Diode Circuits

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

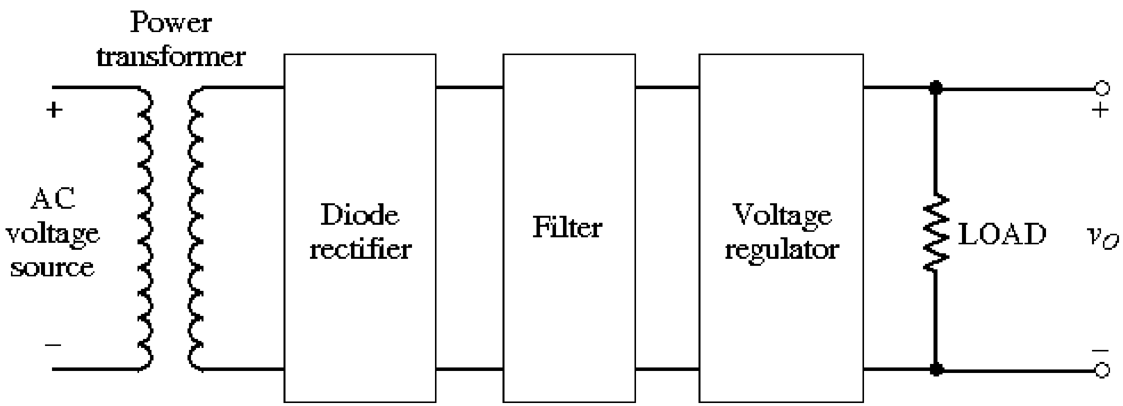
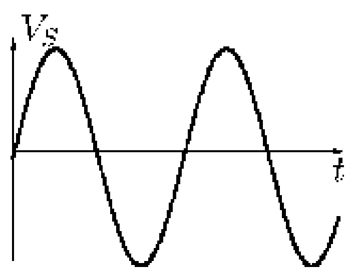
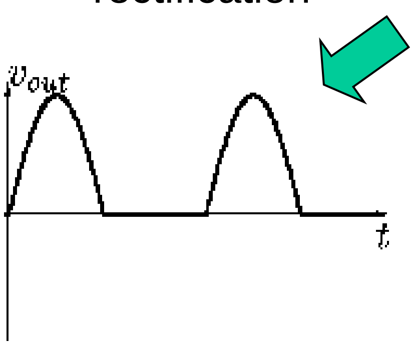


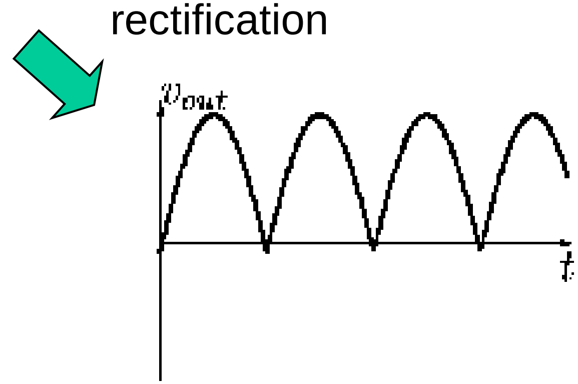
Figure 2.1 Block diagram of an electronic power supply



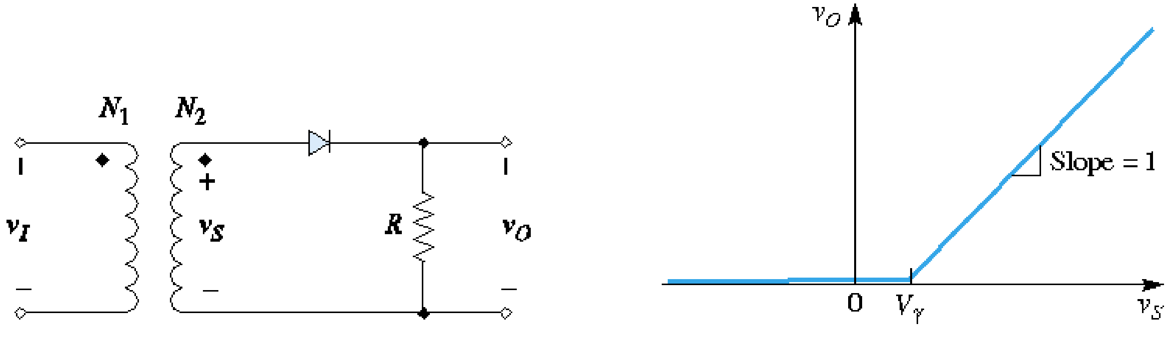
half-wave
rectification



full-wave
rectification

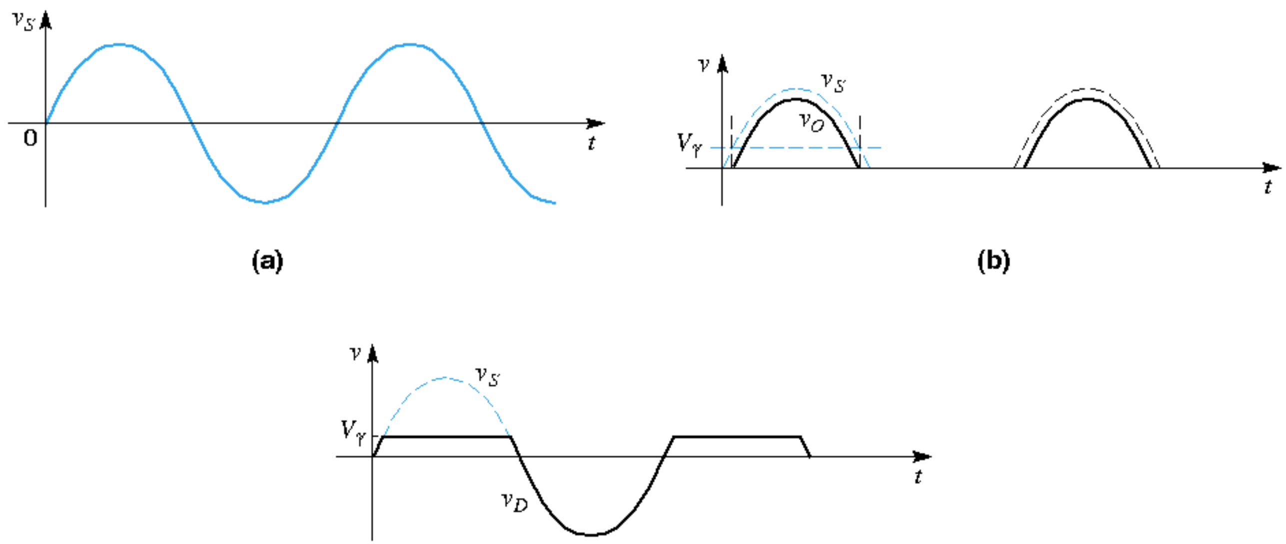


Half-Wave Rectification



(a) (b)

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



(c)

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

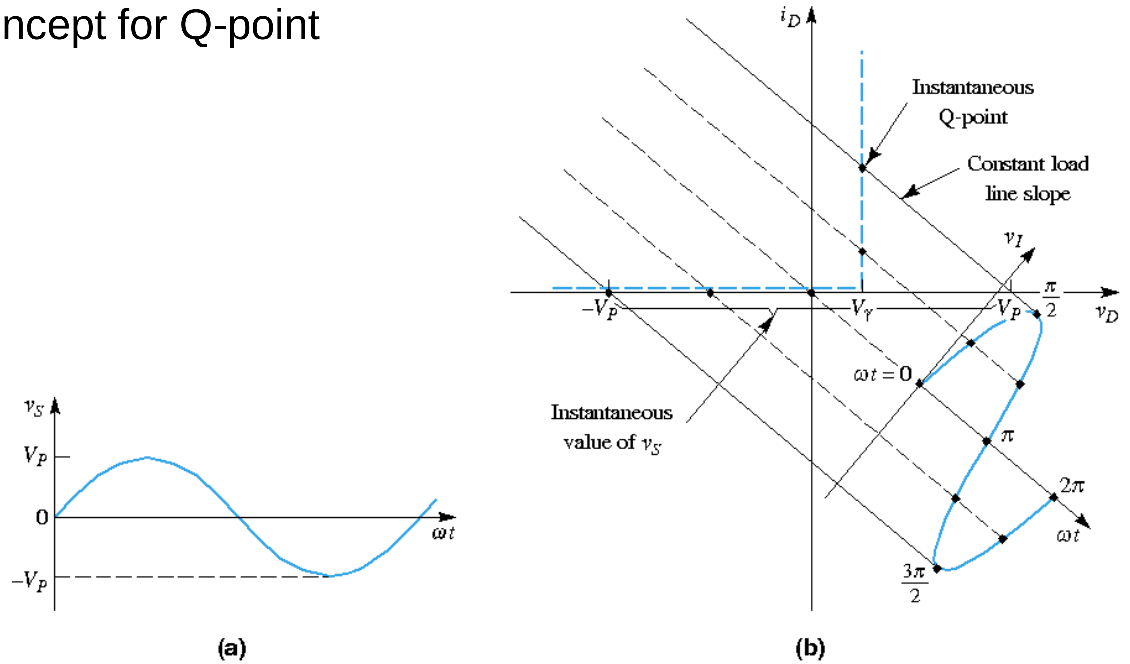


Figure 2.4 Operation of half-wave rectifier circuit: (a) sinusoidal input voltage and (b) diode piecewise linear characteristics and circuit load line at various times

- Battery Charger

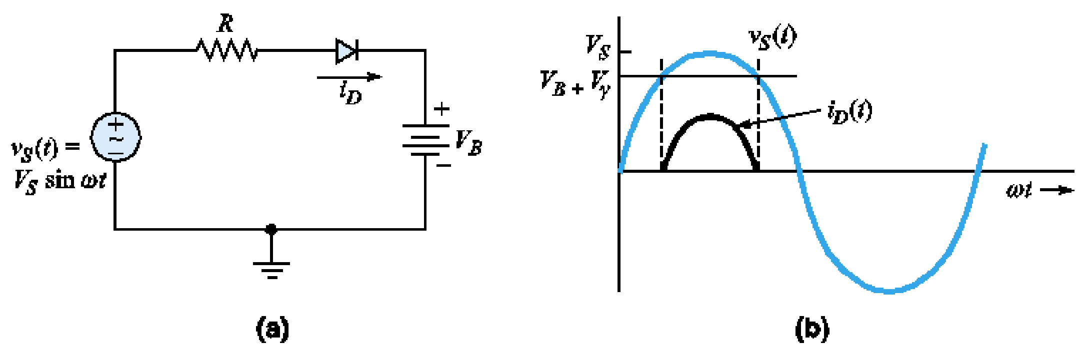


Figure 2.5 (a) Half-wave rectifier used as a battery charger; (b) input voltage and diode current waveforms

