- In many applications, a conducting diode is modeled as having a constant voltage drop, usually approximately 0.7 V.

- A diode biased to operate at a dc current I_D has a small-signal resistance $r_d = V_T/I_D$.

- Rectifiers convert ac voltages into unipolar voltages. Half-wave rectifiers do this by passing the voltage in half of each cycle and blocking the opposite-polarity voltage in the other half of the cycle. Full-wave rectifiers accomplish the task by passing the voltage in half of each cycle and inverting the voltage in the other half-cycle.

- The bridge-rectifier circuit is the preferred full-wave rectifier configuration.

- The variation of the output waveform of the rectifier is reduced considerably by connecting a capacitor C across the output load resistance R. The resulting circuit is the peak rectifier. The output waveform then consists of a dc voltage almost equal to the peak of the input sine wave, V_p, on which is superimposed a ripple component of frequency $2f$ (in the full-wave case) and of peak-to-peak amplitude $V_r = V_p/2fCR$. To reduce this ripple voltage further, a voltage regulator is employed.

- Combination of diodes, resistors, and possibly reference voltages can be used to design voltage limiters that prevent one or both extremities of the output waveform from going beyond predetermined values, the limiting level(s).

- Applying a time-varying waveform to a circuit consisting of a capacitor in series with a diode and taking the output across the diode provides a clamping function. Specifically, depending on the polarity of the diode, either the positive or negative peaks of the signal will be clamped to the voltage at the other terminal of the diode (usually ground). In this way the output waveform has a nonzero average or dc component, and the circuit is known as a dc restorer.

- By cascading a clamping circuit with a peak-rectifier circuit, a voltage doubler is realized.

PROBLEMS

Computer Simulation Problems

SIM Problems identified by the Multisim/PSpice icon are intended to demonstrate the value of using SPICE simulation to verify hand analysis and design, and to investigate important issues such as allowable signal swing and amplifier nonlinear distortion. Instructions to assist in setting up PSPice and Multisim simulations for all the indicated problems can be found in the corresponding files on the website. Note that if a particular parameter value is not specified in the problem statement, you are to make a reasonable assumption.

Section 4.1: The Ideal Diode

4.1 An AA flashlight cell, whose Thévenin equivalent is a voltage source of 1.5 V and a resistance of 1 Ω, is connected to the terminals of an ideal diode. Describe two possible situations that result. What are the diode current and terminal voltage when (a) the connection is between the diode cathode and the positive terminal of the battery and (b) the anode and the positive terminal are connected?

4.2 For the circuits shown in Fig. P4.2 using ideal diodes, find the values of the voltages and currents indicated.

4.3 For the circuits shown in Fig. P4.3 using ideal diodes, find the values of the labeled voltages and currents.

4.4 In each of the ideal-diode circuits shown in Fig. P4.4, v_I is a 1-kHz, 5-V peak sine wave. Sketch the waveform resulting at v_O. What are its positive and negative peak values?

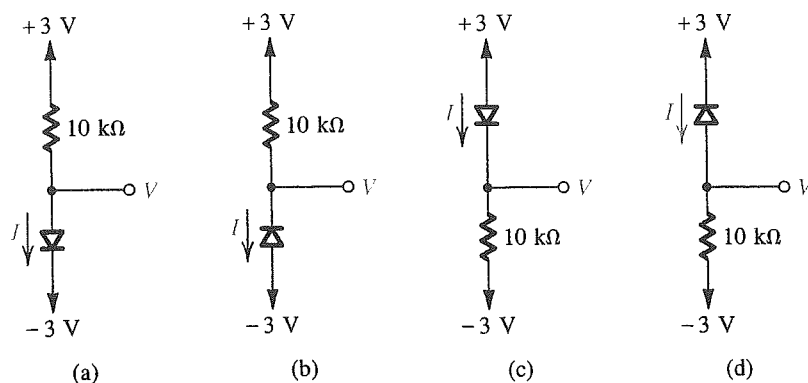**SIM** = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem
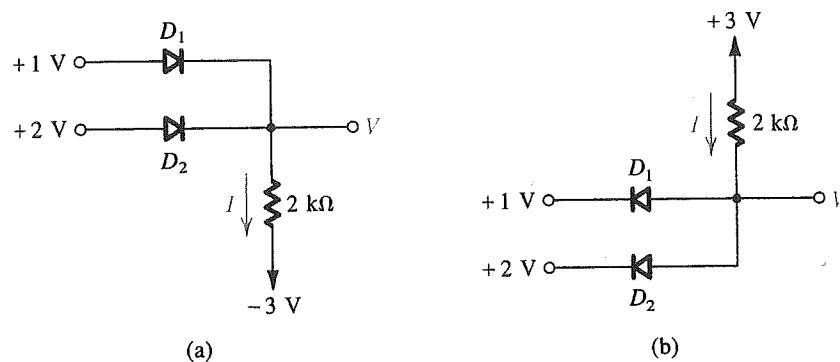
(a)   (b)   (c)   (d)

Figure P4.2

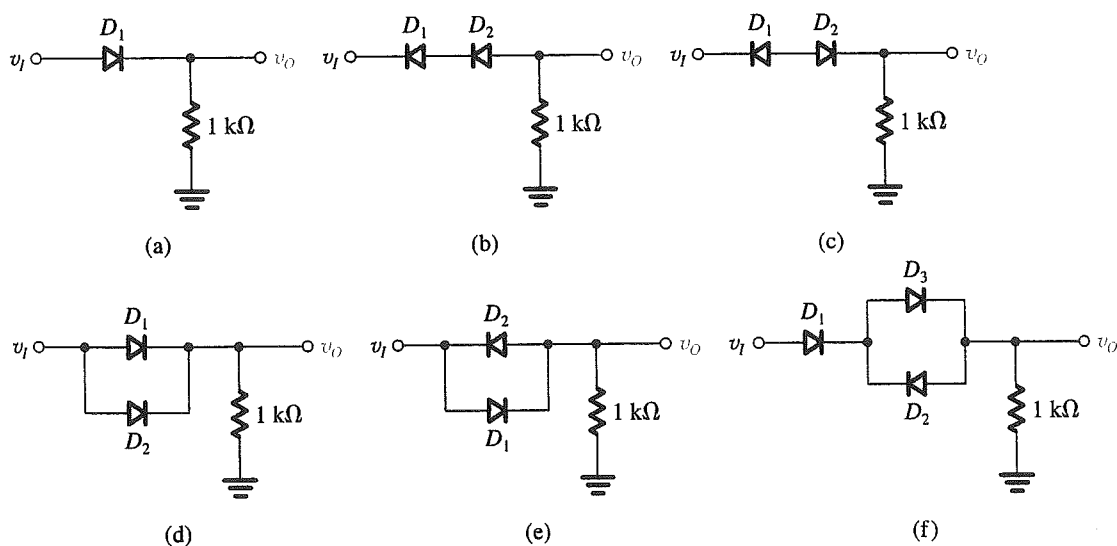

(a)   (b)

Figure P4.3

(a)   (b)   (c)

(d)   (e)   (f)

