9. Rectifier circuits can be used to charge batteries and to convert ac voltages into constant dc voltages. Half-wave rectifiers conduct current only for one polarity of the ac input, whereas full-wave circuits conduct for both polarities.

10. Wave-shaping circuits change the waveform of an input signal and deliver the modified waveform to the output terminals. Clipper circuits remove that portion of the input waveform above (or below) a given level. Clamp circuits add or subtract a dc voltage, so that the positive (or negative) peaks have a specified voltage.

11. The small-signal (incremental) equivalent circuit of a diode consists of a resistance. The value of the resistance depends on the operating point (Q point).

12. Dc sources and coupling capacitors are replaced by short circuits in small-signal ac equivalent circuits. Diodes are replaced with their dynamic resistances.

Problems

Section 10.1: Basic Diode Concepts

P10.1. Draw the circuit symbol for a diode, labeling the anode and cathode.

P10.2. Draw the volt–ampere characteristic of a typical diode and label the various regions.

P10.3. Describe a fluid-flow analogy for a diode.

P10.4. Write the Shockley equation and define all of the terms.

P10.5. Compute the values of V_T for temperatures of 20° C and 150° C.

P10.6. Sketch i versus v to scale for the circuits shown in Figure P10.6. The reverse-breakdown voltages of the Zener diodes are shown. Assume voltages of 0.6 V for all diodes including the Zener diodes when current flows in the forward direction.

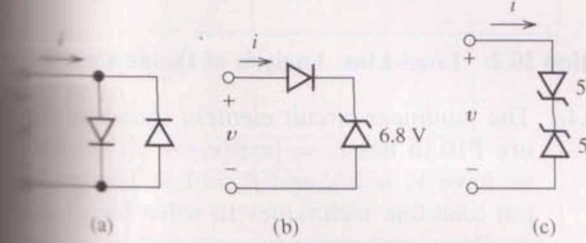


Figure P10.6

P10.7. Repeat Problem P10.6 for the circuits shown in Figure P10.7.

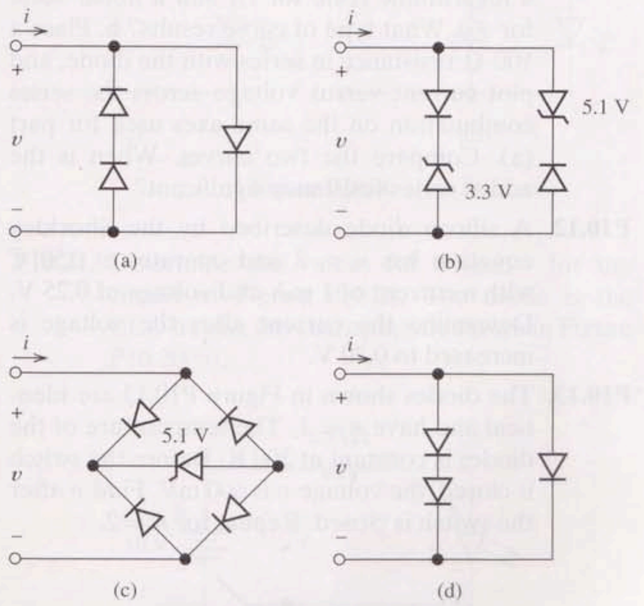


Figure P10.7

*__P10.8.__ A diode operates in forward bias and is described by Equation 10.4, with $V_T = 0.026$ V. For $v_{D1} = 0.600$ V, the current is $i_{D1} = 1$ mA. For $v_{D2} = 0.680$ V, the current is $i_{D2} = 10$ mA. Determine the values of I_s and n.

* Denotes that answers can be found on the OrCAD CD and on the website www.myengineeringlab.com

P10.9. With constant current flowing in the forward direction in a small-signal silicon diode, the voltage across the diode decreases with temperature by about 2 mV/K. Such a diode has a voltage of 0.650 V, with a current of 1 mA at a temperature of 25° C. Find the diode voltage at 1 mA and a temperature of 175° C.

P10.10. We have a junction diode that has $i_D = 0.2$ mA for $v_D = 0.6$ V. Assume that $n = 2$ and $V_T = 0.026$ V. Use the Shockley equation to compute the diode current at $v_D = 0.65$ V and at $v_D = 0.70$ V.

P10.11. We have a diode with $n = 1$, $I_s = 10^{-14}$ A, and $V_T = 26$ mV. **a.** Using a computer program of your choice, obtain a plot of i_D versus v_D for i_D ranging from 10 μA to 10 mA. Choose a logarithmic scale for i_D and a linear scale for v_D. What type of curve results? **b.** Place a 100-Ω resistance in series with the diode, and plot current versus voltage across the series combination on the same axes used for part (a). Compare the two curves. When is the added series resistance significant?

P10.12. A silicon diode described by the Shockley equation has $n = 2$ and operates at 150°C with a current of 1 mA and voltage of 0.25 V. Determine the current after the voltage is increased to 0.30 V.

*__P10.13.__ The diodes shown in Figure P10.13 are identical and have $n = 1$. The temperature of the diodes is constant at 300 K. Before the switch is closed, the voltage v is 600 mV. Find v after the switch is closed. Repeat for $n = 2$.

