I + V_B = (V_S - V_B) + V_S \sin \omega t + V_B$$

or

$$v_O = V_S(1 + \sin \omega (t - (\tfrac{3}{4})T))$$



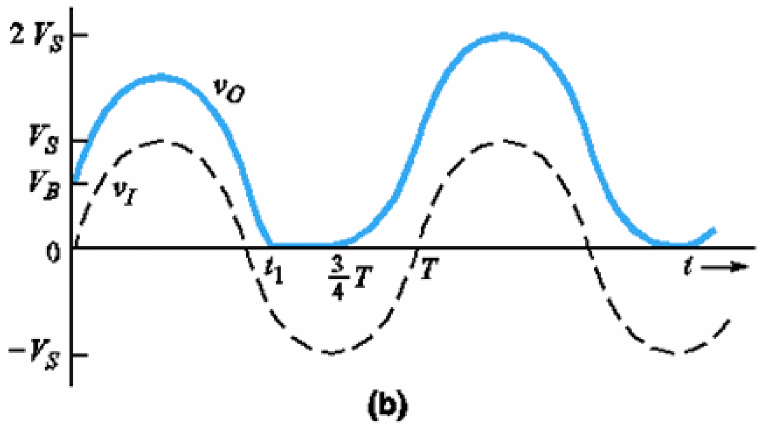
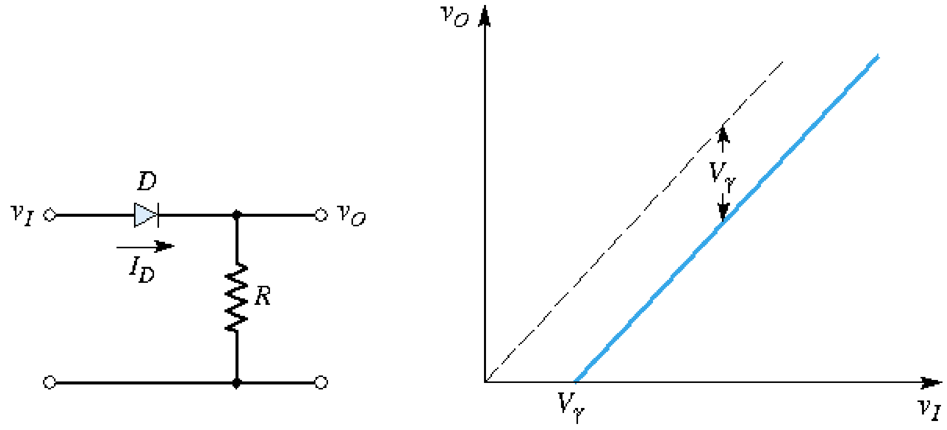


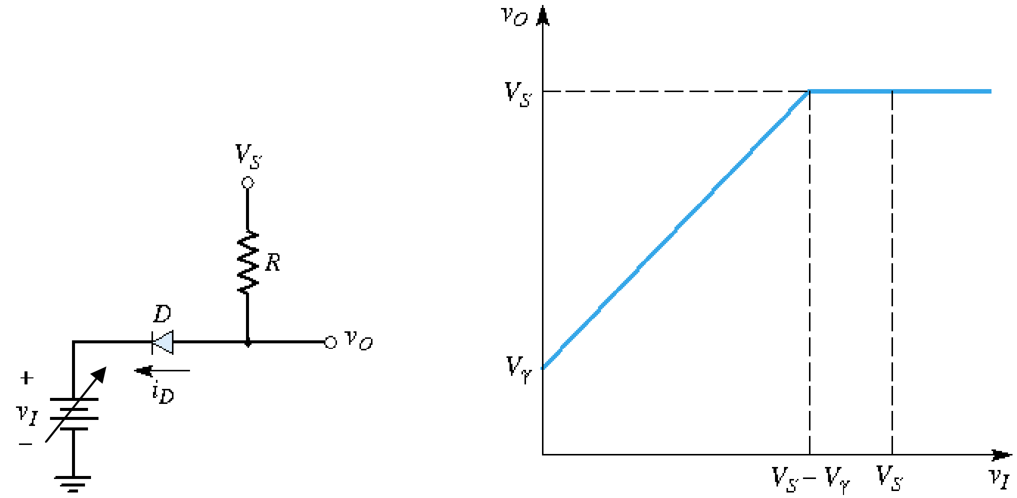
Figure 2.27 (a) Circuit for Example 2.7; (b) input and output waveforms