Figure P4.4

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem
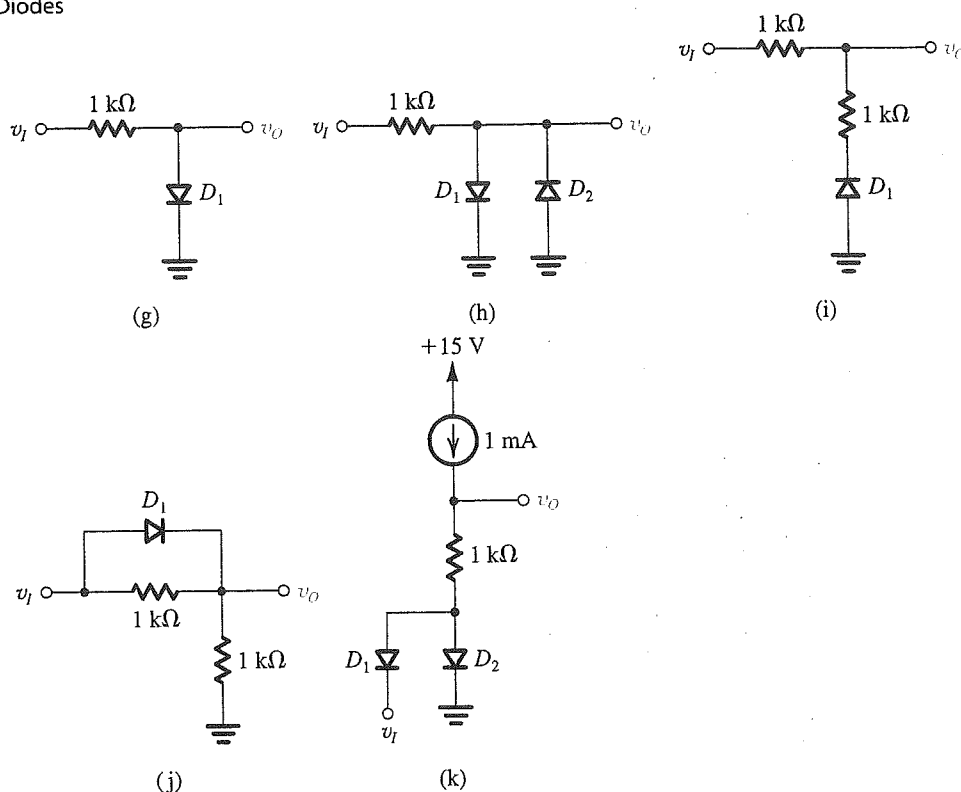
(g)

(h)

(i)

(j)

(k)

Figure P4.4 *continued*

4.5 The circuit shown in Fig. P4.5 is a model for a battery charger. Here v_I is a 6-V peak sine wave, D_1 and D_2 are ideal diodes, I is a 60-mA current source, and B is a 3-V battery. Sketch and label the waveform of the battery current i_B. What is its peak value? What is its average value? If the peak value of v_I is reduced by 10%, what do the peak and average values of i_B become?
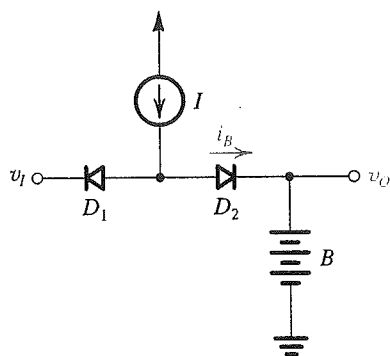
4.6 The circuits shown in Fig. P4.6 can function as logic gates for input voltages that are either high or low. Using "1" to denote the high value and "0" to denote the low value, prepare a table with four columns including all possible input combinations and the resulting values of X and Y. What logic function is X of A and B? What logic function is Y of A and B? For what values of A and B do X and Y have the same value? For what values of A and B do X and Y have opposite values?
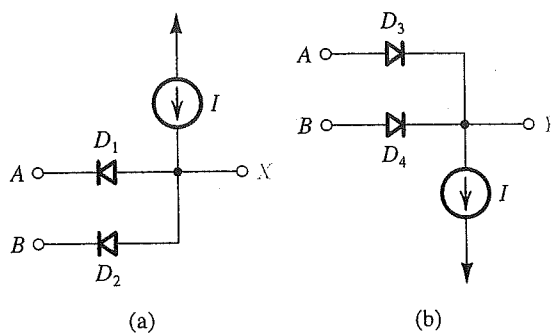

Figure P4.5

(a)

(b)

Figure P4.6

D 4.7 For the logic gate of Fig. 4.5(a), assume ideal diodes and input voltage levels of 0 V and +5 V. Find a suitable value for R so that the current required from each of the input signal sources does not exceed 0.2 mA.

D 4.8 Repeat Problem 4.7 for the logic gate of Fig. 4.5(b).

4.9 Assuming that the diodes in the circuits of Fig. P4.9 are ideal, find the values of the labeled voltages and currents.
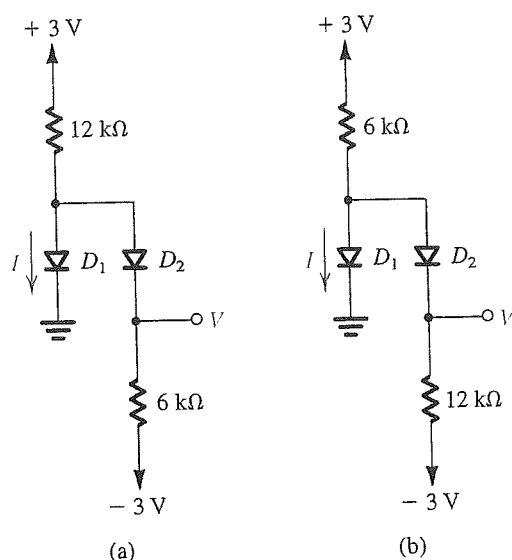

(a)   (b)

Figure P4.9

4.10 Assuming that the diodes in the circuits of Fig. P4.10 are ideal, utilize Thévenin's theorem to simplify the circuits and thus find the values of the labeled currents and voltages.
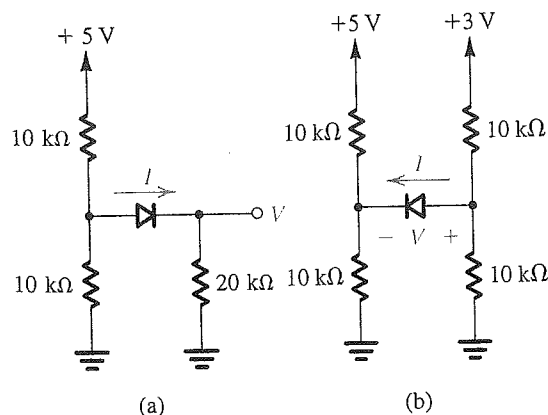

(a)   (b)

Figure P4.10

D 4.11 For the rectifier circuit of Fig. 4.3(a), let the input sine wave have 120-V rms value and assume the diode to be ideal. Select a suitable value for R so that the peak diode current does not exceed 40 mA. What is the greatest reverse voltage that will appear across the diode?

4.12 Consider the rectifier circuit of Fig. 4.3(a) in the event that the input source v_I has a source resistance R_s. For the case $R_s = R$ and assuming the diode to be ideal, sketch and clearly label the transfer characteristic v_O versus v_I.

4.13 A symmetrical square wave of 5-V peak-to-peak amplitude and zero average is applied to a circuit resembling that in Fig. 4.3(a) and employing a 100-Ω resistor. What is the peak output voltage that results? What is the average output voltage that results? What is the peak diode current? What is the average diode current? What is the maximum reverse voltage across the diode?

4.14 Repeat Problem 4.13 for the situation in which the average voltage of the square wave is 1 V, while its peak-to-peak value remains at 5 V.