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:

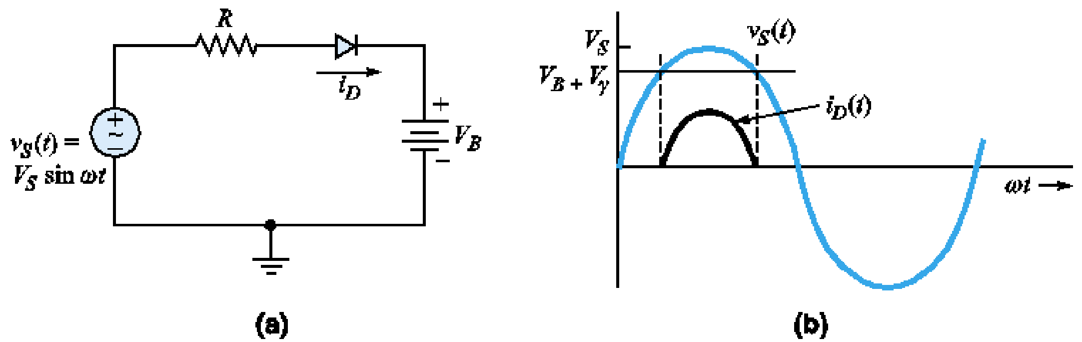


Figure 2.5 (a) Half-wave rectifier used as a battery charger; (b) input voltage and diode current waveforms

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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:

$$v_1 = 24 \sin \omega t_1 = 12.6$$

or

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

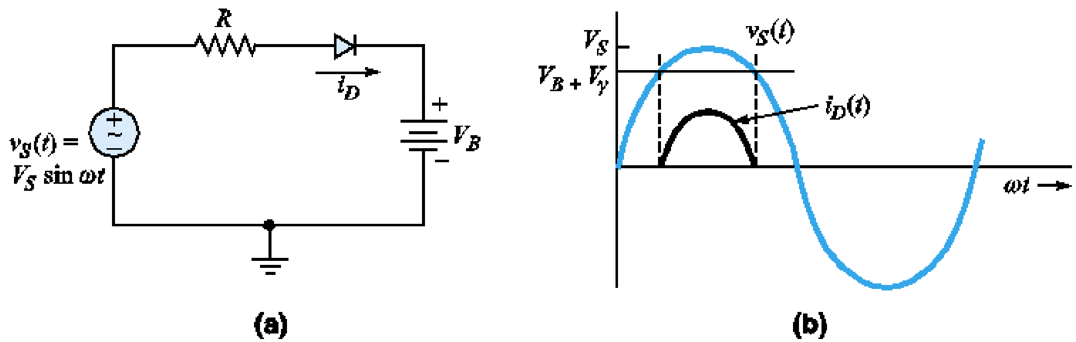


Figure 2.5 (a) Half-wave rectifier used as a battery charger; (b) input voltage and diode current waveforms

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.

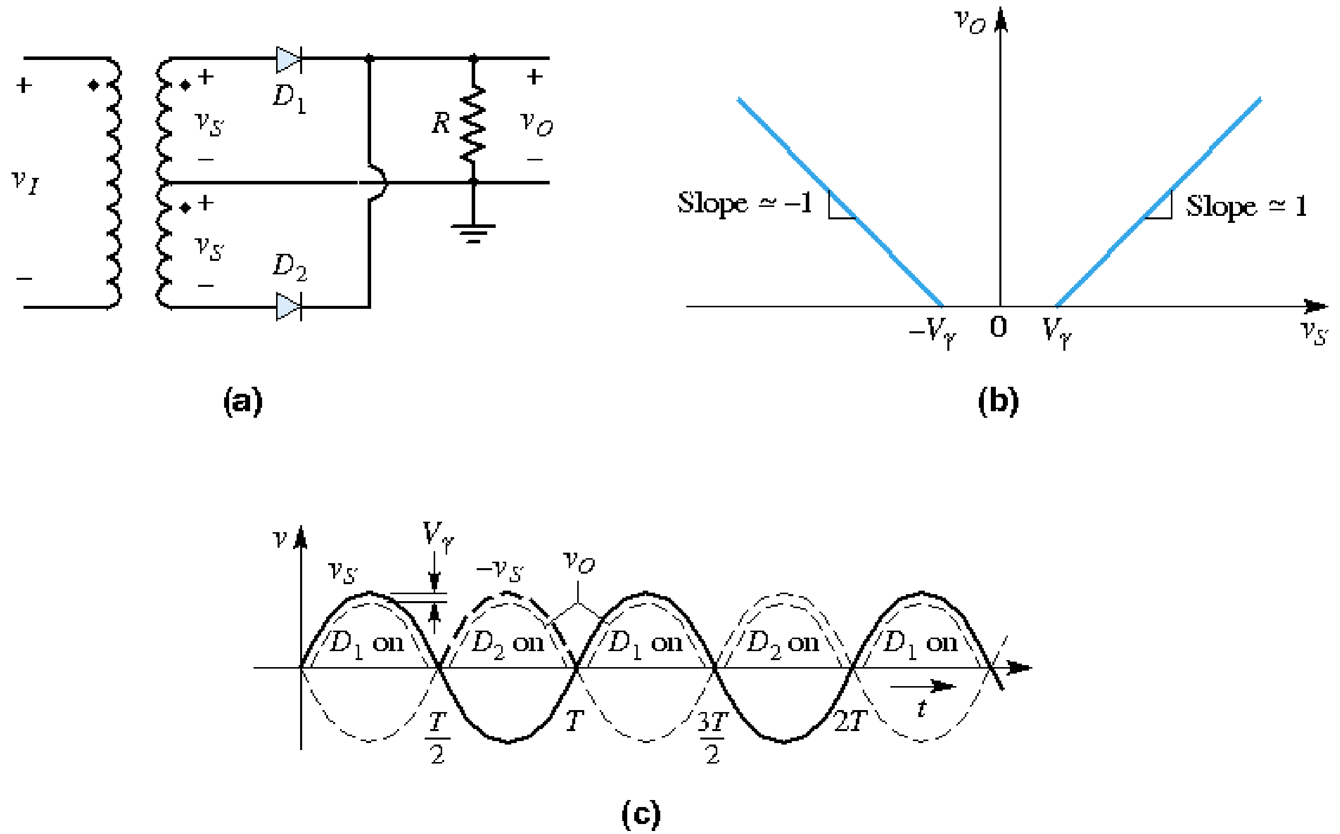
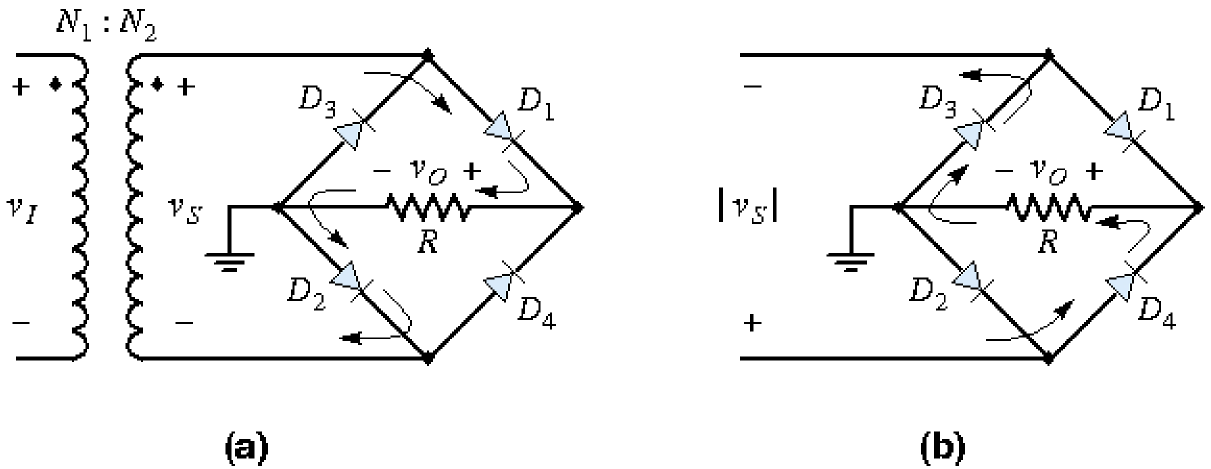


Figure 2.6 Full-wave rectifier: (a) circuit with center-tapped transformer, (b) voltage transfer characteristics, and (c) input and output waveforms