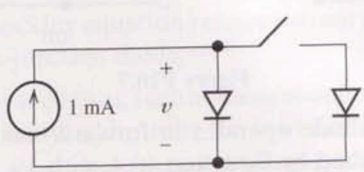


Figure P10.13

P10.14. Suppose we have a junction diode operating at a constant temperature of 300 K. With a forward current of 1 mA, the voltage is 600 mV. Furthermore, with a current of 10 mA, the voltage is 700 mV. Find the value of n for this diode.

*__P10.15.__ **Current hogging.** The diodes shown in Figure P10.15 are identical and have $n = 1$. For each diode, a forward current of 100 mA results in a voltage of 700 mV at a temperature of 300 K. **a.** If both diodes are at 300 K, what are the values of I_A and I_B? **b.** If diode A is at 300 K and diode B is at 305 K, again find I_A and I_B, given that I_s doubles in value for a 5-K increase in temperature. [*Hint:* Answer part (a) by use of symmetry. For part (b), a transcendental equation for the voltage across the diodes can be found. Solve by trial and error. An important observation to be made from this problem is that, starting at the same temperature, the diodes should theoretically each conduct half of the total current. However, if one diode conducts slightly more, it becomes warmer, resulting in even more current. Eventually, one of the diodes "hogs" most of the current. This is particularly noticeable for devices that are thermally isolated from one another with large currents, for which significant heating occurs.]

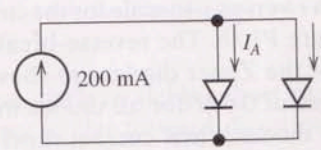


Figure P10.15

Section 10.2: Load-Line Analysis of Diode Circuits

*__P10.16.__ The nonlinear circuit element shown in Figure P10.16 has $i_x = [\exp(v_x) - 1]/10$. Also, we have $V_s = 3$ V and $R_s = 1$ Ω. Use graphical load-line techniques to solve for i_x and v_x. (You may prefer to use a computer program to plot the characteristic and the load line.)

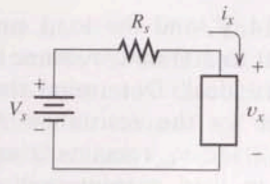


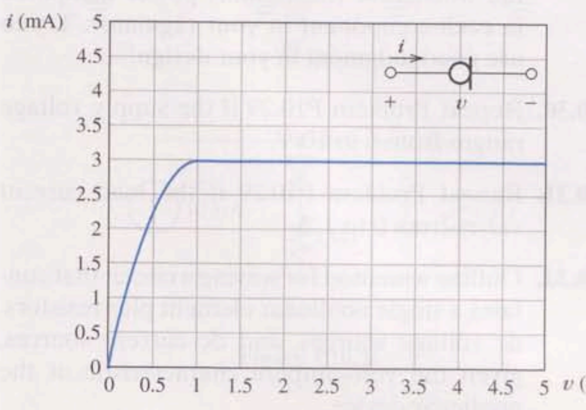
Figure P10.16

P10.17. Repeat Problem P10.16 for $V_s = 20$ V, $R_s = 5\text{ k}\Omega$, and $i_x = 0.01/(1 - v_x/5)^3$ mA.

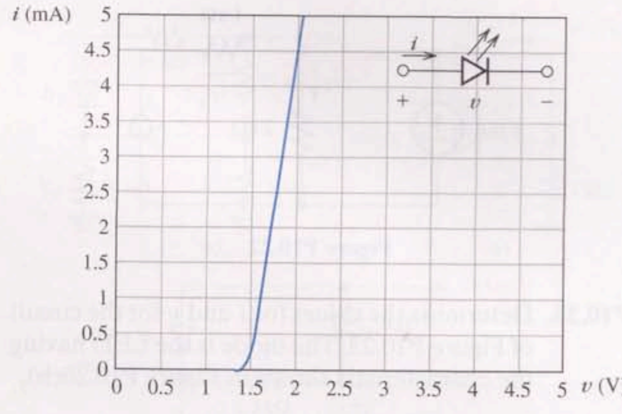
P10.18. Repeat Problem P10.16 for $V_s = 6$ V, $R_s = 3\ \Omega$, and $i_x = v_x^3/8$.

P10.19. Repeat Problem P10.16 for $V_s = 3$ V, $R_s = 1\ \Omega$, and $i_x = v_x + v_x^2$.

P10.20. Several types of special-purpose diodes exist. One is the constant-current diode for which the current is constant over a wide range of voltage. The circuit symbol and volt–ampere characteristic for a constant-current diode are shown in Figure P10.20(a). Another special type is the light-emitting diode (LED) for which the circuit symbol and a typical volt–ampere characteristic are shown in Figure P10.20(b). Sometimes, the series combination of these two devices is used to provide constant current to the LED from a variable voltage shown in Figure P10.20(c). **b.** Sketch the overall volt–ampere characteristic to scale for the parallel combination shown in Figure P10.20(d).



(a) Volt – ampere characteristic of a constant-current diode



(b) Volt – ampere characteristic of a light-emitting diode (LED).