D *4.15 Design a battery-charging circuit, resembling that in Fig. 4.4(a) and using an ideal diode, in which current flows to the 12-V battery 25% of the time with an average value of 100 mA. What peak-to-peak sine-wave voltage is required? What resistance is required? What peak diode current flows? What peak reverse voltage does the diode endure? If resistors can be specified to only one significant digit, and the peak-to-peak voltage only to the nearest volt, what design would you choose to guarantee the required charging current? What fraction of the cycle does diode current flow? What is the average diode current? What is the peak diode current? What peak reverse voltage does the diode endure?

4.16 The circuit of Fig. P4.16 can be used in a signaling system using one wire plus a common ground return. At any moment, the input has one of three values: +3 V, 0 V, –3 V.
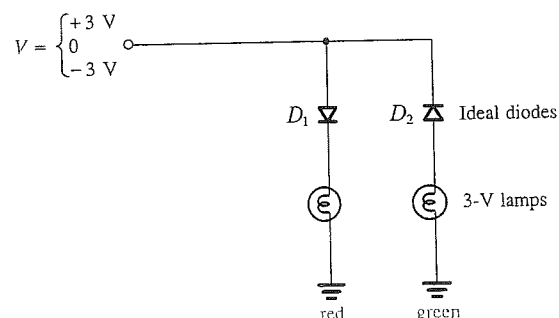

Figure P4.16

What is the status of the lamps for each input value? (Note that the lamps can be located apart from each other and that there may be several of each type of connection, all on one wire!)

Section 4.2: Terminal Characteristics of Junction Diodes

4.17 Calculate the value of the thermal voltage, V_T, at −55°C, 0°C, +40°C, and +125°C. At what temperature is V_T exactly 25 mV?

4.18 At what forward voltage does a diode conduct a current equal to $10,000 I_S$? In terms of I_S, what current flows in the same diode when its forward voltage is 0.7 V?

4.19 A diode for which the forward voltage drop is 0.7 V at 1.0 mA is operated at 0.5 V. What is the value of the current?

4.20 A particular diode is found to conduct 1 mA with a junction voltage of 0.7 V. What current will flow in this diode if the junction voltage is raised to 0.71 V? To 0.8 V? If the junction voltage is lowered to 0.69 V? To 0.6 V? What change in junction voltage will increase the diode current by a factor of 10?

4.21 The following measurements are taken on particular junction diodes for which V is the terminal voltage and I is the diode current. For each diode, estimate values of I_S and the terminal voltage at 10% of the measured current.

(a) $V = 0.700$ V at $I = 1.00$ A
(b) $V = 0.650$ V at $I = 1.00$ mA
(c) $V = 0.650$ V at $I = 10$ μA
(d) $V = 0.700$ V at $I = 100$ mA

4.22 Listed below are the results of measurements taken on several different junction diodes. For each diode, the data provided are the diode current I and the corresponding diode voltage V. In each case, estimate I_S, and the diode voltage at $10I$ and $I/10$.

(a) 10.0 mA, 700 mV
(b) 1.0 mA, 700 mV
(c) 10 A, 800 mV
(d) 1 mA, 700 mV
(e) 10 μA, 600 mV

4.23 The circuit in Fig. P4.23 utilizes three identical diodes having $I_S = 10^{-14}$ A. Find the value of the current I required to obtain an output voltage $V_O = 2.0$ V. If a current of 1 mA is drawn away from the output terminal by a load, what is the change in output voltage?
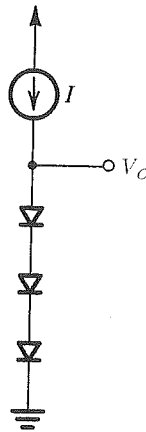

Figure P4.23

4.24 A junction diode is operated in a circuit in which it is supplied with a constant current I. What is the effect on the forward voltage of the diode if an identical diode is connected in parallel?

4.25 Two diodes with saturation currents I_{S1} and I_{S2} are connected in parallel with their cathodes joined together and connected to grounds. The two anodes are joined together and fed with a constant current I. Find the currents I_{D1} and I_{D2} that flow through the two diodes, and the voltage V_D that appears across their parallel combination.

4.26 Four diodes are connected in parallel: anodes joined together and fed with a constant current I, and cathodes joined together and connected to ground. What relative junction areas should these diodes have if their currents must have binary-weighted ratios, with the smallest being 0.1 mA? What value of I is needed?

4.27 In the circuit shown in Fig. P4.27, D_1 has 10 times the junction area of D_2. What value of V results? To obtain a value for V of 60 mV, what current I_2 is needed?
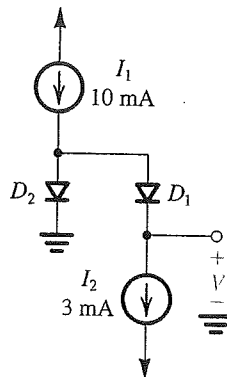

Figure P4.27

4.28 For the circuit shown in Fig. P4.28, both diodes are identical. Find the value of R for which $V = 50$ mV.
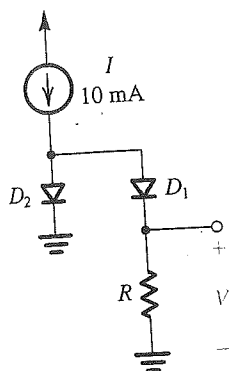

Figure P4.28

4.29 A diode fed with a constant current $I = 1$ mA has a voltage $V = 690$ mV at 20°C. Find the diode voltage at −20°C and at +85°C.

4.30 In the circuit shown in Fig. P4.30, D_1 is a large-area, high-current diode whose reverse leakage is high and independent of applied voltage, while D_2 is a much smaller, low-current diode. At an ambient temperature of 20°C, resistor R_1 is adjusted to make $V_{R1} = V_2 = 520$ mV. Subsequent measurement indicates that R_1 is 520 kΩ. What do you expect the voltages V_{R1} and V_2 to become at 0°C and at 40°C?
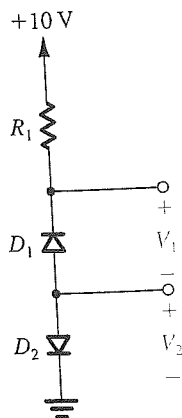

Figure P4.30

4.31 When a 10-A current is applied to a particular diode, it is found that the junction voltage immediately becomes 700 mV. However, as the power being dissipated in the diode raises its temperature, it is found that the voltage decreases and eventually reaches 600 mV. What is the apparent rise in junction temperature? What is the power dissipated in the diode in its final state? What is the temperature rise per watt of power dissipation? (This is called the thermal resistance.)

*4.32 A designer of an instrument that must operate over a wide supply-voltage range, noting that a diode's junction-voltage drop is relatively independent of junction current, considers the use of a large diode to establish a small relatively constant voltage. A power diode, for which the nominal current at 0.8 V is 10 A, is available. If the current source feeding the diode changes in the range 1 mA to 3 mA and if, in addition, the temperature changes by ±20°C, what is the expected range of diode voltage?

*4.33 As an alternative to the idea suggested in Problem 4.32, the designer considers a second approach to producing a relatively constant small voltage from a variable current supply: It relies on the ability to make quite accurate copies of any small current that is available (using a process called current mirroring). The designer proposes to use this idea to supply two diodes of different junction areas with equal currents and to measure their junction-voltage difference. Two types of diodes are available: for a forward voltage of 700 mV, one conducts 0.1 mA, while the other conducts 1 A. Now, for identical currents in the range of 1 mA to 3 mA supplied to each, what range of difference voltages result? What is the effect of a temperature change of ±20°C on this arrangement?