Full-Wave Bridge Rectifier



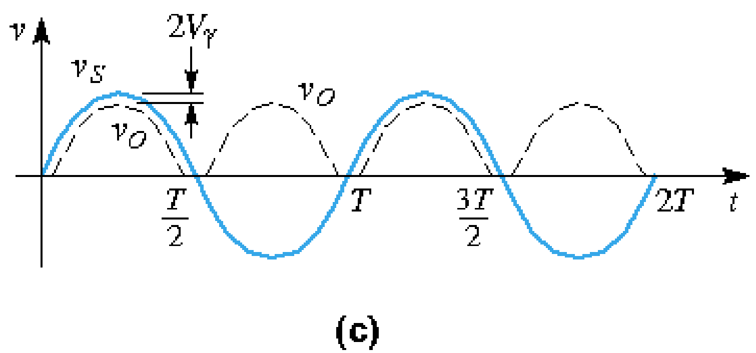
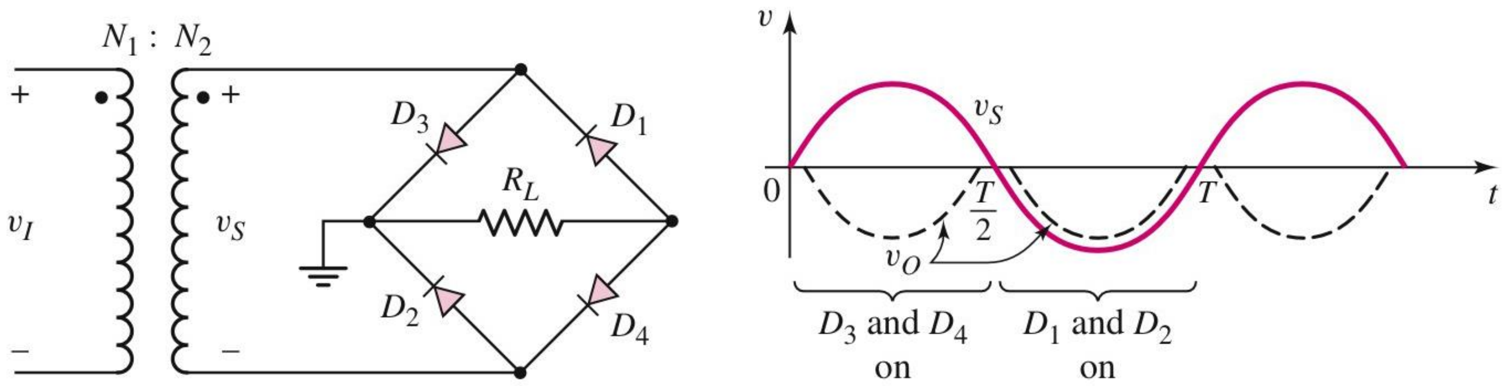


Figure 2.7 A full-wave bridge rectifier: (a) circuit showing the current direction for a positive input cycle, (b) current direction for a negative input cycle, and (c) input and output voltage waveforms

Full-Wave Bridge Rectifier

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

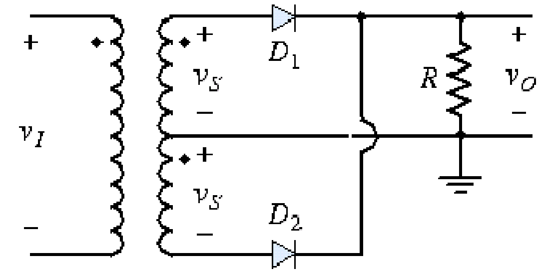


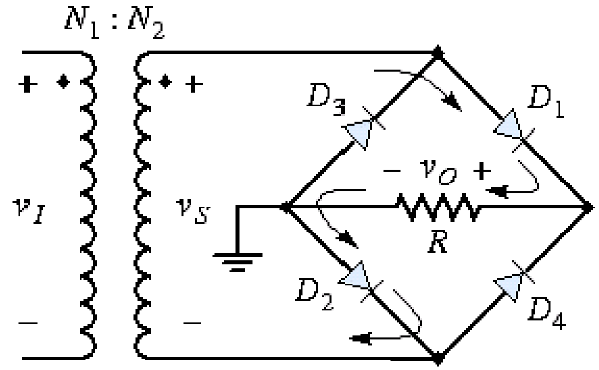
(a) (b)

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:





$N_1 : N_2$
+
+
v_I
v_S
−
−
D_3
D_1
− v_O +
R
D_2
D_4

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

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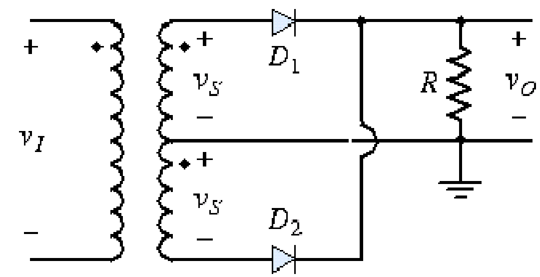
Solution:

For the center-tapped transformer circuit, 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

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

The turn ratio is

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

The peak inverse voltage of a diode is

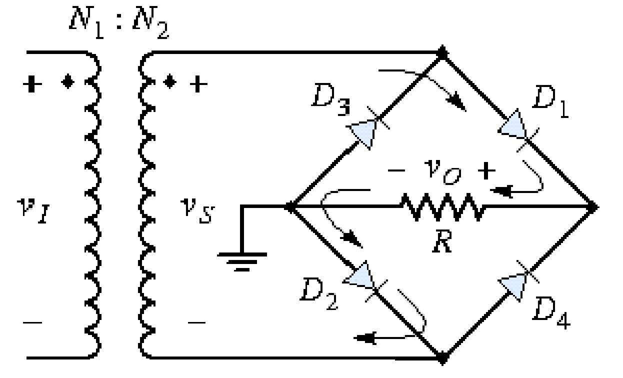
$$\text{PIV} = v_R(\max) = (v_S - V_\gamma) - (-v_S) = 2v_S(\max) - V_\gamma = 2(9.7) - 0.7 = 18.7\,\text{V}$$

For the bridge circuit, 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 turn ratio is

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

The peak inverse voltage of a diode is

$$\text{PIV} = v_R(\max) \Rightarrow (v_S - 2V_r) - (-V_\gamma) = v_S(\max) - V_\gamma = 10.4 - 0.7 = 9.7\,\text{V}$$

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

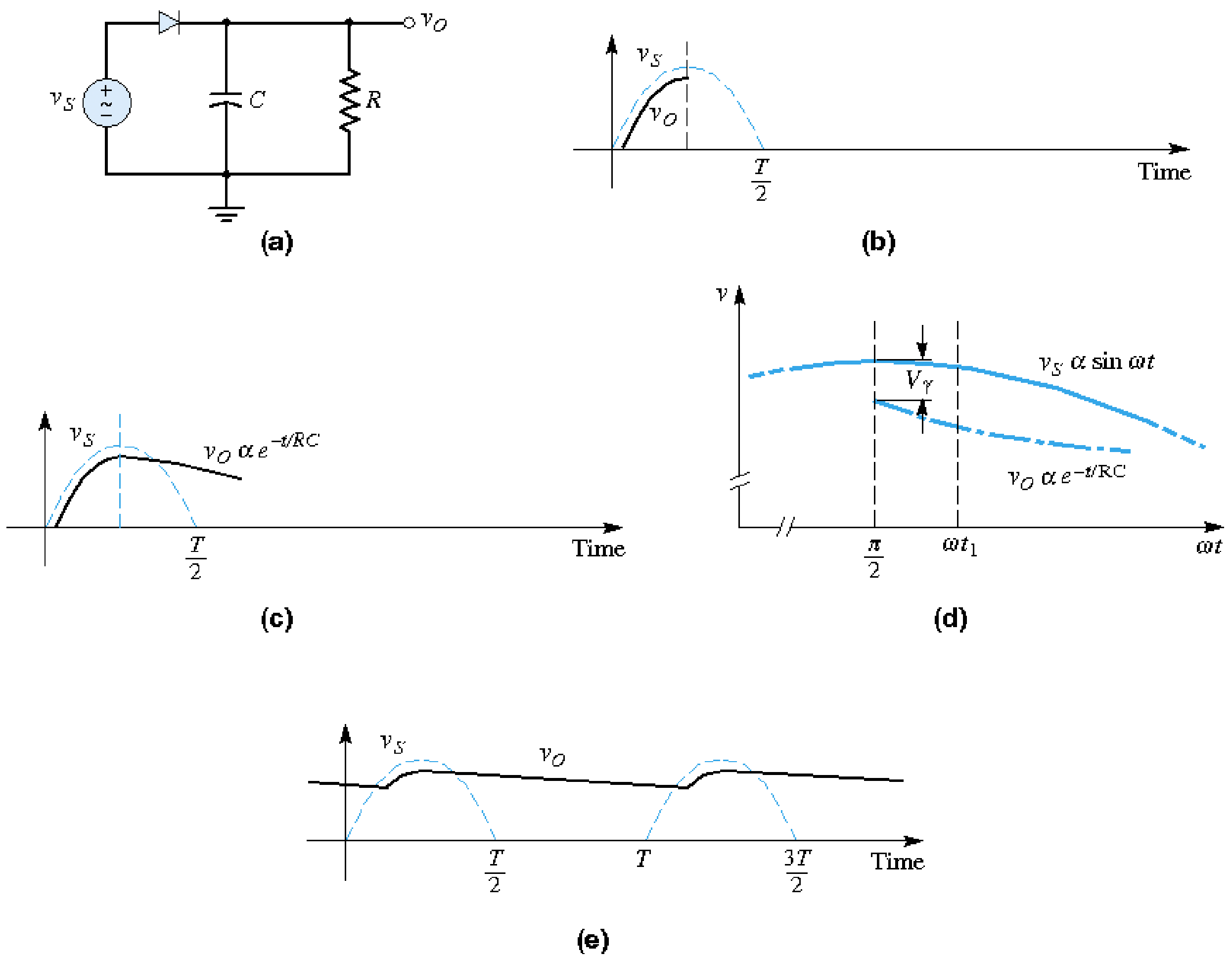


Figure 2.8 Simple filter circuit: (a) half-wave rectifier with an RC filter, (b) positive input voltage and initial portion of output voltage, (c) output voltage resulting from capacitor discharge, (d) expanded view of input and output voltages assuming capacitor discharge begins at $\omega t = \pi/2$,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

Analysis of Filter Circuit for Diode Rectifier

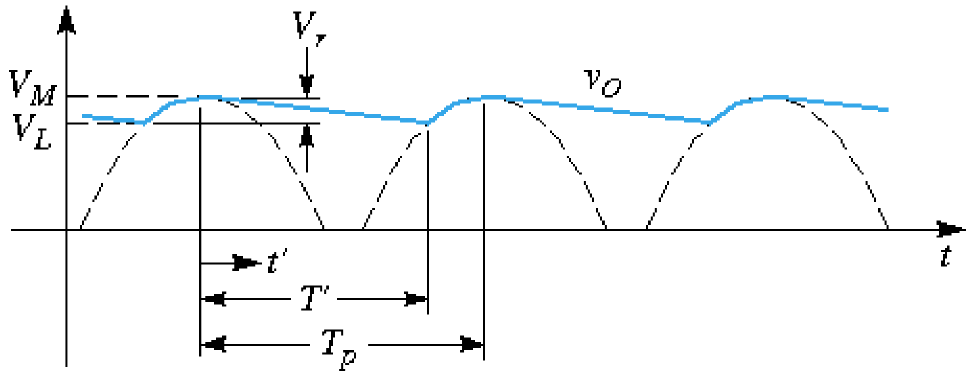


Figure 2.9 Output voltage of a full-wave rectifier with an *RC* filter

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

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

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

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

$e^{-T'/RC} \simeq 1 - T'/RC$

when $RC \gg T'$

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

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:

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 $V_M = 10$ V. Assume the output load resistance is $R = 10$ kΩ and the ripple voltage is to be limited to $V_r = 0.2$ V.

