- *Loop-current method* is similar in concept to the mesh-current method, except that it works with both planar and nonplanar circuits. We discuss this method in Chapter 5.
- *Source transformation* involves replacing, *insofar as its terminal voltage and currents are concerned,* a voltage source and a series resistor with a current source and a parallel resistor (or vice versa). The values of the voltage source, the current source, and the resistor are such that the equivalents have the same open circuit voltage and short circuit current.
- *Thévenin and Norton equivalents* allow any circuit made up of sources and resistors to be replaced, *insofar as its terminal voltage and current are concerned,* by an equivalent circuit containing a voltage source with a series resistor (Thévenin) or by a current source with a parallel resistor (Norton).
- *Superposition* is a method of analyzing a circuit containing multiple *independent* sources by activating one source at a time and summing the resulting voltages and currents to determine the voltages and currents that exist when all the independent sources are active. (*Note:* Dependent sources are not deactivated when applying superposition.)

PROBLEMS

4.1 Assume the current i_g in the circuit in Fig. P4.1 is known. The resistors R_1 through R_5 are also known.

a) How many unknown currents are there?

b) How many independent equations can be written using Kirchhoff's current law?

c) Write an independent set of KCL equations.

d) How many independent equations must be derived from Kirchhoff's voltage law?

e) Write a set of independent KVL equations.

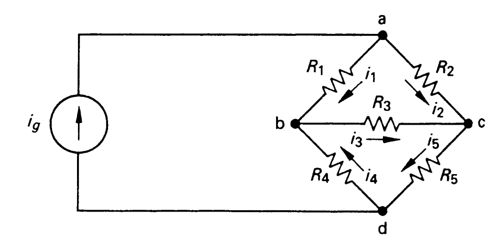

FIGURE P4.1

4.2 Use the node-voltage method to find v_o in the circuit in Fig. P4.2.

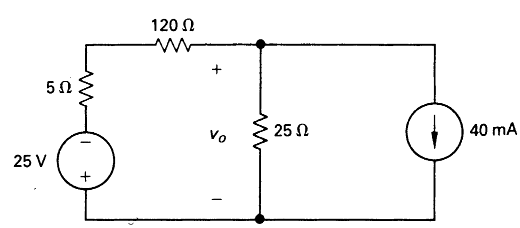

FIGURE P4.2

4.3 Use the node-voltage method to find v_1 and v_2 in the circuit shown in Fig. P4.3.

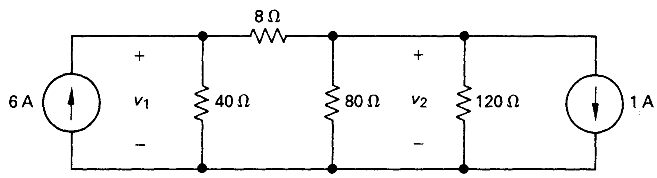

FIGURE P4.3

4.4 Use the node-voltage method to find how much power the 45-V source extracts from the circuit in Fig. P4.4.

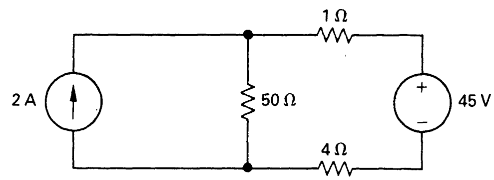

FIGURE P4.4

4.5 Use the node-voltage method to find v_1 and v_2 in the circuit in Fig. P4.5.

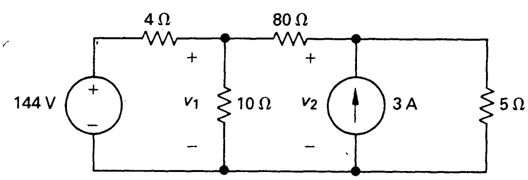

FIGURE P4.5

4.6 a) Use the node-voltage method to find v_1, v_2, and v_3 in the circuit in Fig. P4.6.

b) How much power does the 28-A current source deliver to the circuit?

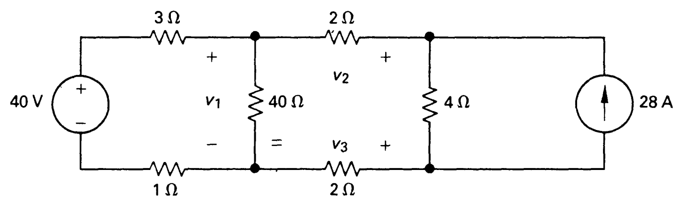

FIGURE P4.6

4.7 a) Use the node-voltage method to find the branch currents i_a through i_e in the circuit shown in Fig. P4.7.

b) Find the total power developed in the circuit.