Section 4.3: Modeling the Diode Forward Characteristic

*4.34 Consider the graphical analysis of the diode circuit of Fig. 4.10 with $V_{DD} = 1$ V, $R = 1$ kΩ, and a diode having $I_S = 10^{-15}$ A. Calculate a small number of points on the diode characteristic in the vicinity of where you expect the load line to intersect it, and use a graphical process to refine your estimate of diode current. What value of diode current and voltage do you find? Analytically, find the voltage corresponding to your estimate of current. By how much does it differ from the graphically estimated value?

4.35 Use the iterative-analysis procedure to determine the diode current and voltage in the circuit of Fig. 4.10 for $V_{DD} = 1$ V, $R = 1$ kΩ, and a diode having $I_S = 10^{-15}$ A.

4.36 A "1-mA diode" (i.e., one that has $v_D = 0.7$ V at $i_D = 1$ mA) is connected in series with a 500-Ω resistor to a 1.0 V supply.

(a) Provide a rough estimate of the diode current you would expect.

(b) Estimate the diode current more closely using iterative analysis.

D 4.37 Assuming the availability of diodes for which $v_D = 0.75$ V at $i_D = 1$ mA, design a circuit that utilizes four diodes connected in series, in series with a resistor R connected to a 15-V power supply. The voltage across the string of diodes is to be 3.3 V.

4.38 A diode operates in a series circuit with a resistance R and a dc source V. A designer, considering using a constant-voltage model, is uncertain whether to use 0.7 V or 0.6 V for V_D. For what value of V is the difference in the calculated values of current only 1%? For $V = 3$ V and $R = 1$ kΩ, what two current estimates would result from the use of the two values of V_D? What is their percentage difference?

4.39 A designer has a supply of diodes for which a current of 2 mA flows at 0.7 V. Using a 1-mA current source, the designer wishes to create a reference voltage of 1.3 V. Suggest a combination of series and parallel diodes that will do the job as well as possible. How many diodes are needed? What voltage is actually achieved?

4.40 Solve the problems in Example 4.2 using the constant-voltage-drop ($V_D = 0.7$ V) diode model.

4.41 For the circuits shown in Fig. P4.2, using the constant-voltage-drop ($V_D = 0.7$ V) diode model, find the voltages and currents indicated.

4.42 For the circuits shown in Fig. P4.3, using the constant-voltage-drop ($V_D = 0.7$ V) diode model, find the voltages and currents indicated.

4.43 For the circuits in Fig. P4.9, using the constant-voltage-drop ($V_D = 0.7$ V) diode model, find the values of the labeled currents and voltages.

4.44 For the circuits in Fig. P4.10, utilize Thévenin's theorem to simplify the circuits and find the values of the labeled currents and voltages. Assume that conducting diodes can be represented by the constant-voltage-drop model ($V_D = 0.7$ V).

D 4.45 Repeat Problem 4.11, representing the diode by the constant-voltage-drop ($V_D = 0.7$ V) model. How different is the resulting design?

4.46 The small-signal model is said to be valid for voltage variations of about 5 mV. To what percentage current change does this correspond? (Consider both positive and negative signals.) What is the maximum allowable voltage signal (positive or negative) if the current change is to be limited to 10%?

4.47 In a particular circuit application, ten "20-mA diodes" (a 20-mA diode is a diode that provides a 0.7-V drop when the current through it is 20 mA) connected in parallel operate at a total current of 0.1 A. For the diodes closely matched, what current flows in each? What is the corresponding small-signal resistance of each diode and of the combination? Compare this with the incremental resistance of a single diode conducting 0.1 A. If each of the 20-mA diodes has a series resistance of 0.2 Ω associated with the wire bonds to the junction, what is the equivalent resistance of the 10 parallel-connected diodes? What connection resistance would a single diode need in order to be totally equivalent? (*Note:* This is why the parallel connection of real diodes can often be used to advantage.)

4.48 In the circuit shown in Fig. P4.48, I is a dc current and v_s is a sinusoidal signal. Capacitors C_1 and C_2 are very large; their function is to couple the signal to and from the diode but block the dc current from flowing into the signal source or the load (not shown). Use the diode small-signal model to show that the signal component of the output voltage is

$$v_o = v_s \frac{V_T}{V_T + IR_s}$$

If $v_s = 10$ mV, find v_o for $I = 1$ mA, 0.1 mA, and 1 μA. Let $R_s = 1$ kΩ. At what value of I does v_o become one-half of v_s? Note that this circuit functions as a signal attenuator with the attenuation factor controlled by the value of the dc current I.
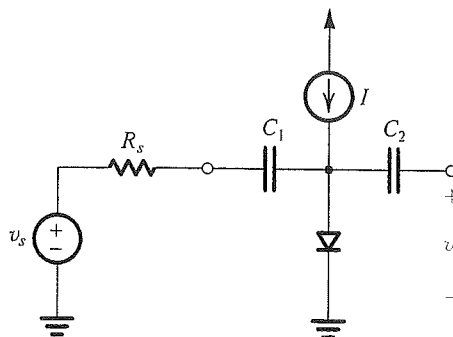

Figure P4.48

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

4.49 In the attenuator circuit of Fig. P4.48, let $R_s = 10\ \text{k}\Omega$. The diode is a 1-mA device; that is, it exhibits a voltage drop of 0.7 V at a dc current of 1 mA. For small input signals, what value of current I is needed for $v_o/v_s = 0.50$? 0.10? 0.01? 0.001? In each case, what is the largest input signal that can be used while ensuring that the signal component of the diode current is limited to ±10% of its dc current? What output signals correspond?

4.50 In the capacitor-coupled attenuator circuit shown in Fig. P4.50, I is a dc current that varies from 0 mA to 1 mA, and C_1 and C_2 are large coupling capacitors. For very small input signals, so that the diodes can be represented by their small-signal resistances r_{d1} and r_{d2}, give the small-signal equivalent circuit and thus show that $\dfrac{v_o}{v_i} = \dfrac{r_{d2}}{r_{d1} + r_{d2}}$ and hence that $\dfrac{v_o}{v_i} = I$, where I is in mA. Find v_o/v_i for $I = 0\ \mu\text{A}$, 1 μA, 10 μA, 100 μA, 500 μA, 600 μA, 900 μA, 990 μA, and 1 mA. Note that this is a signal attenuator whose transmission is linearly controlled by the dc current I.
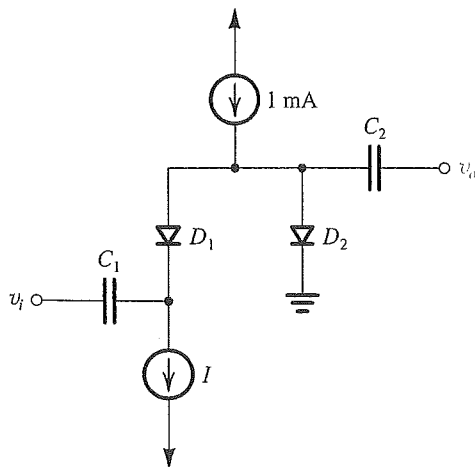

Figure P4.50

*4.51 In the circuit shown in Fig. P4.51, diodes D_1 through D_4 are identical, and each exhibits a voltage drop of 0.7 V at a 1-mA current.

(a) For small input signals (e.g., 10-mV peak), find the small-signal equivalent circuit and use it to determine values of the small-signal transmission v_o/v_i for various values of I: 0 μA, 1 μA, 10 μA, 100 μA, 1 mA, and 10 mA.