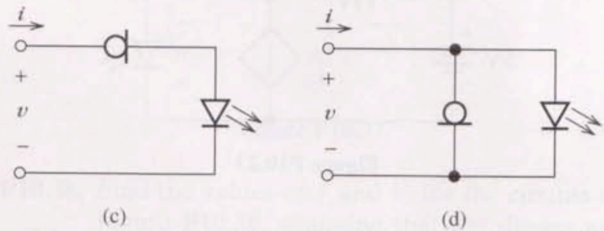


Figure P10.20

P10.21. Determine the values for i and v for the circuit of Figure P10.21. The diode is the LED having the characteristic shown in Figure P10.20(b).

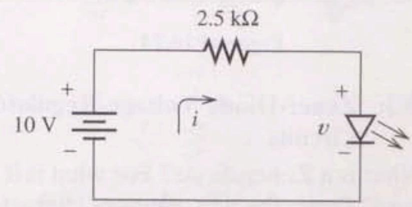


Figure P10.21

P10.22. Determine the values for i_1 and i_2 for the circuit of Figure P10.22. The device is the constant-current diode having the characteristic shown in Figure P10.20(a).

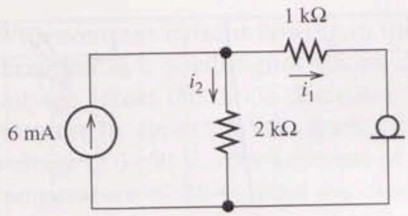


Figure P10.22

P10.23. Determine the values for i and v for the circuit of Figure P10.23. The diode is the LED having the characteristic shown in Figure P10.20(b).

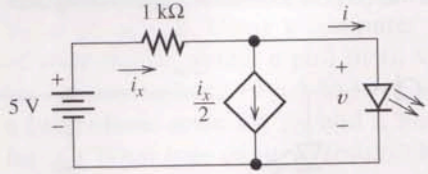


Figure P10.23

P10.24. Repeat Problem P10.23 for the circuit of Figure P10.24.

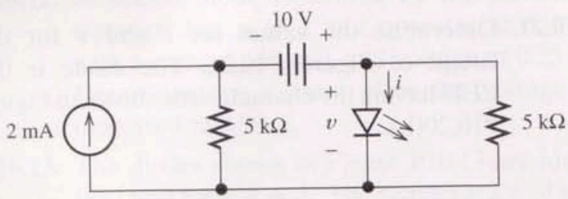


Figure P10.24

Section 10.3: Zener-Diode Voltage-Regulator Circuits

P10.25. What is a Zener diode? For what is it typically used? Draw the volt–ampere characteristic of an ideal 5.8-V Zener diode.

***P10.26.** Draw the circuit diagram of a simple voltage regulator.

P10.27. Consider the Zener-diode regulator shown in Figure 10.14 on page 479. What is the minimum load resistance for which v_o is 10 V?

P10.28. Consider the voltage regulator shown in Figure P10.28. The source voltage V_s varies from 10 to 14 V, and the load current i_L varies from 50 to 100 mA. Assume that the Zener diode is ideal. Determine the largest value allowed for the resistance R_s so that the load voltage v_L remains constant with variations in load current and source voltage. Determine the maximum power dissipation in R_s.

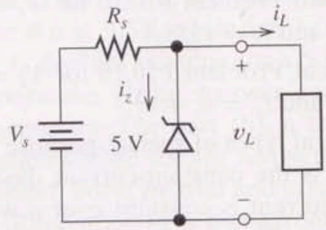


Figure P10.28

P10.29. Design a voltage-regulator circuit to provide a constant voltage of 5 V to a load from a variable supply voltage. The load current varies from 0 to 100 mA, and the source voltage varies from 8 to 10 V. You may assume that ideal Zener diodes are available. Resistors of any value may be specified. Draw the circuit diagram of your regulator, and specify the value of each component. Also, find the worst case (maximum) power dissipated in each component in your regulator. Try to use good judgment in your design.

P10.30. Repeat Problem P10.29 if the supply voltage ranges from 6 to 10 V.

P10.31. Repeat Problem P10.29 if the load current varies from 0 to 1 A.

P10.32. Outline a method for solving a circuit that contains a single nonlinear element plus resistors, dc voltage sources, and dc current sources, given the volt–ampere characteristic of the nonlinear device.

***P10.33.** A certain linear two-terminal circuit has terminals a and b. Under open-circuit conditions, we have $v_{ab} = 10$ V. A short circuit is connected across the terminals, and a current of 2 A flows from a to b through the short circuit. Determine the value of v_{ab} when a nonlinear element that has $i_{ab} = \sqrt[3]{v_{ab}}$ is connected across the terminals.

Section 10.4: Ideal-Diode Model

P10.34. What is an ideal diode? Draw its volt–ampere characteristic. After solving a circuit with ideal diodes, what check is necessary for diodes initially assumed to be on? Off?

P10.35. Two ideal diodes are placed in series, pointing in opposite directions. What is the equivalent circuit for the combination? What is the equivalent circuit if the diodes are in parallel and pointing in opposite directions?

P10.36. Find the values of I and V for the circuits of Figure P10.36, assuming that the diodes are ideal.