Solution:

$$C = \frac{V_M}{2fRV_r} = \frac{10}{2(60)(10\times10^3)(0.2)} \Rightarrow 41.7\mu\text{F}$$

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

Current in the Filter Circuit for Diode Rectifier

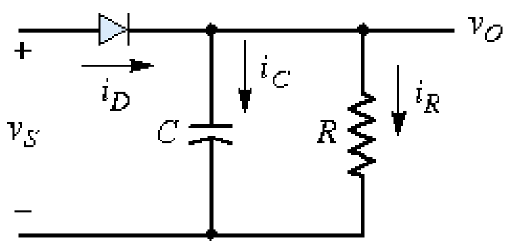


Figure 2.11 Equivalent circuit of a full-wave rectifier during capacitor charging cycle

$$i_D = i_C + i_R$$

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

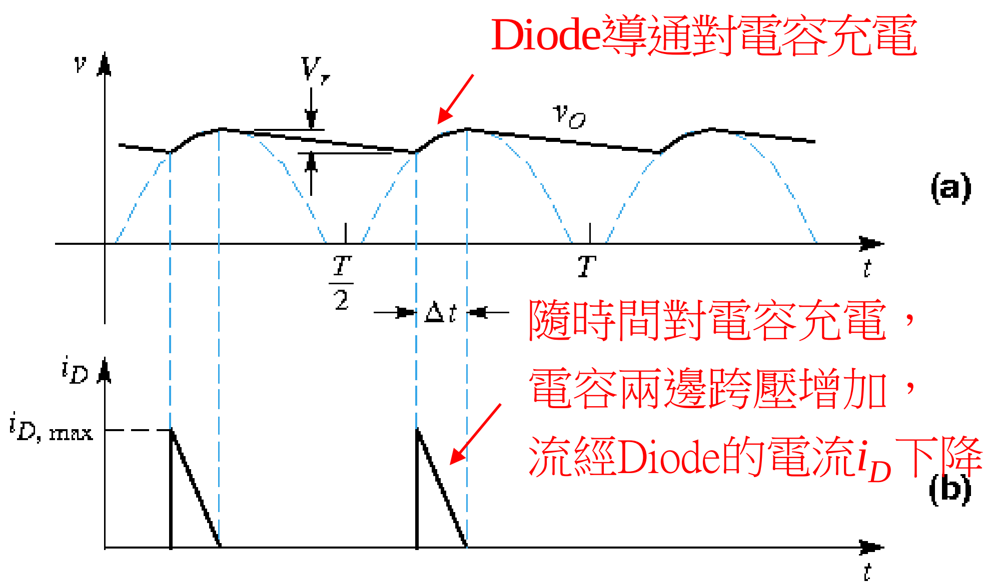
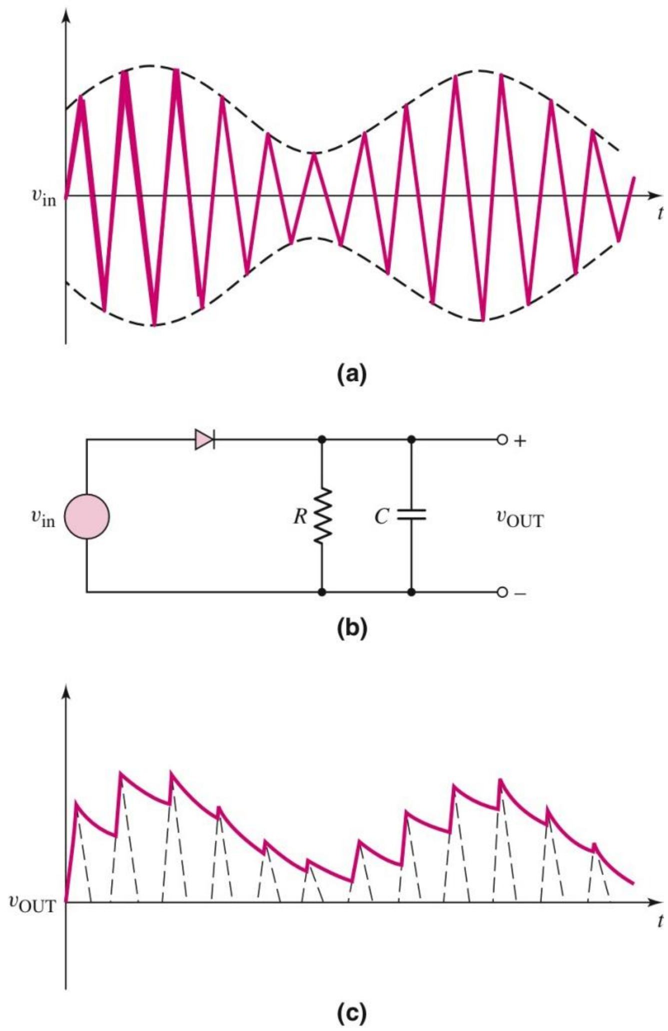


Figure 2.10 Output of a full-wave rectifier with an *RC* filter: (a) diode conduction time and (b) diode current

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.

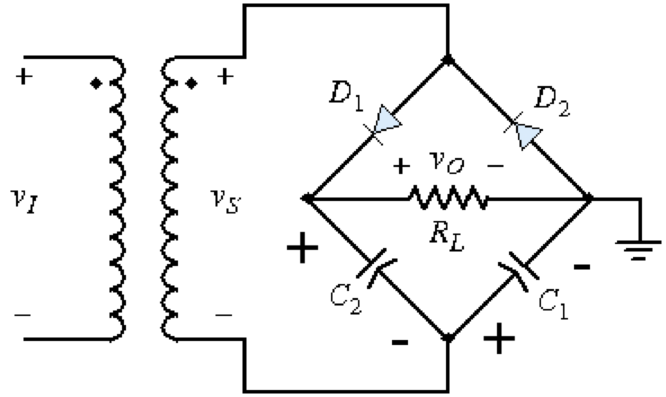


Figure 2.13 A voltage doubler circuit

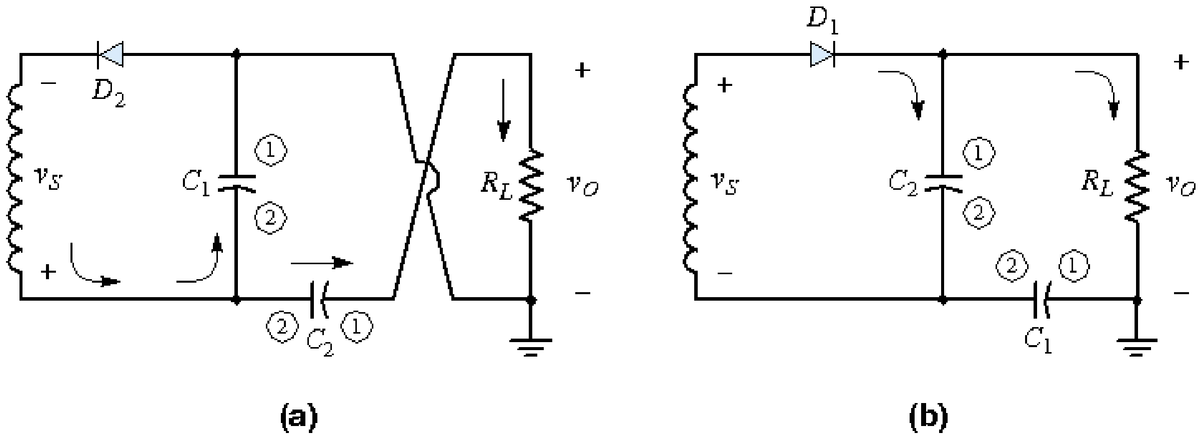


Figure 2.14 Equivalent circuit of the voltage doubler circuit: (a) negative input cycle and (b) positive input cycle

Clipper Circuits

- Clipper circuits are used to eliminate portions of a signal that are above or/and below a specified level. 半波整流就是一個剪波器電路
- Transfer characteristics of a limiter circuits