(b) For a forward-conducting diode, what is the largest signal-voltage magnitude that it can support while the corresponding signal current is limited to 10% of the dc bias current? Now, for the circuit in Fig. P4.51, for 10-mV peak input, what is the smallest value of I for which the diode currents remain within ±10% of their dc values?

(c) For $I = 1$ mA, what is the largest possible output signal for which the diode currents deviate by at most 10% of their dc values? What is the corresponding peak input? What is the total current in each diode?
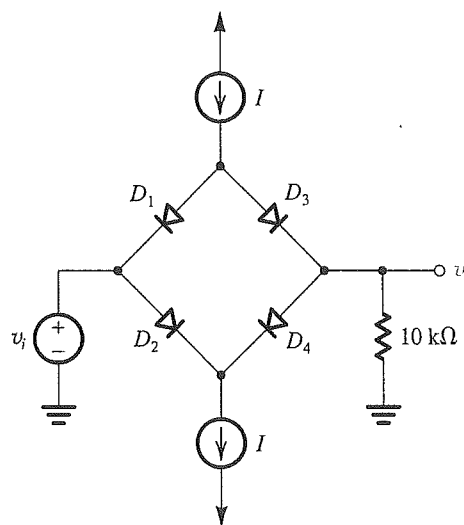

Figure P4.51

**4.52 In Problem 4.51 we investigated the operation of the circuit in Fig. P4.51 for small input signals. In this problem we wish to find the voltage-transfer characteristic (VTC) v_o versus v_i for $-12\ \text{V} \leq v_i \leq 12\ \text{V}$ for the case $I = 1$ mA and each of the diodes exhibits a voltage drop of 0.7 V at a current of 1 mA. Toward this end, use the diode exponential characteristic to construct a table that gives the values of: the current i_o in the 10-kΩ resistor, the current in each of the four diodes, the voltage drop across each of the four diodes, and the input voltage v_i, for $v_o = 0$, +1 V, +2 V, +5 V, +9 V, +9.9 V, +9.99 V, +10.5 V, +11 V, and +12 V. Use these data, with extrapolation to negative values of v_i and v_o, to sketch the required VTC. Also sketch the VTC that results if I is reduced to 0.5 mA. (*Hint*: From symmetry, observe that as v_o increases and i_o correspondingly increases, i_{D3} and i_{D2} increase by equal amounts and i_{D4} and i_{D1} decrease by (the same) equal amounts.)

SIM *4.53 In the circuit shown in Fig. P4.53, I is a dc current and v_i is a sinusoidal signal with small amplitude (less than 10 mV) and a frequency of 100 kHz. Representing the diode by its small-signal resistance r_d, which is a function of I, sketch the small-signal equivalent circuit and use it to determine the sinusoidal output voltage V_o, and thus find the phase shift between V_i and V_o. Find the value of I that will provide a phase shift of $-45°$, and find the range of phase shift achieved as I is varied over the range of 0.1 times to 10 times this value.
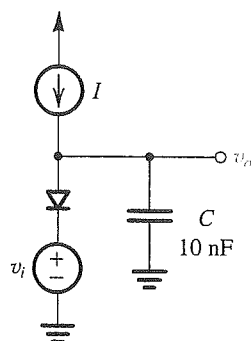

Figure P4.53

*4.54 Consider the voltage-regulator circuit shown in Fig. P4.54. The value of R is selected to obtain an output voltage V_o (across the diode) of 0.7 V.
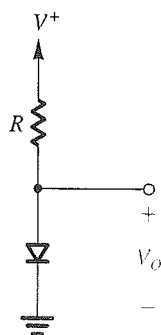

Figure P4.54

(a) Use the diode small-signal model to show that the change in output voltage corresponding to a change of 1 V in V^+ is

$$\frac{\Delta V_o}{\Delta V^+} = \frac{V_T}{V^+ + V_T - 0.7}$$

This quantity is known as the line regulation and is usually expressed in mV/V.

(b) Generalize the expression above for the case of m diodes connected in series and the value of R adjusted so that the voltage across each diode is 0.7 V (and $V_o = 0.7m$ V).
(c) Calculate the value of line regulation for the case $V^+ = 15$ V (nominally) and (i) $m = 1$ and (ii) $m = 4$.

*4.55 Consider the voltage-regulator circuit shown in Fig P4.54 under the condition that a load current I_L is drawn from the output terminal.

(a) If the value of I_L is sufficiently small that the corresponding change in regulator output voltage ΔV_o is small enough to justify using the diode small-signal model, show that

$$\frac{\Delta V_o}{I_L} = -\left(r_d \parallel R\right)$$

This quantity is known as the load regulation and is usually expressed in mV/mA.

(b) If the value of R is selected such that at no load the voltage across the diode is 0.7 V and the diode current is I_D, show that the expression derived in (a) becomes

$$\frac{\Delta V_o}{I_L} = -\frac{V_T}{I_D}\frac{V^+ - 0.7}{V^+ - 0.7 + V_T}$$

Select the lowest possible value for I_D that results in a load regulation whose magnitude is ≤ 5 mV/mA. If V^+ is nominally 15 V, what value of R is required? Also, specify the diode required in terms of its I_S.
(c) Generalize the expression derived in (b) for the case of m diodes connected in series and R adjusted to obtain $V_o = 0.7m$ V at no load.

D *4.56 Design a diode voltage regulator to supply 1.5 V to a 1.5-kΩ load. Use two diodes specified to have a 0.7-V drop at a current of 1 mA. The diodes are to be connected to a +5-V supply through a resistor R. Specify the value for R. What is the diode current with the load connected? What is the increase resulting in the output voltage when the load is disconnected? What change results if the load resistance is reduced to 1 kΩ? To 750 Ω? To 500 Ω? (Hint: Use the small-signal diode model to calculate all changes in output voltage.)

D *4.57 A voltage regulator consisting of two diodes in series fed with a constant-current source is used as a replacement for a single carbon–zinc cell (battery) of nominal voltage 1.5 V. The regulator load current varies from 2 mA to

7 mA. Constant-current supplies of 5 mA, 10 mA, and 15 mA are available. Which would you choose, and why? What change in output voltage would result when the load current varies over its full range?

**4.58 A particular design of a voltage regulator is shown in Fig. P4.58. Diodes D_1 and D_2 are 10-mA units; that is, each has a voltage drop of 0.7 V at a current of 10 mA. Use the diode exponential model and iterative analysis to answer the following questions:
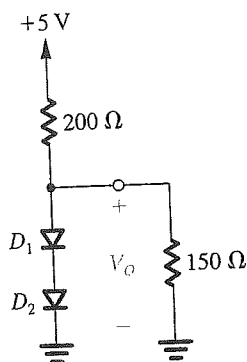
+5 V

Figure P4.58

(a) What is the regulator output voltage V_O with the 150-Ω load connected?

(b) Find V_O with no load.

(c) With the load connected, to what value can the 5-V supply be lowered while maintaining the loaded output voltage within 0.1 V of its nominal value?

(d) What does the loaded output voltage become when the 5-V supply is raised by the same amount as the drop found in (c)?

(e) For the range of changes explored in (c) and (d), by what percentage does the output voltage change for each percentage change of supply voltage in the worst case?

Section 4.4: Operation in the Reverse Breakdown Region—Zener Diodes

4.59 Partial specifications of a collection of zener diodes are provided below. For each, identify the missing parameter and estimate its value. Note from Fig. 4.19 that $V_{ZK} \simeq V_{Z0}$ and I_{ZK} is very small.