Analysis of Single Diode Circuits



(a) (b)

Figure 2.30 Diode and resistor in series: (a) circuit and (b) voltage transfer characteristics



(a) (b)

Figure 2.31 Diode with input voltage source: (a) circuit and (b) voltage transfer characteristics

Analysis of Two-Diode Circuit

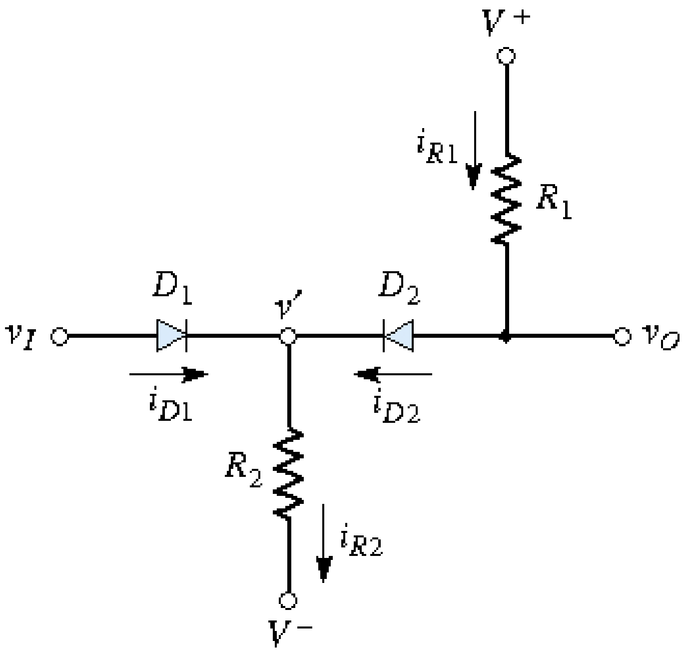


Figure 2.32 A two-diode circuit

Diode States:

(1) D_1 off, D_2 off

(2) D_1 off, D_2 on

(3) D_1 on, D_2 on

(4) D_1 on, D_2 off

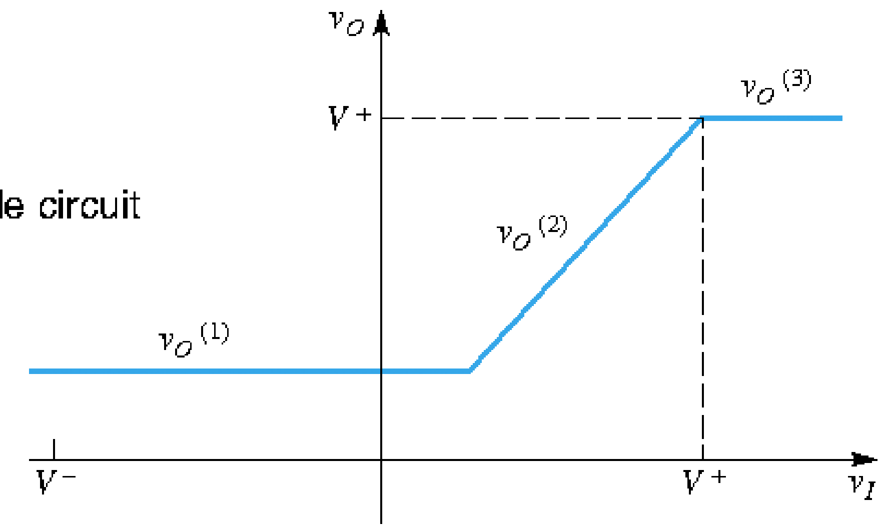
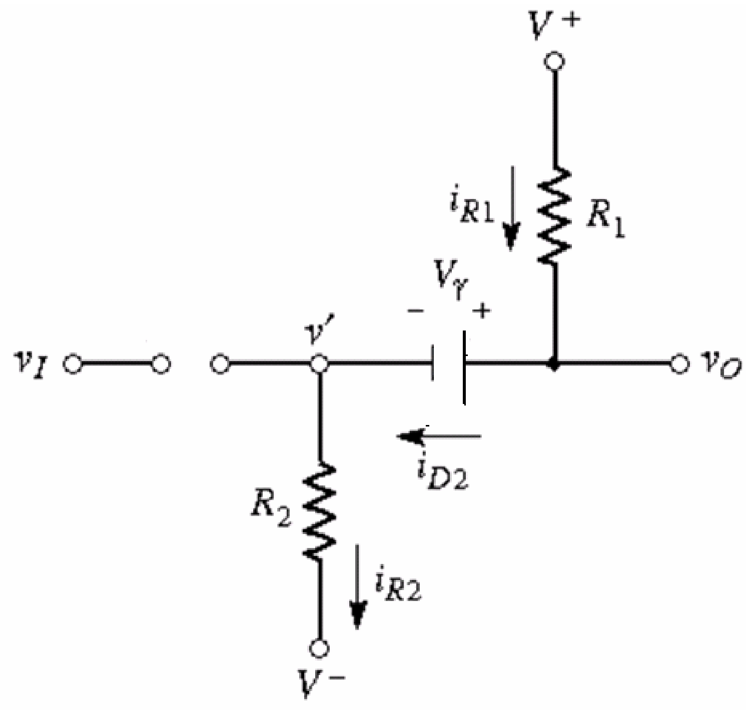


Figure 2.33 Voltage transfer characteristics for the two-diode circuit in Figure 2.32

Analysis of Two-Diode Circuit (1)

- D1: off, D2: on



Let $V^{+} > V^{-} + V_{\gamma}$.

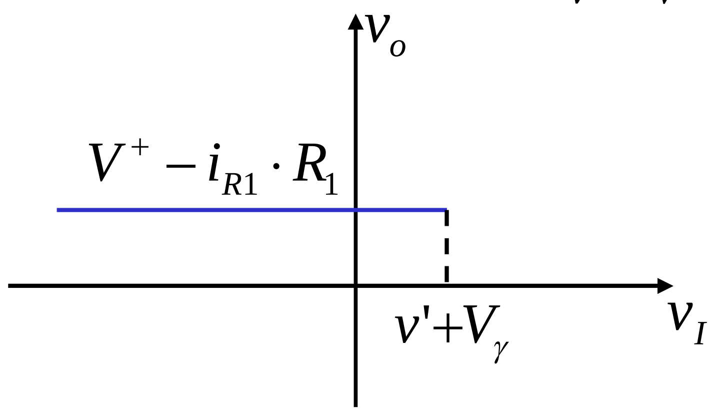
If D_1 is off, then D_2 is always on.

D_2 on : $V^{+} > V^{-} + V_{\gamma}$,

$$i_{R1} = \frac{V^{+} - V_{\gamma} - V^{-}}{R_1 + R_2}, v_o = V^{+} - i_{R1} \cdot R_1$$