輸入輸出電壓關係：

1. $\dfrac{v_0^-}{A_v} \le v_I \le \dfrac{v_0^+}{A_v}$，是線性關係

2. $v_I > \dfrac{v_0^+}{A_v}$ 或 $v_I < \dfrac{v_0^-}{A_v}$，是截平

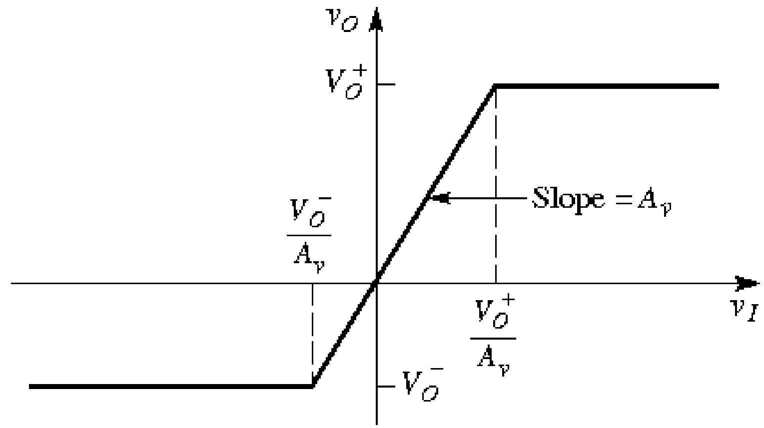


Figure 2.18 General voltage transfer characteristics of a limiter circuit

- Single diode clipper

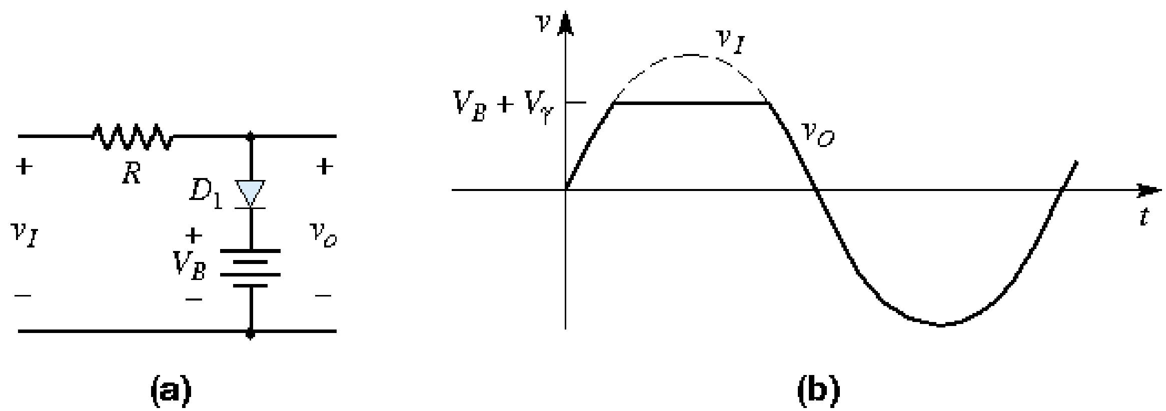
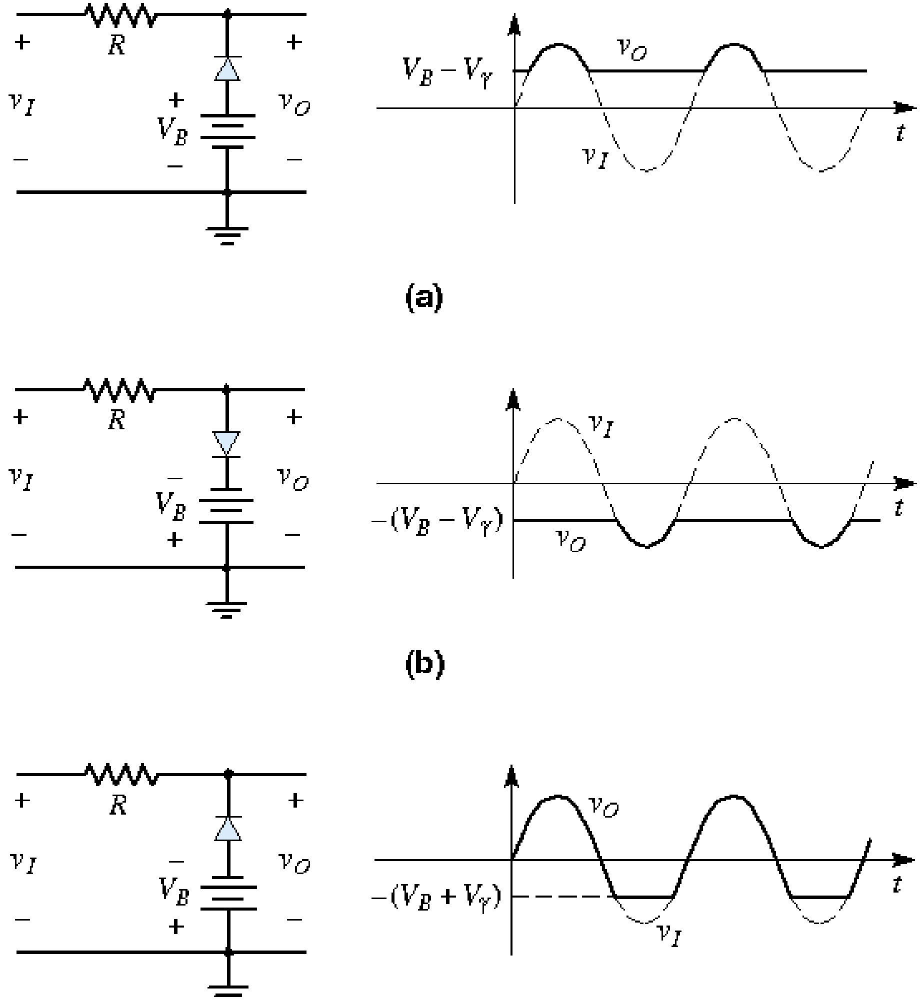


Figure 2.19 Single-diode clipper: (a) circuit and (b) output response

Parallel-Based Clipper



$$if\ \ V_B - V_\gamma > V_I$$
$$then\ \ V_O = V_B - V_\gamma$$

$$if\ \ V_I > V_\gamma - V_B$$
$$then\ \ V_O = V_\gamma - V_B$$

$$if\ \ -V_B - V_\gamma > V_I$$
$$then\ \ V_O = -V_B - V_\gamma$$

Figure 2.20 Additional diode clipper circuits and their corresponding output responses

Parallel-Based Clipper

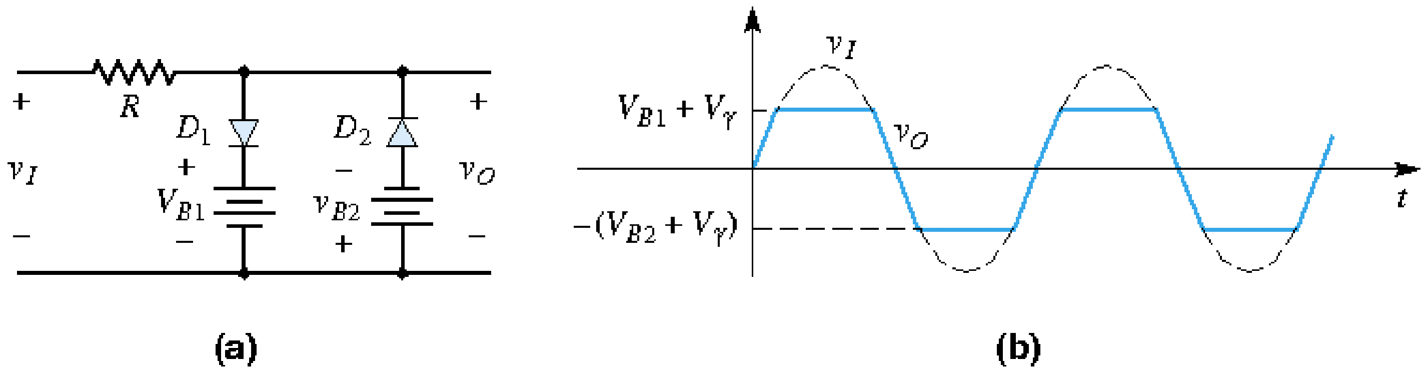


Figure 2.21 A parallel-based diode clipper circuit and its output response

(1) $V_I > V_\gamma + V_{B1}$

D_1導通、D_2不導通 $\Rightarrow$ $V_O = V_\gamma + V_{B1}$

(2) $-V_I > V_\gamma + V_{B1} \Rightarrow -V_{B2} - V_\gamma > V_I$

D_2導通、D_1不導通 $\Rightarrow$ $V_O = -V_\gamma - V_{B1}$

(3) Otherwise

D_2、D_1都不導通 $\Rightarrow$ $V_O = V_I$

Series-Based Clipper

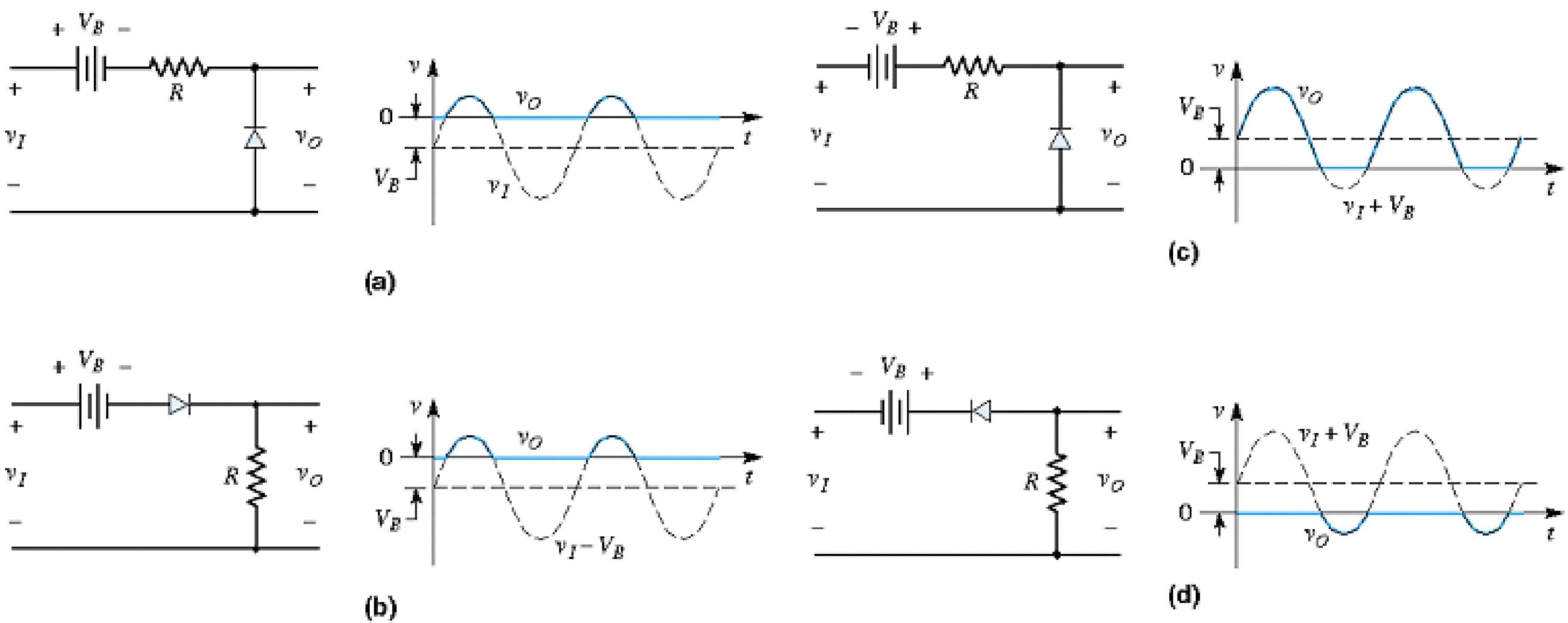


Figure 2.23 Series-based diode clipper circuits and their corresponding output responses

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.