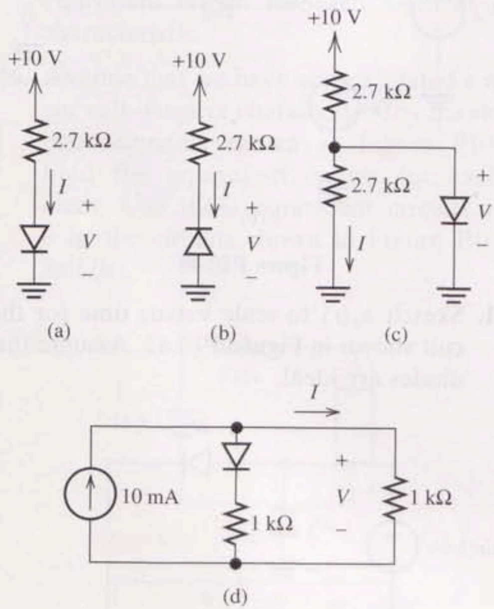


Figure P10.36

***P10.37.** Find the values of I and V for the circuits of Figure P10.37, assuming that the diodes are ideal.

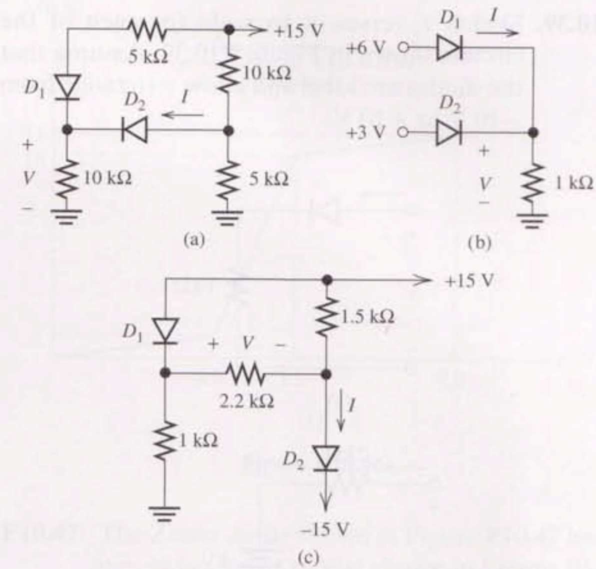


Figure P10.37

P10.38. Find the values of I and V for the circuits of Figure P10.38, assuming that the diodes are ideal. For part (b), consider $V_{in} = 0$, 2, 6, and 10 V. Also, for part (b) of the figure, plot V versus V_{in} for V_{in} ranging from −10 V to 10 V.

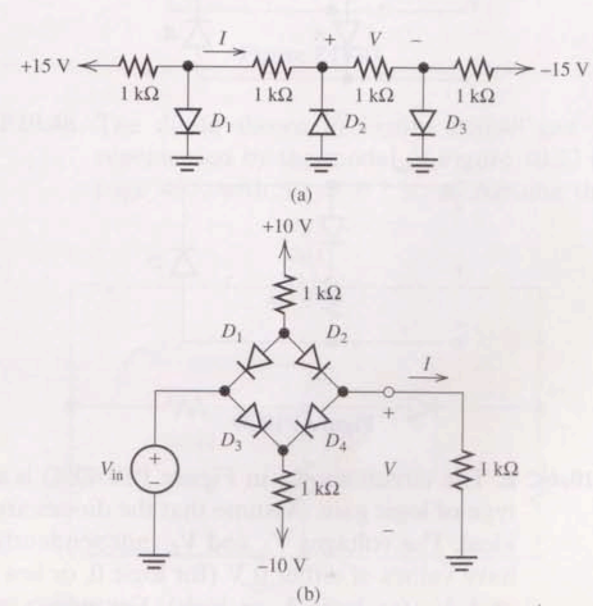


Figure P10.38

P10.39. Sketch i versus v to scale for each of the circuits shown in Figure P10.39. Assume that the diodes are ideal and allow v to range from -10 V to $+10$ V.

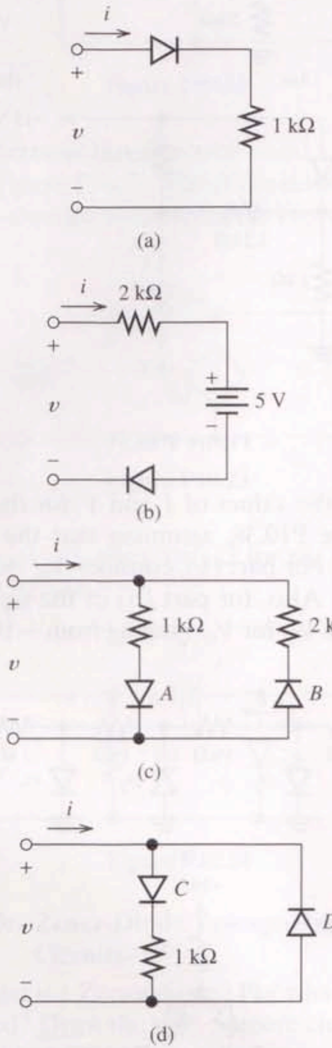


Figure P10.39

P10.40. **a.** The circuit shown in Figure P10.40(a) is a type of logic gate. Assume that the diodes are ideal. The voltages V_A and V_B independently have values of either 0 V (for logic 0, or low) or 5 V (for logic 1, or high). For which of the four combinations of input voltages is the output high (i.e., $V_o = 5$ V)? What type of logic gate is this? **b.** Repeat for the circuit of Figure P10.40(b).