(a) $V_Z = 10.0$ V, $V_{ZK} = 9.6$ V, and $I_{ZT} = 50$ mA
(b) $I_{ZT} = 10$ mA, $V_Z = 9.1$ V, and $r_z = 30 \Omega$

(c) $r_z = 2 \Omega$, $V_Z = 6.8$ V, and $V_{ZK} = 6.6$ V
(d) $V_Z = 18$ V, $I_{ZT} = 5$ mA, and $V_{ZK} = 17.6$ V
(e) $I_{ZT} = 200$ mA, $V_Z = 7.5$ V, and $r_z = 1.5 \Omega$

Assuming that the power rating of a breakdown diode is established at about twice the specified zener current (I_{ZT}), what is the power rating of each of the diodes described above?

D 4.60 A designer requires a shunt regulator of approximately 20 V. Two kinds of zener diodes are available: 6.8-V devices with r_z of 10 Ω and 5.1-V devices with r_z of 25 Ω. For the two major choices possible, find the load regulation. In this calculation neglect the effect of the regulator resistance R.

4.61 A shunt regulator utilizing a zener diode with an incremental resistance of 8 Ω is fed through an 82-Ω resistor. If the raw supply changes by 1.0 V, what is the corresponding change in the regulated output voltage?

4.62 A 9.1-V zener diode exhibits its nominal voltage at a test current of 20 mA. At this current the incremental resistance is specified as 10 Ω. Find V_{Z0} of the zener model. Find the zener voltage at a current of 10 mA and at 50 mA.

D 4.63 Design a 7.5-V zener regulator circuit using a 7.5-V zener specified at 10 mA. The zener has an incremental resistance $r_z = 30 \Omega$ and a knee current of 0.5 mA. The regulator operates from a 10-V supply and has a 1.5-kΩ load. What is the value of R you have chosen? What is the regulator output voltage when the supply is 10% high? Is 10% low? What is the output voltage when both the supply is 10% high and the load is removed? What is the smallest possible load resistor that can be used while the zener operates at a current no lower than the knee current while the supply is 10% low? What is the load voltage in this case?

D 4.64 Provide two designs of shunt regulators utilizing the 1N5235 zener diode, which is specified as follows: $V_Z = 6.8$ V and $r_z = 5 \Omega$ for $I_Z = 20$ mA; at $I_Z = 0.25$ mA (nearer the knee), $r_z = 750 \Omega$. For both designs, the supply voltage is nominally 9 V and varies by ±1 V. For the first design, assume that the availability of supply current is not a problem, and thus operate the diode at 20 mA. For the second design, assume that the current from the raw supply is limited, and therefore you are forced to operate the diode at 0.25 mA. For the purpose of these initial designs, assume no load. For each design find the value of R and the line regulation.

D *4.65 A zener shunt regulator employs a 9.1-V zener diode for which $V_Z = 9.1$ V at $I_Z = 9$ mA, with $r_z = 40 \Omega$ and

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$I_{ZK} = 0.5$ mA. The available supply voltage of 15 V can vary as much as $\pm10\%$. For this diode, what is the value of V_{Z0}? For a nominal load resistance R_L of 1 kΩ and a nominal zener current of 10 mA, what current must flow in the supply resistor R? For the nominal value of supply voltage, select a value for resistor R, specified to one significant digit, to provide at least that current. What nominal output voltage results? For a $\pm10\%$ change in the supply voltage, what variation in output voltage results? If the load current is reduced by 50%, what increase in V_O results? What is the smallest value of load resistance that can be tolerated while maintaining regulation when the supply voltage is low? What is the lowest possible output voltage that results? Calculate values for the line regulation and for the load regulation for this circuit using the numerical results obtained in this problem.

D *4.66 It is required to design a zener shunt regulator to provide a regulated voltage of about 10 V. The available 10-V, 1-W zener of type 1N4740 is specified to have a 10-V drop at a test current of 25 mA. At this current, its r_z is 7 Ω. The raw supply, V_S, available has a nominal value of 20 V but can vary by as much as $\pm25\%$. The regulator is required to supply a load current of 0 mA to 20 mA. Design for a minimum zener current of 5 mA.

(a) Find V_{Z0}.
(b) Calculate the required value of R.
(c) Find the line regulation. What is the change in V_O expressed as a percentage, corresponding to the $\pm25\%$ change in V_S?
(d) Find the load regulation. By what percentage does V_O change from the no-load to the full-load condition?
(e) What is the maximum current that the zener in your design is required to conduct? What is the zener power dissipation under this condition?

Section 4.5: Rectifier Circuits

4.67 Consider the half-wave rectifier circuit of Fig. 4.23(a) with the diode reversed. Let v_S be a sinusoid with 10-V peak amplitude, and let $R = 1$ kΩ. Use the constant-voltage-drop diode model with $V_D = 0.7$ V.

(a) Sketch the transfer characteristic.
(b) Sketch the waveform of v_O.
(c) Find the average value of v_O.
(d) Find the peak current in the diode.
(e) Find the PIV of the diode.

4.68 Using the exponential diode characteristic, show that for v_S and v_O both greater than zero, the circuit of Fig. 4.23(a) has the transfer characteristic

$$v_O = v_S - v_D \left(\text{at } i_D = 1 \text{ mA}\right) - V_T \ln\left(v_O/R\right)$$

where v_S and v_O are in volts and R is in kilohms. Note that this relationship can be used to obtain the voltage transfer characteristic v_O vs. v_S by finding v_S corresponding to various values of v_O.

SIM 4.69 Consider a half-wave rectifier circuit with a triangular-wave input of 5-V peak-to-peak amplitude and zero average, and with $R = 1$ kΩ. Assume that the diode can be represented by the constant-voltage-drop model with $V_D = 0.7$ V. Find the average value of v_O.

4.70 A half-wave rectifier circuit with a 1-kΩ load operates from a 120-V (rms) 60-Hz household supply through a 12-to-1 step-down transformer. It uses a silicon diode that can be modeled to have a 0.7-V drop for any current. What is the peak voltage of the rectified output? For what fraction of the cycle does the diode conduct? What is the average output voltage? What is the average current in the load?

4.71 A full-wave rectifier circuit with a 1-kΩ load operates from a 120-V (rms) 60-Hz household supply through a 6-to-1 transformer having a center-tapped secondary winding. It uses two silicon diodes that can be modeled to have a 0.7-V drop for all currents. What is the peak voltage of the rectified output? For what fraction of a cycle does each diode conduct? What is the average output voltage? What is the average current in the load?

4.72 A full-wave bridge-rectifier circuit with a 1-kΩ load operates from a 120-V (rms) 60-Hz household supply through a 12-to-1 step-down transformer having a single secondary winding. It uses four diodes, each of which can be modeled to have a 0.7-V drop for any current. What is the peak value of the rectified voltage across the load? For what fraction of a cycle does each diode conduct? What is the average voltage across the load? What is the average current through the load?

D 4.73 It is required to design a full-wave rectifier circuit using the circuit of Fig. 4.24 to provide an average output voltage of:
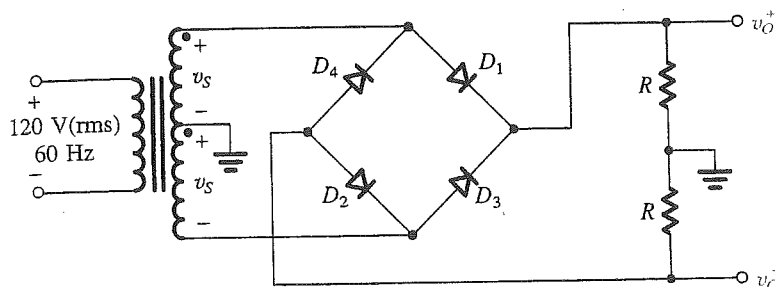
(a) 10 V
(b) 100 V

Figure P4.76

In each case find the required turns ratio of the transformer. Assume that a conducting diode has a voltage drop of 0.7 V. The ac line voltage is 120 V rms.