$v_I(t) = V_M \sin \omega t$

將訊號位移一個DC準位：

1. $v_I \nearrow$, 對電容充電, v_C跨壓達 $\approx v_M - v_r$
2. v_I從峰值下降後, Diode不導通, $v_0(t) = v_I - v_C$

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

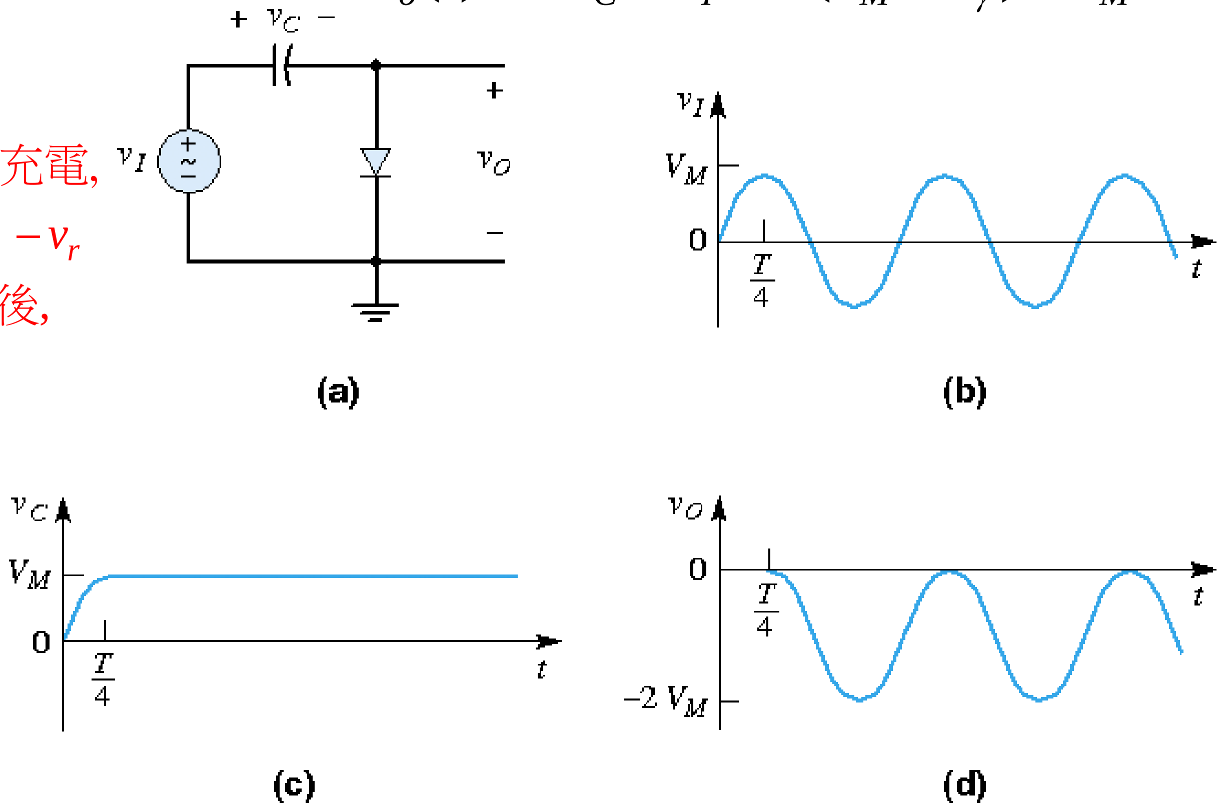


Figure 2.25 Action of a diode clamper circuit: (a) a typical diode clamper circuit, (b) the sinusoidal input signal, (c) the capacitor voltage, and (d) the output voltage

Clampers

- Clamping Circuit Including an Independent Voltage Source

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

$$V_M = v_C + V_r + V_B$$
$$\Rightarrow v_C = V_M - V_B - V_r$$

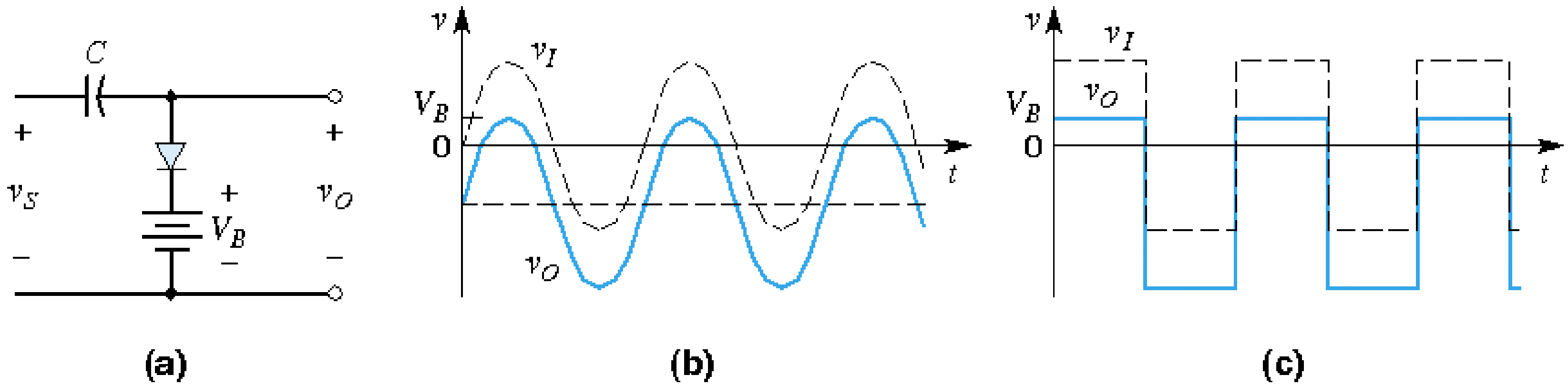


Figure 2.26 Action of a diode clamper circuit with a voltage source: (a) the circuit, (b) steady-state sinusoidal input and output signals, and (c) steady-state square-wave input and output signals

Analysis of Single Diode Circuits

(1) $v_I > V_\gamma$

D導通 $\Rightarrow\ v_o = v_I - V_r$

(2) $v_I < V_\gamma$

D不導通 $\Rightarrow\ v_o = 0$

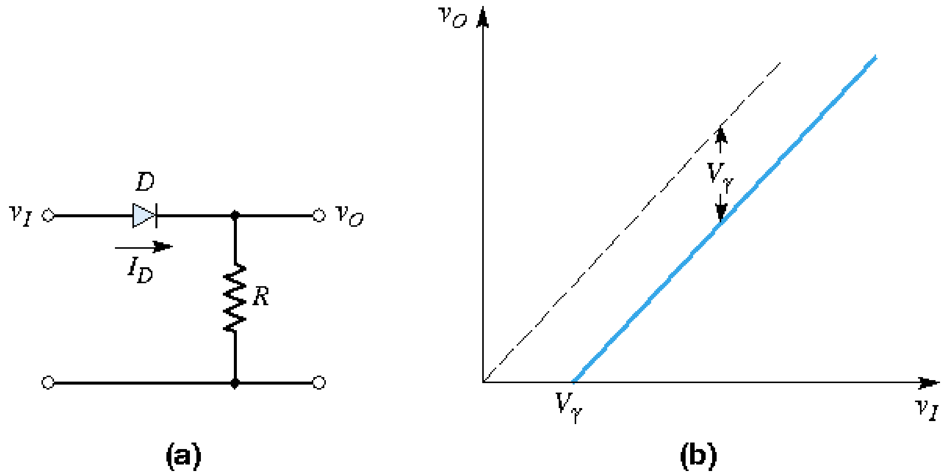


Figure 2.30 Diode and resistor in series: (a) circuit and (b) voltage transfer characteristics

(1) $v_S > v_I + V_\gamma$

D導通 $\Rightarrow\ v_o = v_I + V_r$

(2) $v_S < v_I + V_\gamma$

D不導通 $\Rightarrow\ v_o = v_S$

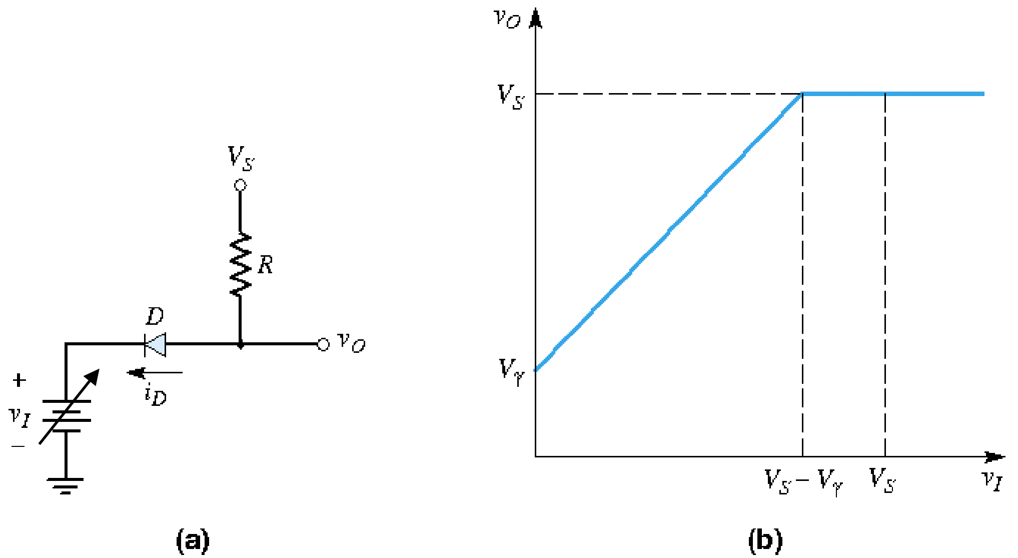


Figure 2.31 Diode with input voltage source: (a) circuit and (b) voltage transfer characteristics