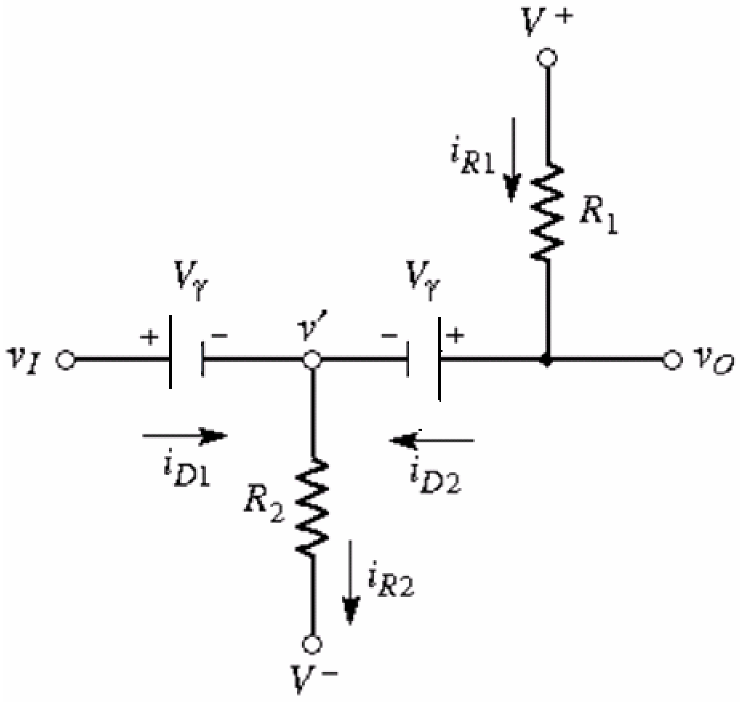
D_1 off : $v_I < v' + V_{\gamma}$,

$$v' = V^{-} + i_{R2} \cdot R_2, i_{R2} = i_{D2} = i_{R1}$$



Analysis of Two-Diode Circuit (2)

- D1: on, D2: on

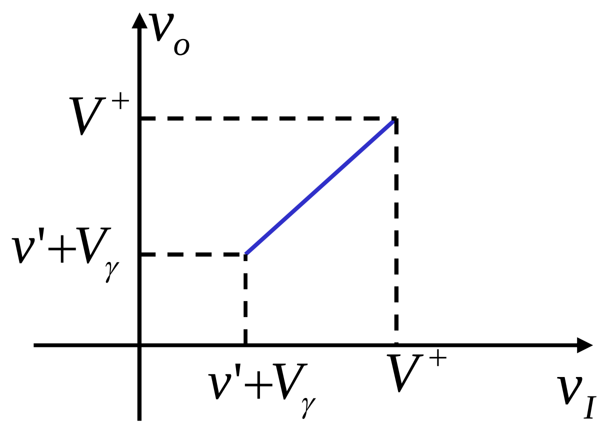


$$D_1 \text{ on} : v_I > v' + V_\gamma ,$$

$$v' = v_I - V_\gamma , i_{R2} = \frac{v_I - V_\gamma - V^-}{R_2}$$

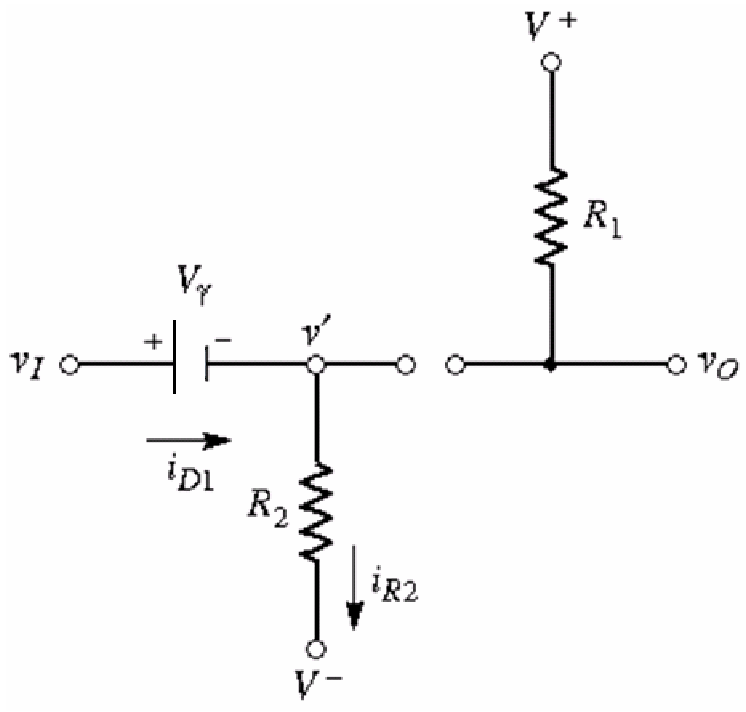
$$D_2 \text{ on} : V^+ > v' + V_\gamma = v_I ,$$