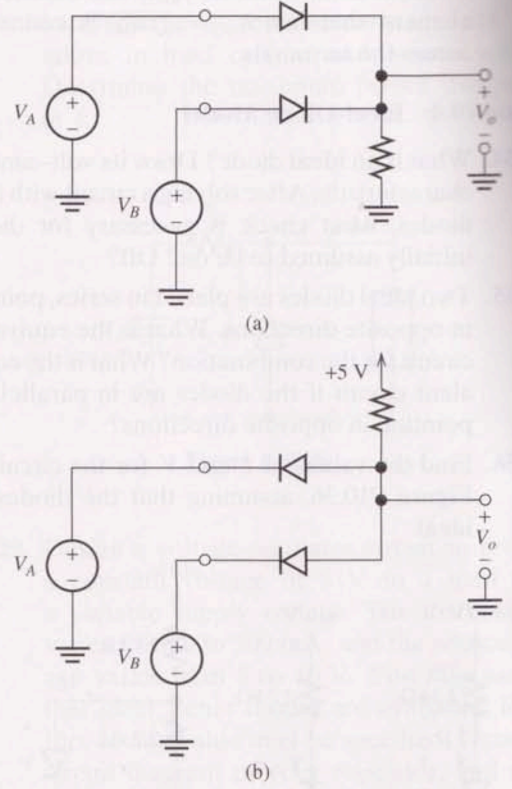


Figure P10.40

P10.41. Sketch $v_o(t)$ to scale versus time for the circuit shown in Figure P10.41. Assume that the diodes are ideal.

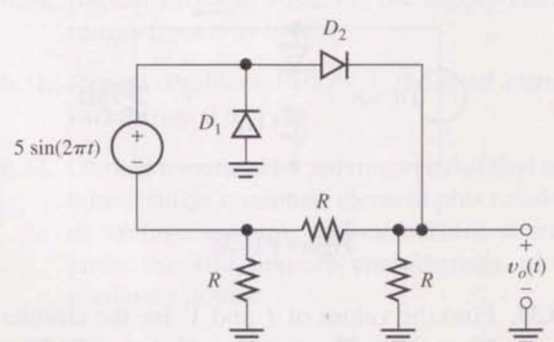


Figure P10.41

Section 10.5: Piecewise-Linear Diode Models

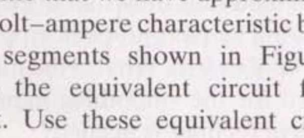
P10.42. If a nonlinear two-terminal device is modeled by the piecewise-linear approach, what is the equivalent circuit of the device for each linear segment?

P10.43. A resistor R_a is in series with a voltage source V_a. Draw the circuit. Label the voltage across the combination as v and the current as i. Draw and label the volt–ampere characteristic (i versus v).

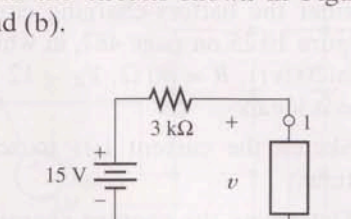
P10.44. The volt–ampere characteristic of a certain two-terminal device is a straight line that passes through the points (2 V, 5 mA) and (3 V, 15 mA). The current reference points into the positive reference for the voltage. Determine the equivalent circuit for this device.

P10.45. Consider the volt–ampere characteristic of an ideal 10-V Zener diode shown in Figure 10.14 on page 479. Determine the piecewise-linear equivalent circuit for each segment of the characteristic.

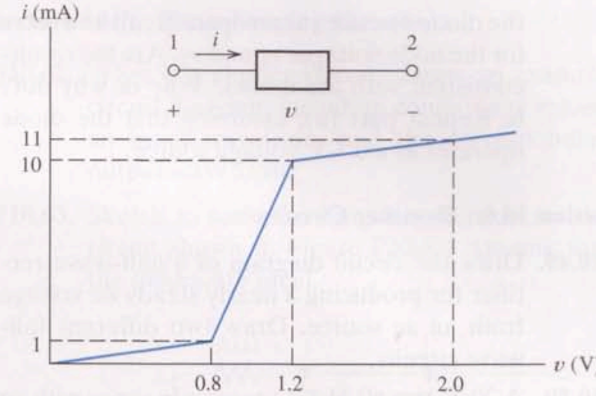
***P10.46.** Assume that we have approximated a nonlinear volt–ampere characteristic by the straight-line segments shown in Figure P10.46(c). Find the equivalent circuit for each segment. Use these equivalent circuits to find v in the circuits shown in Figure P10.46(a) and (b).



(a)



(b)



(c)

Figure P10.46

***P10.47.** The Zener diode shown in Figure P10.47 has a piecewise-linear model shown in Figure 10.19 on page 484. Plot load voltage v_L versus load current i_L for i_L ranging from 0 to 100 mA.