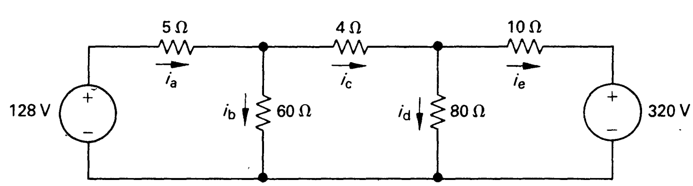

FIGURE P4.7

4.8 Use the node-voltage method to find the total power dissipated in the circuit in Fig. P4.8.

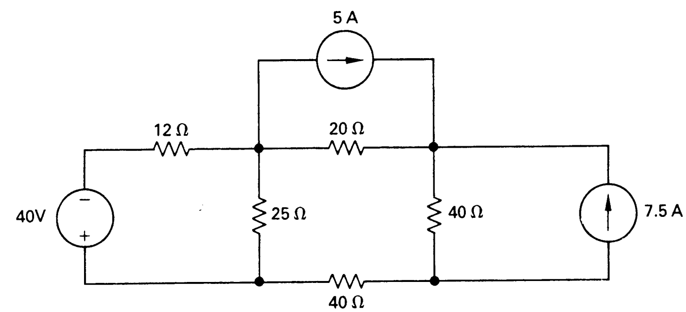

FIGURE P4.8

4.9 a) Use the node-voltage method to find the branch currents i_1 through i_6 in the circuit shown in Fig. P4.9.

b) Test your solution for the branch currents by showing that the total power dissipated equals the total power developed.

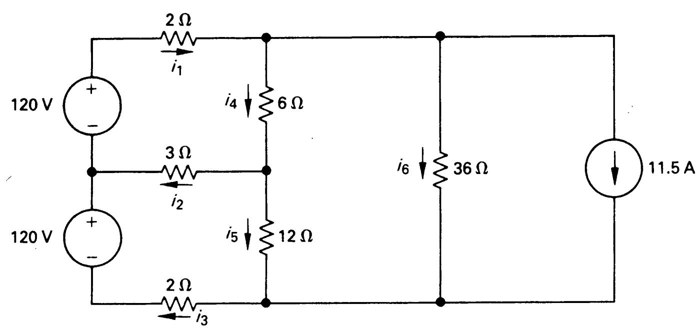

FIGURE P4.9

4.10 Use the node-voltage method to find v_1 and the power delivered by the 2-A current source in the circuit in Fig. P4.10.

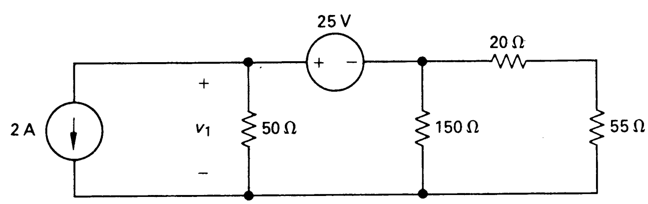

FIGURE P4.10

4.11 a) Use the node-voltage method to find the branch currents i_1, i_2, and i_3 in the circuit in Fig. P4.11.

b) Check your solution for i_1, i_2, and i_3 by showing that the power dissipated in the circuit equals the power developed.

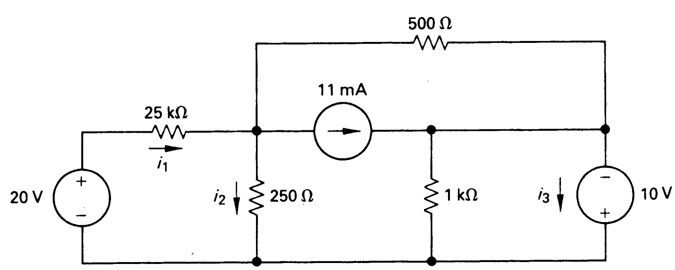

FIGURE P4.11

4.12 a) Find the power developed by the 40-mA current source in the circuit in Fig. P4.2.

b) Find the power developed by the 25-V voltage source in the circuit in Fig. P4.2.

c) Verify that the total power developed equals the total power dissipated.