D 4.74 Repeat Problem 4.73 for the bridge-rectifier circuit of Fig. 4.25.

D 4.75 Consider the full-wave rectifier in Fig. 4.24 when the transformer turns ratio is such that the voltage across the entire secondary winding is 20 V rms. If the input ac line voltage (120 V rms) fluctuates by as much as $\pm 10\%$, find the required PIV of the diodes. (Remember to use a factor of safety in your design.)

4.76 The circuit in Fig. P4.76 implements a complementary-output rectifier. Sketch and clearly label the waveforms of v_O^+ and v_O^-. Assume a 0.7-V drop across each conducting diode. If the magnitude of the average of each output is to be 12 V, find the required amplitude of the sine wave across the entire secondary winding. What is the PIV of each diode?

4.77 Augment the rectifier circuit of Problem 4.70 with a capacitor chosen to provide a peak-to-peak ripple voltage of (i) 10% of the peak output and (ii) 1% of the peak output. In each case:

(a) What average output voltage results?
(b) What fraction of the cycle does the diode conduct?
(c) What is the average diode current?
(d) What is the peak diode current?

4.78 Repeat Problem 4.77 for the rectifier in Problem 4.71.

4.79 Repeat Problem 4.77 for the rectifier in Problem 4.72.

D *4.80 It is required to use a peak rectifier to design a dc power supply that provides an average dc output voltage of 12 V on which a maximum of ± 1-V ripple is allowed. The rectifier feeds a load of 200 Ω. The rectifier is fed from the line voltage (120 V rms, 60 Hz) through a transformer. The diodes available have 0.7-V drop when conducting. If the designer opts for the half-wave circuit:

(a) Specify the rms voltage that must appear across the transformer secondary.
(b) Find the required value of the filter capacitor.
(c) Find the maximum reverse voltage that will appear across the diode, and specify the PIV rating of the diode.
(d) Calculate the average current through the diode during conduction.
(e) Calculate the peak diode current.

D *4.81 Repeat Problem 4.80 for the case in which the designer opts for a full-wave circuit utilizing a center-tapped transformer.

D *4.82 Repeat Problem 4.80 for the case in which the designer opts for a full-wave bridge-rectifier circuit.

D *4.83 Consider a half-wave peak rectifier fed with a voltage v_S having a triangular waveform with 24-V peak-to-peak amplitude, zero average, and 1-kHz frequency. Assume that the diode has a 0.7-V drop when conducting. Let the load resistance $R = 100$ Ω and the filter capacitor $C = 100$ μF. Find the average dc output voltage, the time interval during which the diode conducts, the average diode current during conduction, and the maximum diode current.

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

D *4.84 Consider the circuit in Fig. P4.76 with two equal filter capacitors placed across the load resistors R. Assume that the diodes available exhibit a 0.7-V drop when conducting. Design the circuit to provide ± 12-V dc output voltages with a peak-to-peak ripple no greater than 1 V. Each supply should be capable of providing 100-mA dc current to its load resistor R. Completely specify the capacitors, diodes, and the transformer.

4.85 The op amp in the precision rectifier circuit of Fig. P4.85 is ideal with output saturation levels of ± 13 V. Assume that when conducting the diode exhibits a constant voltage drop of 0.7 V. Find v_-, v_O, and v_A for:

(a) $v_I = +1$ V
(b) $v_I = +3$ V
(c) $v_I = -1$ V
(d) $v_I = -3$ V

Also, find the average output voltage obtained when v_I is a symmetrical square wave of 1-kHz frequency, 5-V amplitude, and zero average.
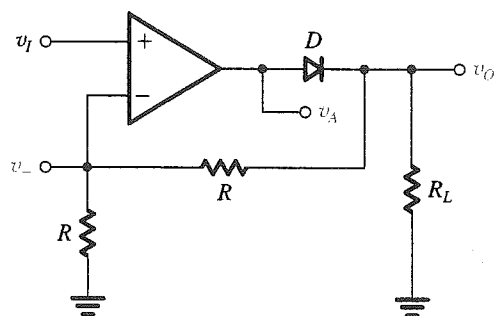
Figure P4.85

4.86 The op amp in the circuit of Fig. P4.86 is ideal with output saturation levels of ± 12 V. The diodes exhibit a constant 0.7-V drop when conducting. Find v_-, v_A, and v_O for:

(a) $v_I = +1$ V
(b) $v_I = +3$ V
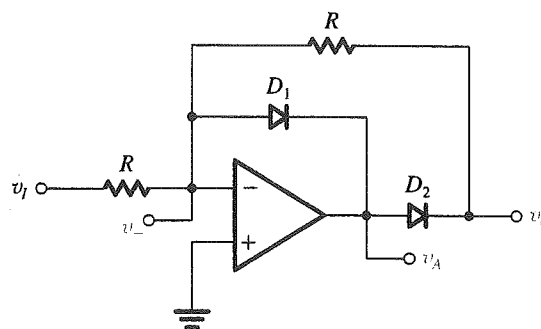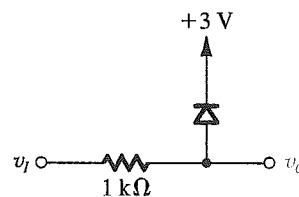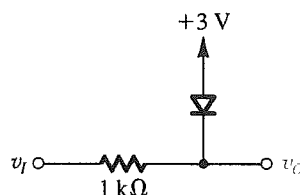
(c) $v_I = -1$ V
(d) $v_I = -3$ V

Figure P4.86

Section 4.6: Limiting and Clamping Circuits

4.87 Sketch the transfer characteristic v_O versus v_I for the limiter circuits shown in Fig. P4.87. All diodes begin conducting at a forward voltage drop of 0.5 V and have voltage drops of 0.7 V when conducting a current $i_D \geq 1$ mA.
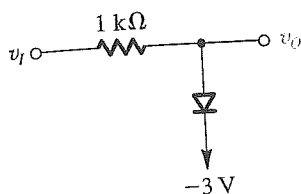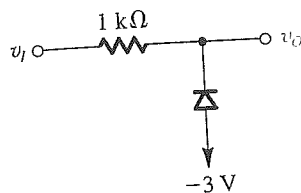

(a)

(b)

Figure P4.87

(c)

(d)

Figure P4.87 *continued*

4.88 The circuits in Fig. P4.87(a) and (d) are connected as follows: The two input terminals are tied together, and the two output terminals are tied together. Sketch the transfer characteristic of the circuit resulting, assuming that the cut-in voltage of the diodes is 0.5 V and their voltage drop when conducting a current $i_D \geq 1$ mA is 0.7 V.

4.89 Repeat Problem 4.88 for the two circuits in Fig. P4.87(a) and (b) connected together as follows: The two input terminals are tied together, and the two output terminals are tied together.