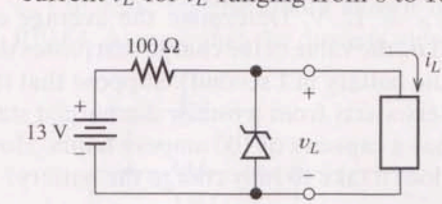


Figure P10.47

P10.48. The diode shown in Figure P10.48 can be represented by the model of Figure 10.23 on page 485, with $V_f = 0.7$ V. **a.** Assume that

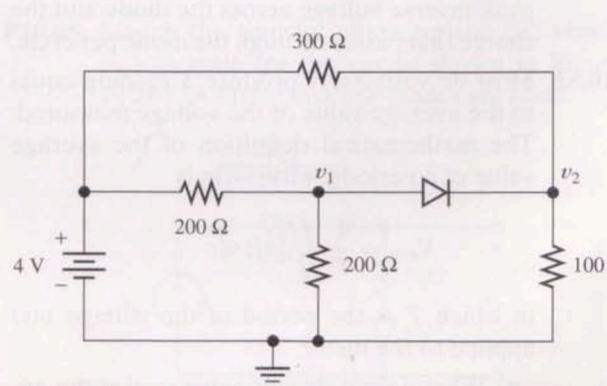


Figure P10.48

the diode operates as an open circuit and solve for the node voltages v_1 and v_2. Are the results consistent with the model? Why or why not?

b. Repeat part (a), assuming that the diode operates as a 0.7-V voltage source.

Section 10.6: Rectifier Circuits

P10.49. Draw the circuit diagram of a half-wave rectifier for producing a nearly steady dc voltage from an ac source. Draw two different full-wave circuits.

P10.50. A 20-V-rms 60-Hz ac source is in series with an ideal diode and a 100-Ω resistance. Determine the peak current and peak inverse voltage (PIV) for the diode.

P10.51. Consider the battery charging circuit shown in Figure 10.25 on page 487. The ac source has a peak value of 24 V and a frequency of 60 Hz. The resistance is 2 Ω, the diode is ideal, and $V_B = 12$ V. Determine the average current (i.e., the value of the charge that passes through the battery in 1 second). Suppose that the battery starts from a totally discharged state and has a capacity of 100 ampere hours. How long does it take to fully charge the battery?

P10.52. Consider the half-wave rectifier shown in Figure 10.26 on page 487. The ac source has an rms value of 20 V and a frequency of 60 Hz. The diodes are ideal, and the capacitance is very large, so the ripple voltage V_r is very small. The load is a 100-Ω resistance. Determine the peak inverse voltage across the diode and the charge that passes through the diode per cycle.

P10.53. Most dc voltmeters produce a reading equal to the average value of the voltage measured. The mathematical definition of the average value of a periodic waveform is

$$V_{\text{avg}} = \frac{1}{T}\int_0^T v(t)dt$$

in which T is the period of the voltage $v(t)$ applied to the meter.

a. What does a dc voltmeter read if the applied voltage is $v(t) = V_m \sin(\omega t)$?

b. What does the meter read if the applied voltage is a half-wave rectified version of the sinewave?

c. What does the meter read if the applied voltage is a full-wave rectified version of the sinewave?

***P10.54.** Design a half-wave rectifier power supply to deliver an average voltage of 9 V with a peak-to-peak ripple of 2 V to a load. The average load current is 100 mA. Assume that ideal diodes and 60-Hz ac voltage sources of any amplitudes needed are available. Draw the circuit diagram for your design. Specify the values of all components used.

P10.55. Repeat Problem P10.54 with a full-wave bridge rectifier.

P10.56. Repeat Problem P10.54 with two diodes and out-of-phase voltage sources to form a full-wave rectifier.

P10.57. Repeat Problem P10.54, assuming that the diodes have forward drops of 0.8 V.

***P10.58.** A half-wave rectifier is needed to supply 15-V dc to a load that draws an average current of 250 mA. The peak-to-peak ripple is required to be 0.2 V or less. What is the minimum value allowed for the smoothing capacitance? If a full-wave rectifier is needed?

P10.59. Consider the battery-charging circuit shown in Figure 10.25 on page 487, in which $v_s(t) = 20\sin(200\pi t)$, $R = 80$ Ω, $V_B = 12$ V, and the diode is ideal.

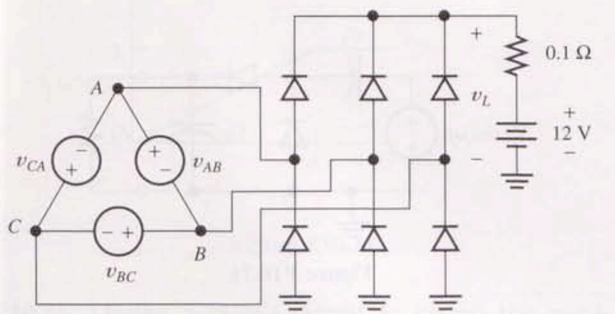
a. Sketch the current $i(t)$ to scale versus time.

b. Determine the average charging current for the battery.

(*Hint:* The average current is the charge that flows through the battery in one cycle, divided by the period.)

P10.60. **a.** Consider the full-wave rectifier shown in Figure 10.27 on page 489, with a large smoothing capacitance placed in parallel with the load R_L and $V_m = 12$ V. Assuming that the diodes are ideal, what is the approximate value of the load voltage? What peak inverse voltage (PIV) appears across the diodes? **b.** Repeat for the full-wave bridge shown in Figure 10.28 on page 490.