$$v_o = v_I , i_{R1} = \frac{V^+ - v_I}{R_1}$$



Analysis of Two-Diode Circuit (3)

- D1: on, D2: off

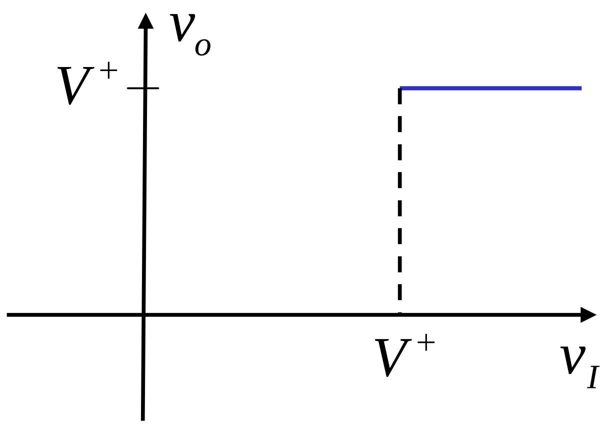


$$D_1 \text{ on}: v_I > V_\gamma + V^-,$$

$$v' = v_I - V_\gamma, i_{R2} = \frac{v_I - V_\gamma - V^-}{R2}$$

$$D_2 \text{ off}: V^+ < v' + V_\gamma = v_I,$$

$$v_o = V^+, i_{R1} = 0$$



Example 2.8 **Objective:** Determine the output voltage and diode currents for the circuit shown in Figure 2.32, for two values of input voltage.

Assume the circuit parameters are $R_1 = 5\,\text{k}\Omega$, $R_2 = 10\,\text{k}\Omega$, $V_\gamma = 0.7\,\text{V}$, $V^+ = +5\,\text{V}$, and $V^- = -5\,\text{V}$. Determine v_O, i_{D1}, and i_{D2} for $v_I = 0$ and $v_I = 4\,\text{V}$.

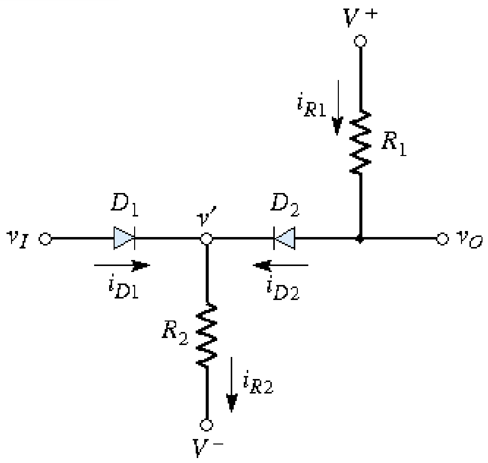


Figure 2.32 A two-diode circuit

Solution: For $v_I = 0$, assume initially that D_1 is off. The currents are then

$$i_{R1} = i_{D2} = i_{R2} = \frac{V^+ - V_\gamma - V^-}{R_1 + R_2} = \frac{5 - 0.7 - (-5)}{5 + 10} = 0.62\,\text{mA}$$

The output voltage is

$$v_O = V^+ - i_{R1}R_1 = 5 - (0.62)(5) = 1.9\,\text{V}$$

and v' is

$$v' = v_O - V_\gamma = 1.9 - 0.7 = 1.2\,\text{V}$$

From these results, we see that diode D_1 is indeed cut off, $i_{D1} = 0$, and our analysis is valid.