Analysis of Two-Diode Circuit

Assume $V^+ - V^- > V_r$

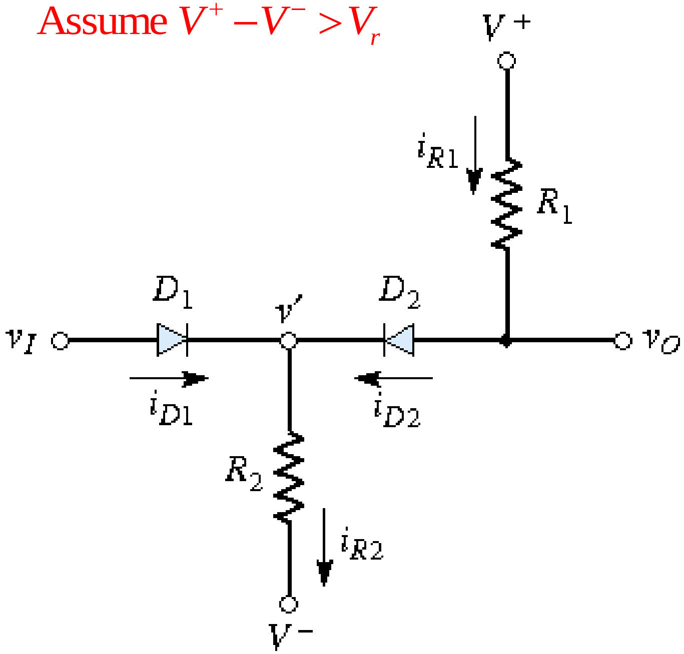


Figure 2.32 A two-diode circuit

Diode States:

(1) D_1 off, D_2 off $\Leftarrow$不可能發生

(2) D_1 off, D_2 on

(3) D_1 on, D_2 on

(4) D_1 on, D_2 off

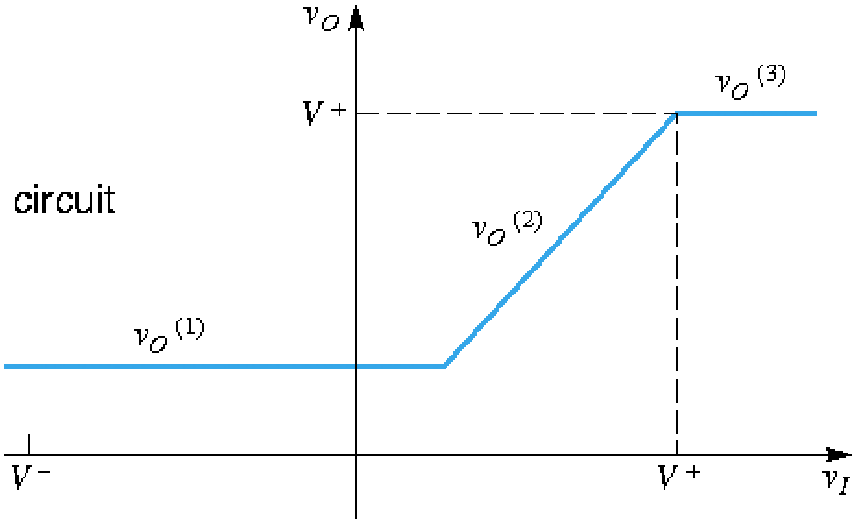
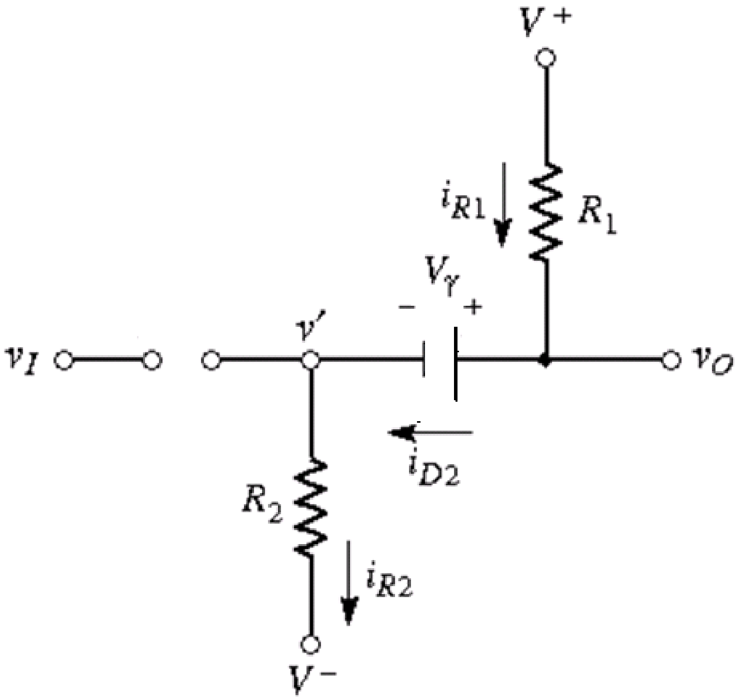


Figure 2.33 Voltage transfer characteristics for the two-diode circuit in Figure 2.32

Analysis of Two-Diode Circuit (1)

- D1: off, D2: on



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

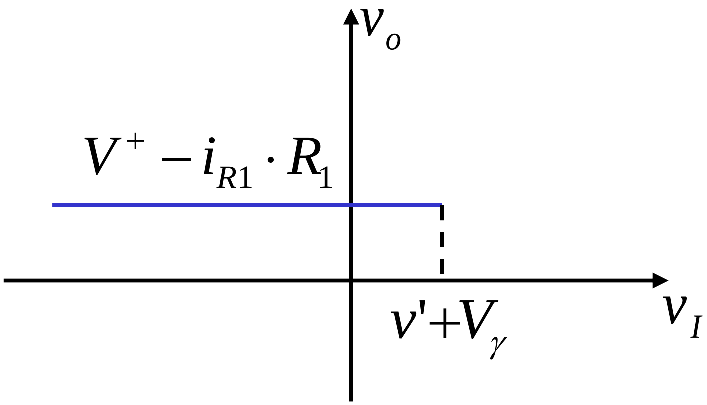
If D_1 is off, then D_2 is always on.

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

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

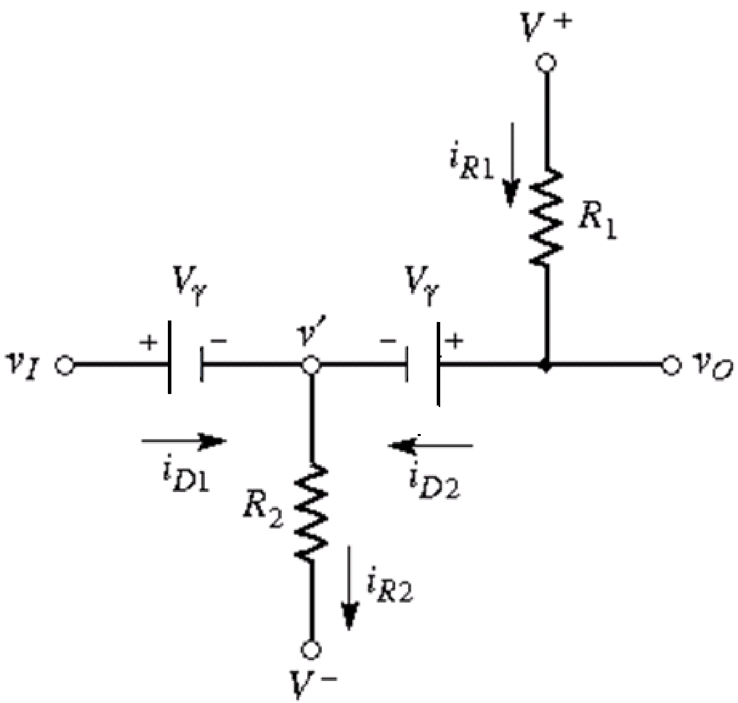
D_1 off : $v_I - v' < V_\gamma$,

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



Analysis of Two-Diode Circuit (2)

- D1: on, D2: on

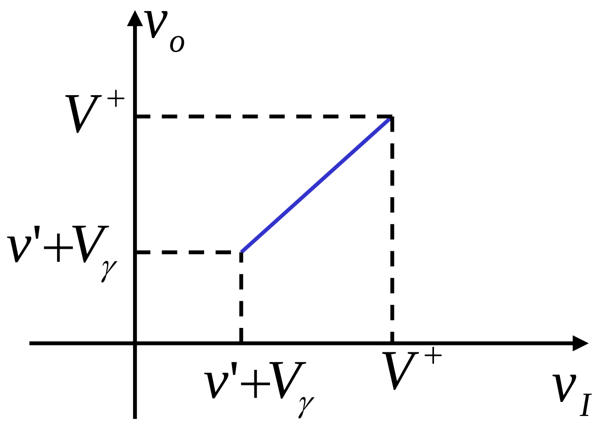


$$D_1 \text{ on}: v_I - v' > V_\gamma,$$

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

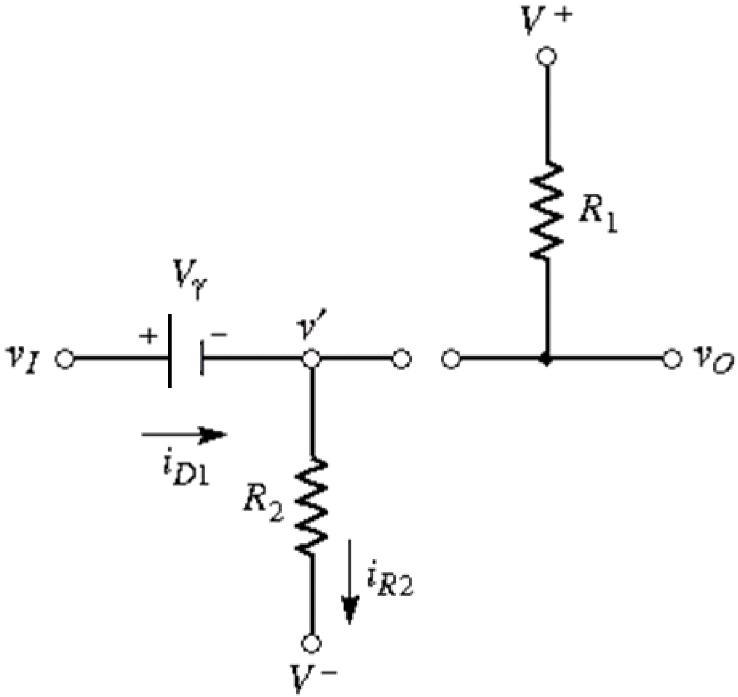
$$D_2 \text{ on}: V^+ - v' > V_\gamma \;\Rightarrow\; V^+ > v' + V_\gamma = v_I,$$

$$v_o = v' + V_\gamma = v_I, \; i_{R1} = \frac{V^+ - v_o}{R_1} = \frac{V^+ - v_I}{R_1}$$