P10.61. Figure P10.61 shows the equivalent circuit for a typical automotive battery charging system. The three-phase delta-connected source represents the stator coils of the alternator. (Three-phase ac sources are discussed in Section 5.7. Actually, the alternator stator is usually wye connected, but the terminal voltages are the same as for the equivalent delta.) Not shown in the figure is a voltage regulator that controls the current applied to the rotor coil of the alternator and, consequently, V_m and the charging current to the battery. **a.** Sketch the load voltage $v_L(t)$ to scale versus time. Assume ideal diodes and that V_m is large enough that current flows into the battery at all times. (*Hint:* Each source and four of the diodes form a full-wave bridge rectifier.) **b.** Determine the peak-to-peak ripple and the average load voltage in terms of V_m. **c.** Determine the value of V_m needed to provide an average charging current of 30 A. **d.** What additional factors would need to be considered in a realistic computation of V_m?



$$v_{AB} = V_m \cos(\omega t)$$
$$v_{BC} = V_m \cos(\omega t - 120°)$$
$$v_{CA} = V_m \cos(\omega t + 120°)$$

Figure P10.61 Idealized model of an automotive battery-charging system.

Section 10.7: Wave-Shaping Circuits

P10.62. What is a clipper circuit? Draw an example circuit diagram, including component values, an input waveform, and the corresponding output waveform.

P10.63. Sketch to scale the output waveform for the circuit shown in Figure P10.63. Assume that the diodes are ideal.

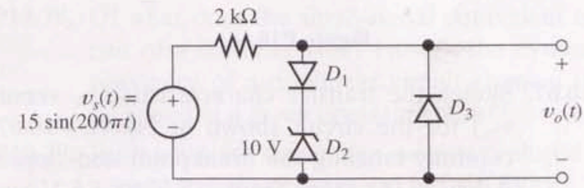


Figure P10.63

P10.64. Sketch the transfer characteristic (v_o versus v_{in}) to scale for the circuit shown in Figure P10.64. Assume that the diode is ideal.

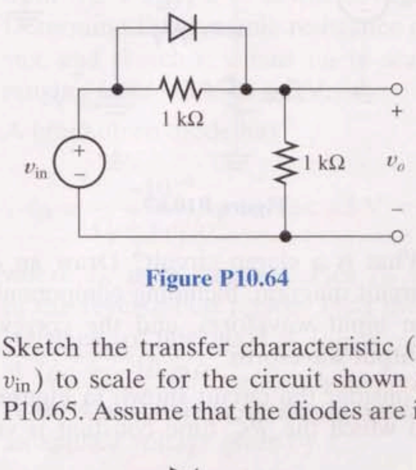


Figure P10.64

P10.65. Sketch the transfer characteristic (v_o versus v_{in}) to scale for the circuit shown in Figure P10.65. Assume that the diodes are ideal.

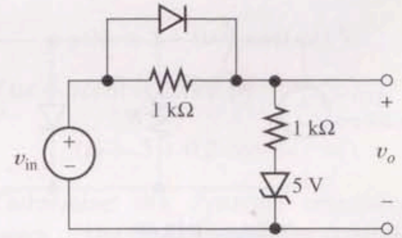


Figure P10.65

P10.66. Sketch the transfer characteristic (v_o versus v_{in}) to scale for the circuit shown in Figure P10.66. Allow v_{in} to range from −5 V to +5 V and assume that the diodes are ideal.

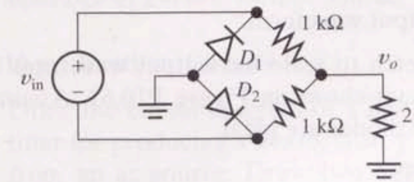


Figure P10.66

P10.67. Sketch the transfer characteristic (v_o versus v_{in}) for the circuit shown in Figure P10.67, carefully labeling the breakpoint and slopes. Allow v_{in} to range from −5 V to +5 V and assume that the diodes are ideal.

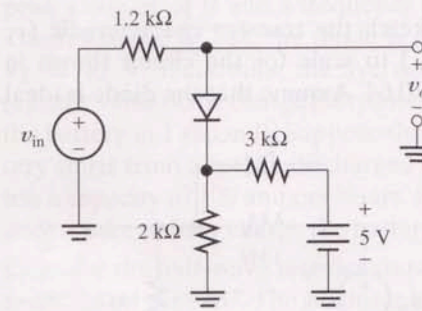


Figure P10.67

P10.68. What is a clamp circuit? Draw an example circuit diagram, including component values, an input waveform, and the corresponding output waveform.

P10.69. Consider the circuit shown in Figure P10.69, in which the RC time constant is very long compared with the period of the input and in which the diode is ideal. Sketch $v_o(t)$ to scale versus time.

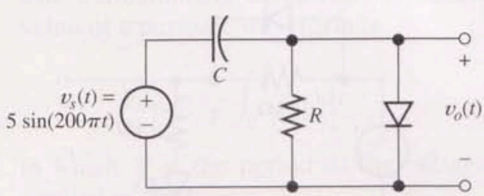


Figure P10.69

***P10.70.** Sketch to scale the steady-state output waveform for the circuit shown in Figure P10.70. Assume that RC is much larger than the period of the input voltage and that the diodes are ideal.