For $v_I = 4\,\text{V}$, we see from Figure 2.33 that $v_O = v_I$; therefore, $v_O = v_I = 4\,\text{V}$. In this region, both D_1 and D_2 are on, and

$$i_{R1} = i_{D2} = \frac{V^+ - v_O}{R_1} = \frac{5 - 4}{5} = 0.2\,\text{mA}$$

Note that $v' = v_O - V_\gamma = 4 - 0.7 = 3.3\,\text{V}$. Thus,

$$i_{R2} = \frac{v' - V^-}{R_2} = \frac{3.3 - (-5)}{10} = 0.83\,\text{mA}$$

The current through D_1 is found from $i_{D1} + i_{D2} = i_{R2}$ or

$$i_{D1} = i_{R2} - i_{D2} = 0.83 - 0.2 = 0.63\,\text{mA}$$

EXAMPLE 2.11

Objective: Determine the current I_{D2} and the voltage V_O in the multidiode circuit shown in Figure 2.42. Assume $V_\gamma = 0.7$ V for each diode.

Solution: To begin, initially assume that both diodes D_1 and D_2 are in their conducting state.

Summing currents at the V_A and V_B nodes, we have

$$\frac{15 - V_A}{10} = I_{D2} + \frac{V_A}{5} \tag{2.40}$$

and

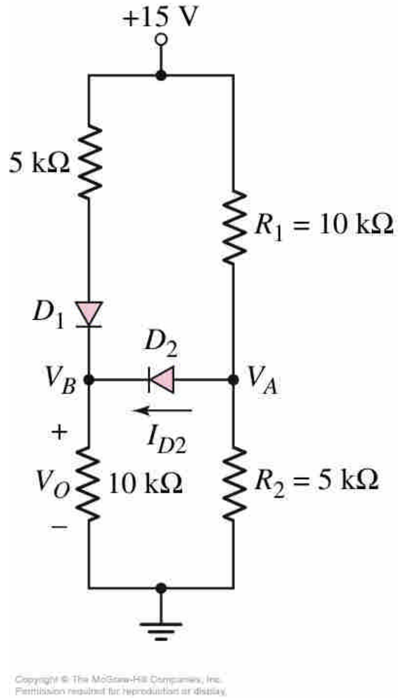
$$\frac{15 - (V_B + 0.7)}{5} + I_{D2} = \frac{V_B}{10} \tag{2.41}$$

We note that $V_B = V_A - 0.7$. Combining the two equations and eliminating I_{D2}, we find

$$V_A = 7.62 \text{ V} \qquad \text{and} \qquad V_B = 6.92 \text{ V}$$

From Equation (2.40) above, we obtain

$$\frac{15 - 7.62}{10} = I_{D2} + \frac{7.62}{5} \Rightarrow I_{D2} = -0.786 \text{ mA}$$



We assumed that D_2 was on, so that a negative diode current is inconsistent with that initial assumption.

Now assume that diode D_2 is off and D_1 is on. To find the node voltages, we can simply use voltage dividers as

$$V_A = \left(\frac{5}{5 + 10}\right)(15) = 5\ \mathrm{V}$$

and

$$V_B = V_o = \left(\frac{10}{10 + 5}\right)(15 - 0.7) = 9.53\ \mathrm{V}$$

These voltages show that diode D_2 is indeed reverse biased so that $I_{D2} = 0$.

Comment: To begin an analysis of a multidiode circuit, we must assume a conducting state, on or off, for each diode. We then perform the analysis and verify whether our initial assumptions are correct or incorrect. If the initial assumption is incorrect, we need to make a new assumption and perform the analysis again. This process must continue until the assumptions are verified as correct.