Analysis of Two-Diode Circuit (3)

- D1: on, D2: off

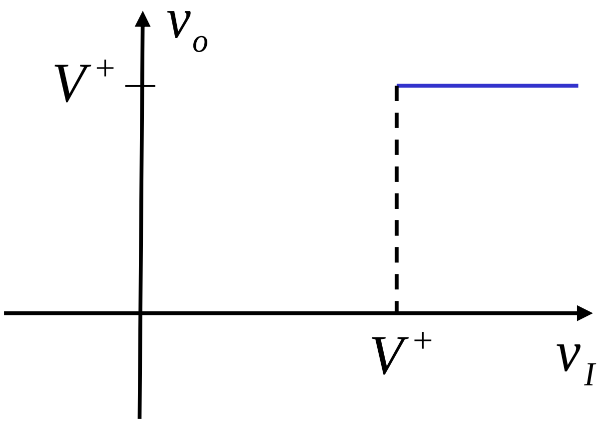


$$D_1 \text{ on}: v_I - V^- > V_\gamma,$$

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

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

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



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 $v_I = 4\,\text{V}$.

Solution:

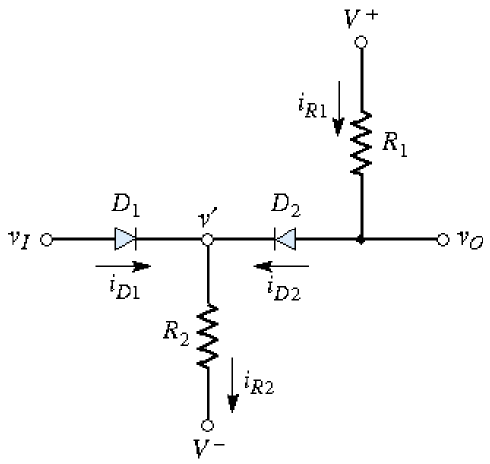


Figure 2.32 A two-diode circuit

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 $v_I = 4\,\text{V}$.

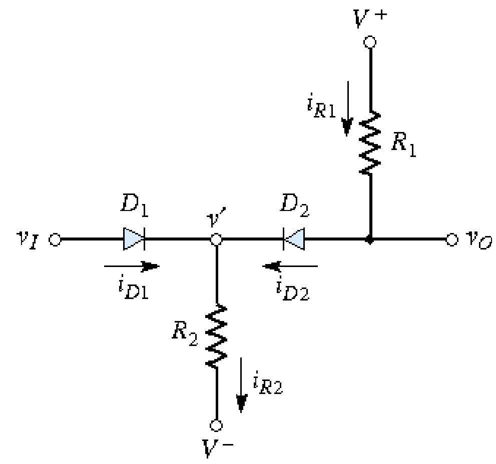


Figure 2.32 A two-diode circuit

Solution:

(1) $v_I = 0$

Assume D_1 off, D_2 on

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

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

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

The D_1 is indeed cut off, since $i_{D1} = 0$. Hence, the analysis is valid.

(2) $v_I = 4V$

Assume D_1 on, D_2 on $\Rightarrow$ $v_o = v_I = 4V$

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

$$v' = v_o - V_r = 4 - 0.7 = 3.3V$$

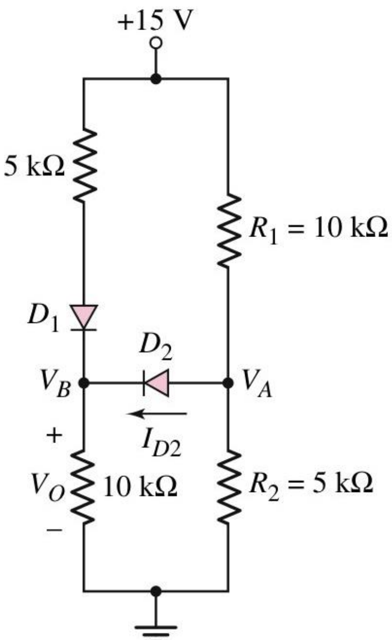
$$i_{R2} = \frac{v' - V^-}{R_2} = \frac{3.3 - (-5)}{10} = 0.83\,\text{mA}$$

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

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:



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:

Assume D_1 on & D_2 on

$$(a)\quad \frac{15-V_A}{10} = I_{D2} + \frac{V_A}{5}$$

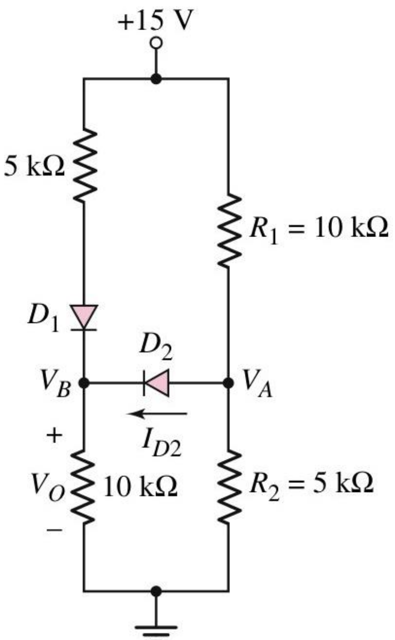
$$(b)\quad V_A = V_B + 0.7$$

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

$$\Rightarrow V_A = 7.62\,\text{V} \quad \text{and} \quad V_B = 6.92\,\text{V}$$

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

矛盾(假設“D_2 on”is incorrect)



Assume D_1 on & D_2 off

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

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

Hence, the diode D_2 is indeed reverse biased, and $I_{D2} = 0$.

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.

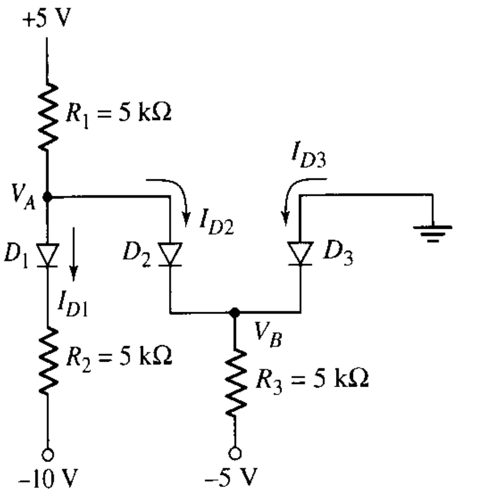


Figure 2.43 Diode circuit for Example 2.12

Solution:

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.

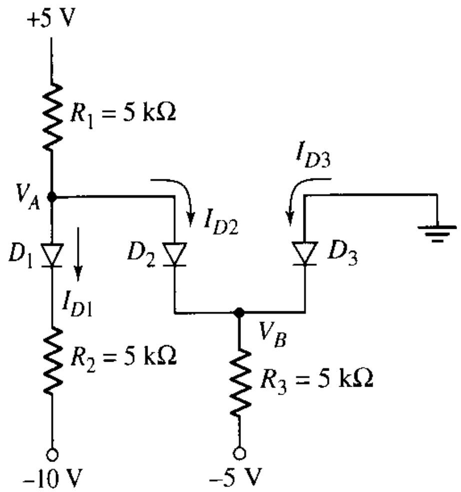


Figure 2.43 Diode circuit for Example 2.12

Solution:

(1) Assume D_1, D_2, D_3 are on

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

The current at the node:

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

Since $V_A = 0$, we obtain

$$\frac{5}{5} = I_{D2} + \frac{9.3}{5} \Rightarrow I_{D2} = -0.86\,\text{mA}$$ 矛盾(Assume D_2 is incorrect)

(2) Assume D_1 & D_3 are on, D_2 is off

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

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

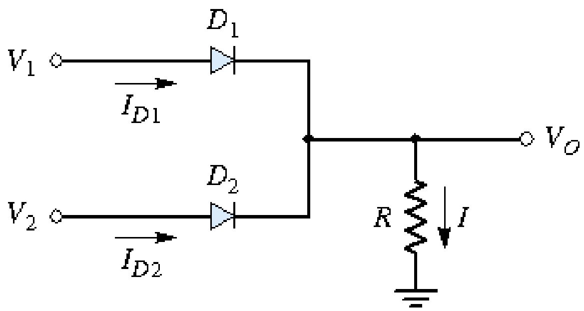


Figure 2.37 A two-input diode OR logic circuit

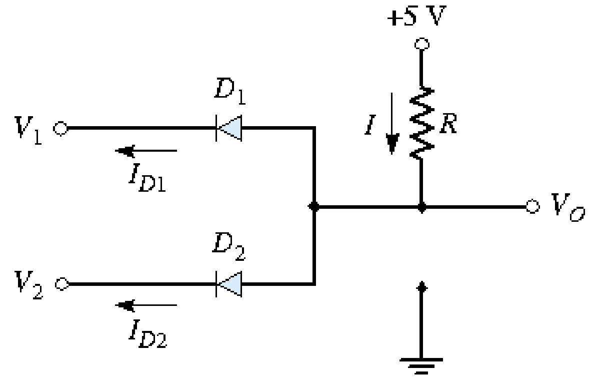


Figure 2.38 A two-input diode AND logic circuit

Table 2.1 Two-diode OR logic circuit response

	V_1(V)	V_2(V)	V_O(V)
D_1 off, D_2 off	0	0	0
D_1 on, D_2 off	5	0	4.3
D_1 off, D_2 on	0	5	4.3
D_1 on, D_2 on	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	D_1 on, D_2 on
5	0	0.7	D_1 off, D_2 on
0	5	0.7	D_1 on, D_2 off
5	5	5	D_1 off, D_2 off