4.90 Sketch and clearly label the transfer characteristic of the circuit in Fig. P4.90 for $-15\,\text{V} \leq v_I \leq +15$ V. Assume that
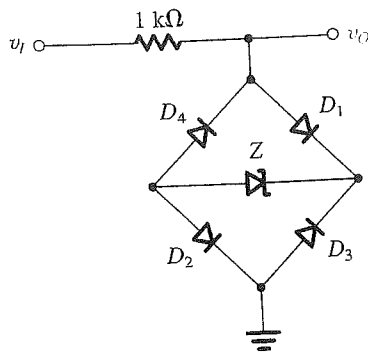

Figure P4.90

the diodes can be represented by the constant-voltage-drop model with $V_D = 0.7$ V. Also assume that the zener voltage is 6.8 V and that r_z is negligibly small.

*****4.91** Plot the transfer characteristic of the circuit in Fig. P4.91 by evaluating v_I corresponding to $v_O = 0.5$ V, 0.6 V, 0.7 V, 0.8 V, 0 V, –0.5 V, –0.6 V, –0.7 V, and –0.8 V. Use the exponential model for the diodes, and assume that they have 0.7-V drops at 1-mA currents. Characterize the circuit as a hard or soft limiter. What is the value of K? Estimate L_+ and L_-.
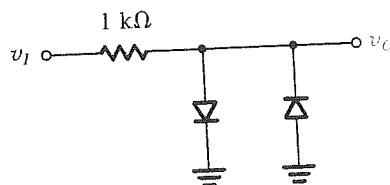

Figure P4.91

4.92 Design limiter circuits using only diodes and 10-kΩ resistors to provide an output signal limited to the range:

(a) –0.7 V and above
(b) +2.1 V and below
(c) ±1.4 V

Assume that each diode has a 0.7-V drop when conducting.

4.93 Design a two-sided limiting circuit using a resistor, two diodes, and two power supplies to feed a 1-kΩ load with nominal limiting levels of ±2.2 V. Use diodes modeled by a constant 0.7 V. In the nonlimiting region, the voltage gain should be at least 0.94 V/V.

*****4.94** In the circuit shown in Fig. P4.94, the diodes exhibit a 0.7-V drop at 0.1 mA. For inputs over the range of ±5 V, use the diode exponential model to provide a calibrated sketch of the voltages at outputs B and C versus v_A. For a 5-V peak,

CHAPTER 4 PROBLEMS

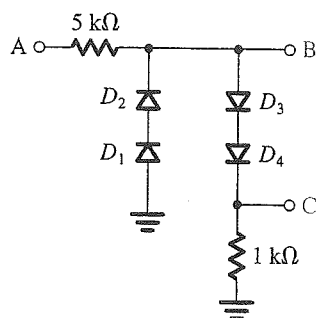100-Hz sinusoid applied at A, sketch the signals at nodes B and C.

Figure P4.94

**4.95 Sketch and label the voltage-transfer characteristic v_O versus v_I of the circuit shown in Fig. P4.95 over a ± 10-V range of input signals. Use the diode exponential model and assume that all diodes are 1-mA units (i.e., each exhibits a 0.7-V drop at a current of 1 mA). What are the slopes of the characteristics at the extreme ± 10-V levels?
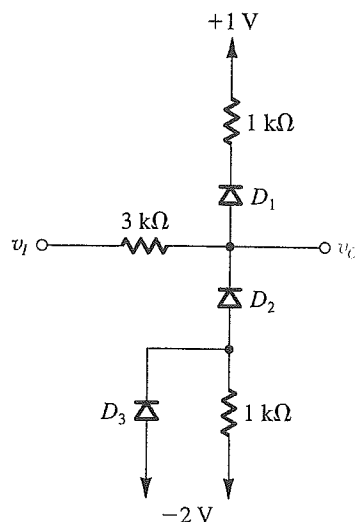

Figure P4.95

4.96 A clamped capacitor using an ideal diode with cathode grounded is supplied with a sine wave of 5-V rms. What is the average (dc) value of the resulting output?

*4.97 For the circuits in Fig. P4.97, each utilizing an ideal diode (or diodes), sketch the output for the input shown. Label the most positive and most negative output levels. Assume $CR \gg T$.
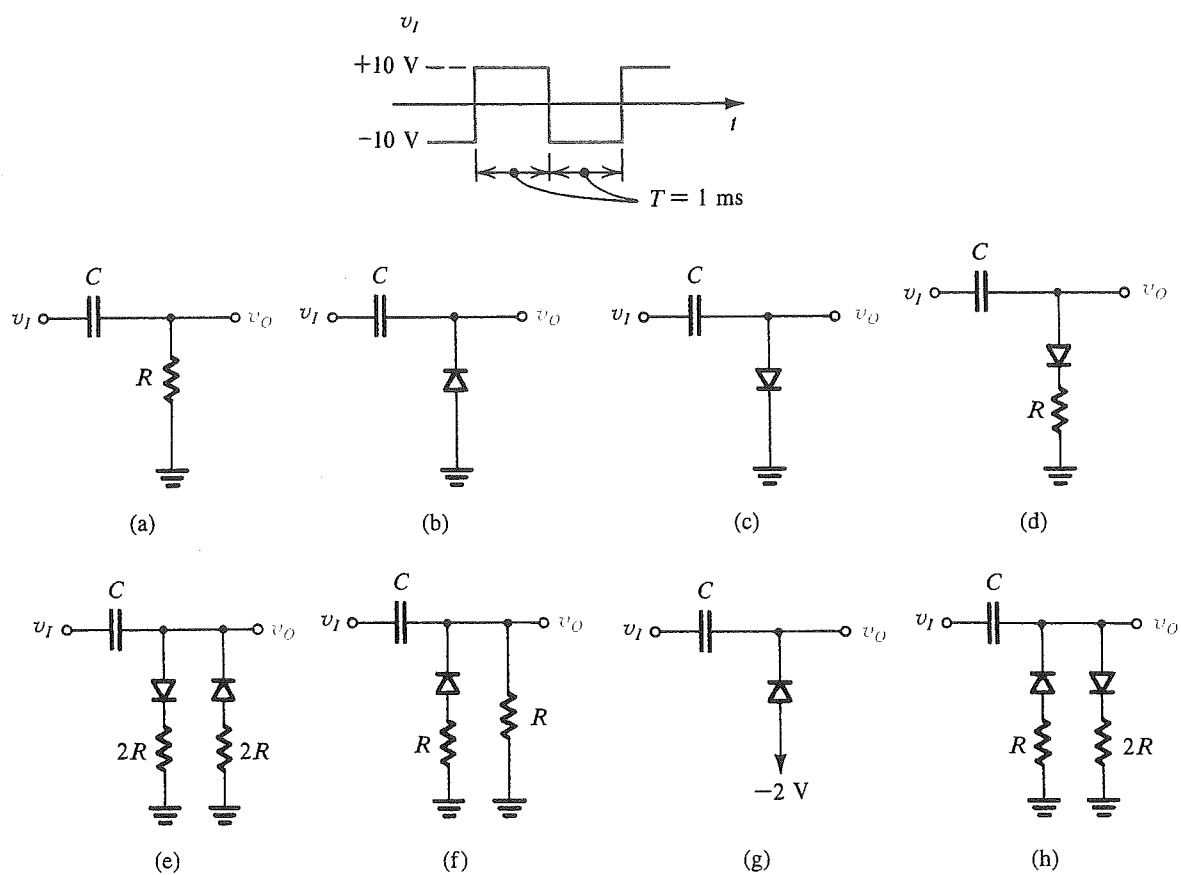
(a)   (b)   (c)   (d)

(e)   (f)   (g)   (h)

Figure P4.97