EXAMPLE 2.12

Objective: Determine the current in each diode and the voltages V_A and V_B in the multidiode circuit shown in Figure 2.43. Let $V_\gamma = 0.7$ V for each diode.

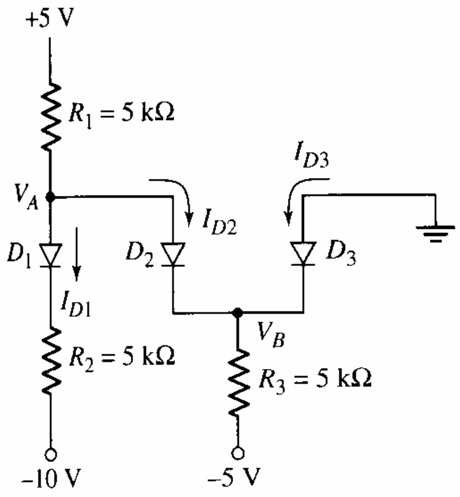


Figure 2.43 Diode circuit for Example 2.12

Solution: Initially assume each diode is in its conducting state. Starting with D_3 and considering the voltages, we see that

$$V_B = -0.7 \text{ V} \qquad \text{and} \qquad V_A = 0$$

Summing currents at the V_A node, we find

$$\frac{5 - V_A}{5} = I_{D2} + \frac{(V_A - 0.7) - (-10)}{5}$$

Since $V_A = 0$, we obtain

$$\frac{5}{5} = I_{D2} + \frac{9.3}{5} \Rightarrow I_{D2} = -0.86\,\text{mA}$$

which is inconsistent with the assumption that all diodes are "on" (an "on" diode would have a positive diode current).

Now assume that D_1 and D_3 are on and D_2 is off. We see that

$$I_{D1} = \frac{5 - 0.7 - (-10)}{5 + 5} = 1.43\,\text{mA}$$

and

$$I_{D3} = \frac{(0 - 0.7) - (-5)}{5} = 0.86\,\text{mA}$$

We find the voltages as

$$V_B = -0.7\ \text{V}$$

and

$$V_A = 5 - (1.43)(5) = -2.15\ \text{V}$$

From the values of V_A and V_B, the diode D_2 is indeed reverse biased and off, so $I_{D2} = 0$.