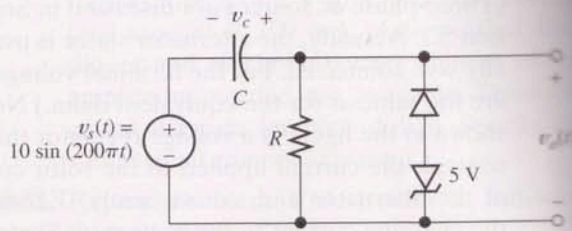


Figure P10.70

P10.71. Voltage-doubler circuit. Consider the circuit of Figure P10.71. The capacitors are very large, so they discharge only a very small amount per cycle. (Thus, no ac voltage appears across the capacitors, and the ac input plus the dc voltage of C_1 must appear at point A.) Sketch the voltage at point A versus time. Find the voltage across the load. Why is this called a voltage doubler? What is the peak inverse voltage across each diode?

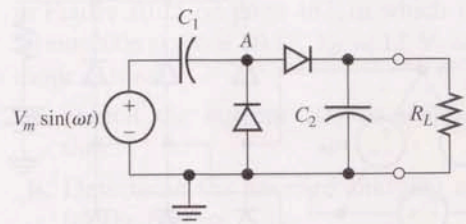


Figure P10.71

***P10.72.** Design a clipper circuit to clip off the portions of an input voltage that fall above 3 V or below −5 V. Assume that diodes having a constant forward drop of 0.7 V are available. Ideal Zener diodes of any breakdown voltage required are available. Dc voltage sources of any value needed are available.

P10.73. Repeat Problem P10.72, with clipping levels of +2 V and +5 V (i.e., every part of the input waveform below +2 or above +5 is clipped off).

P10.74. Design circuits that have the transfer characteristics shown in Figure P10.74. Assume that v_{in} ranges from −10 to +10 V. Use diodes, Zener diodes, and resistors of any values needed. Assume a 0.6-V forward drop for all diodes and that the Zener diodes have an ideal characteristic in the breakdown region. Power-supply voltages of ±15 V are available.

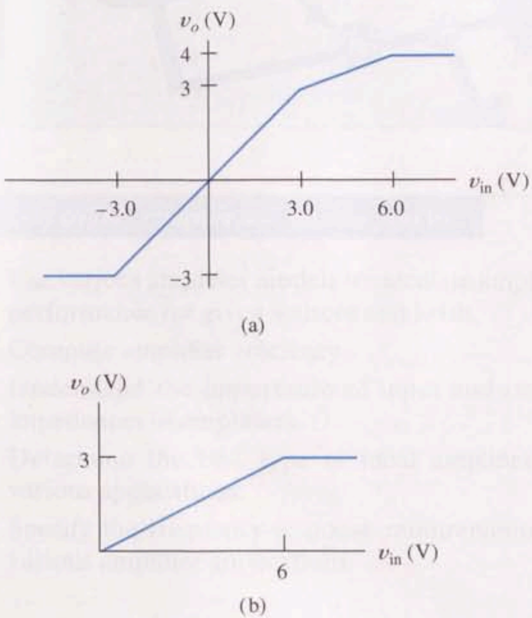


Figure P10.74

***P10.75.** Design a clamp circuit to clamp the negative extreme of a periodic input waveform to −5 V. Use diodes, Zener diodes, and resistors of any values required. Assume a 0.6-V forward drop for all diodes and that the Zener diodes have an ideal characteristic in the breakdown region. Power-supply voltages of ±15 V are available.

P10.76. Repeat Problem P10.75 for a clamp voltage of +5 V.

Section 10.8: Linear Small-Signal Equivalent Circuits

P10.77. A certain diode has $I_{DQ} = 4$ mA and $i_d(t) = 0.5\cos(200\pi t)$ mA. Find an expression for $i_D(t)$, and sketch it to scale versus time.

P10.78. Of what does the small-signal equivalent circuit of a diode consist? How is the dynamic resistance of a nonlinear circuit element determined at a given operating point?

P10.79. With what are dc voltage sources replaced in a small-signal ac equivalent circuit? Why?

P10.80. With what should we replace a dc current source in a small-signal ac equivalent circuit? Justify your answer.

***P10.81.** A certain nonlinear device has $i_D = v_D^3/8$. Sketch i_D versus v_D to scale for v_D ranging from −2 V to +2 V. Is this device a diode? Determine the dynamic resistance of the device and sketch it versus v_D to scale for v_D ranging from −2 V to +2 V.

P10.82. A breakdown diode has

$$i_D = \frac{-10^{-6}}{(1 + v_D/5)^3} \quad \text{for } -5\text{ V} < v_D < 0$$

where i_D is in amperes. Plot i_D versus v_D in the reverse-bias region. Find the dynamic resistance of this diode at $I_{DQ} = -1$ mA and at $I_{DQ} = -10$ mA.

P10.83. A certain nonlinear device is operating with an applied voltage given by

$$v_D(t) = 5 + 0.01\cos(\omega t)\text{ V}$$

The current is given by

$$i_D(t) = 3 + 0.2\cos(\omega t)\text{ mA}$$

Determine the dynamic resistance and Q point of the device under the conditions given.