Diode Logic Circuits

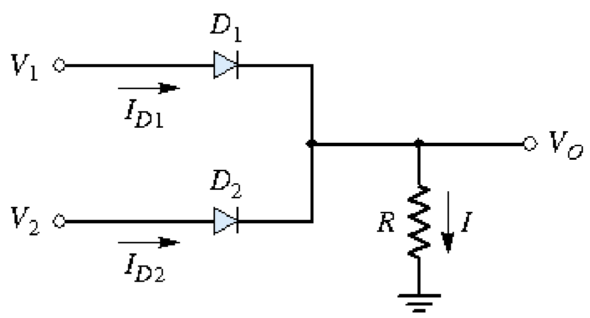


Figure 2.37 A two-input diode OR logic circuit

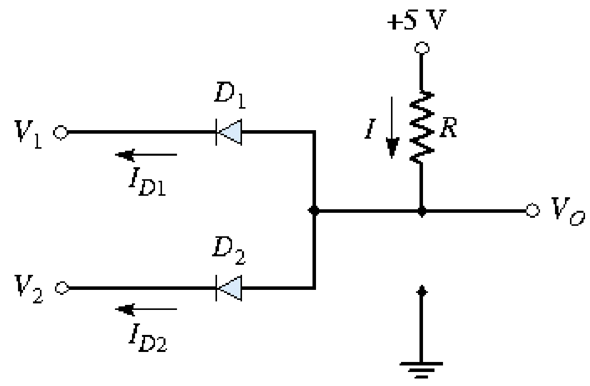


Figure 2.38 A two-input diode AND logic circuit

Table 2.1 Two-diode OR logic circuit response

V_1(V)	V_2(V)	V_O(V)
0	0	0
5	0	4.3
0	5	4.3
5	5	4.3

Table 2.2 Two-diode AND logic circuit response

V_1(V)	V_2(V)	V_O(V)
0	0	0.7
5	0	0.7
0	5	0.7
5	5	5

Photodiode Circuit

- If the photon intensity is zero, the only current through the diode is the reverse-saturation current, which is normally very small.
- Photons striking the diode create excess electrons and holes in the depletion region. The electric field separates these excess carriers and sweeps them out of the depletion region, thus creating a **photocurrent** in the reverse-bias direction.

$$I_{ph} = \eta e \Phi A$$

η : quantum efficiency, e : electronic charge

Φ : photon flux density, A : junction area

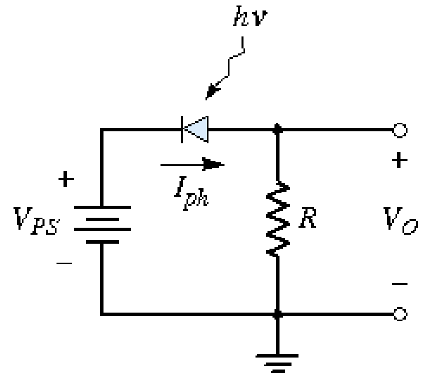


Figure 2.39 A photodiode circuit

Example 2.10 **Objective:** Calculate the photocurrent generated in a photodiode.

For the photodiode shown in Figure 2.39 assume the quantum efficiency is 1, the junction area is 10^{-2} cm^2, and the incident photon flux is 5×10^{17} cm^{-2}– s^{-1}.

Solution: From Equation (2.28), the photocurrent is

$$I_{ph} = \eta e \Phi A = (1)(1.6 \times 10^{-19})(5 \times 10^{17})(10^{-2}) \Rightarrow 0.8\,\text{mA}$$

Light-Emitting Diode (LED) Circuits

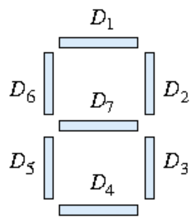


Figure 2.40 Seven-segment LED display

Example 2.11 **Objective:** Determine the value of R required to limit the current in the circuit in Figure 2.41 when the input is in the low state.

Assume that a diode current of 10 mA produces the desired light output, and that the corresponding forward-bias voltage drop is 1.7 V.

Solution: If $V_I = 0.2$ V in the "low" state, then the diode current is

$$I = \frac{5 - V_\gamma - V_I}{R}$$

The resistance R is then determined as

$$R = \frac{5 - V_\gamma - V_I}{I} = \frac{5 - 1.7 - 0.2}{10} \Rightarrow 310\ \Omega$$

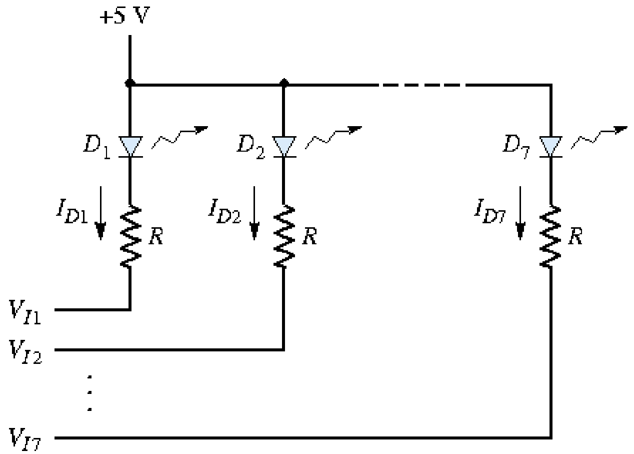


Figure 2.41 Control circuit for the seven-segment LED display

Comment: Typical LED current-limiting resistor values are in the range of 300 to 350 Ω.