4.13 A 100-Ω resistor is connected in series with the 40-mA current source in the circuit in Fig. P4.2.

a) Find v_o.

b) Find the power developed by the 40-mA current source.

c) Find the power developed by the 25-V voltage source.

d) Verify that the total power developed equals the total power dissipated.

e) What effect will any finite resistance connected in series with the 40-mA current source have on the value of v_o?

4.14 Use the node-voltage method to find the value of v_o in the circuit in Fig. P4.14.

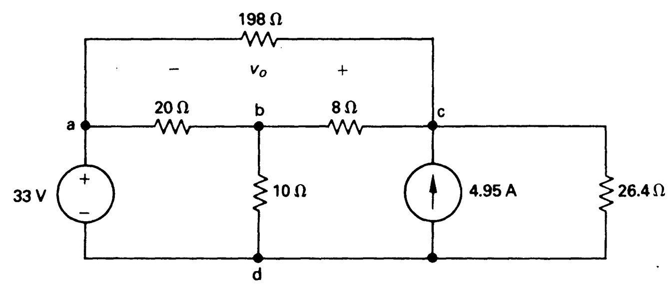

FIGURE P4.14

4.15 Check the solution for v_o in Problem 4.14 by first using a Y-to-Δ transformation to eliminate node b.

4.16 a) Use the node-voltage method to find the power dissipated in the 2-Ω resistor in the circuit in Fig. P4.16.

b) Find the power supplied by the 230-V source.

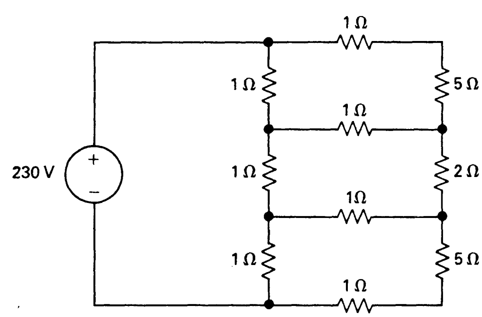

FIGURE P4.16

4.17 Use the node-voltage method to find v_o in the circuit in Fig. P4.17.

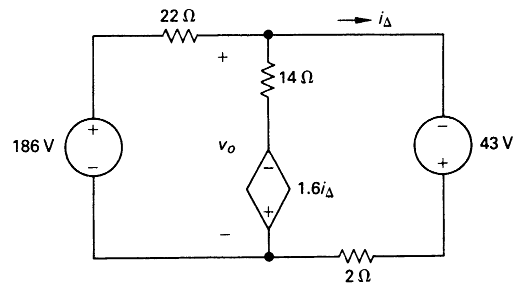

FIGURE P4.17

4.18 Use the node-voltage method to calculate the power delivered by the dependent voltage source in the circuit in Fig. P4.18.

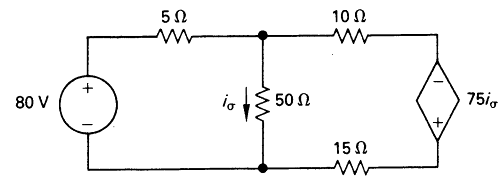

FIGURE P4.18

4.19 Use the node-voltage method to determine how much power the dependent voltage source in Fig. P4.19 delivers to the circuit.

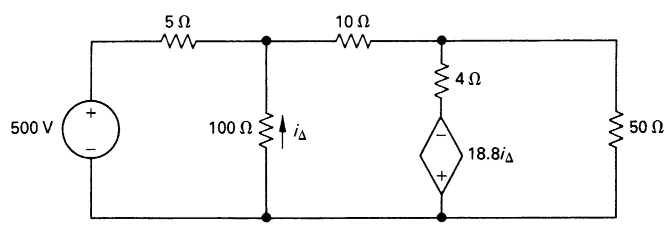

FIGURE P4.19

4.20 Use the node-voltage method to find v_Δ in the circuit in Fig. P4.20.

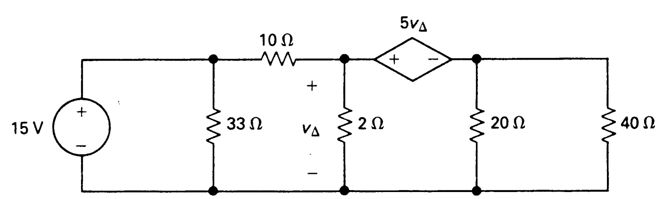

FIGURE P4.20

4.21 a) Find the node voltages v_1, v_2, and v_3 in the circuit in Fig. P4.21.

b) Find the total power dissipated in the circuit.

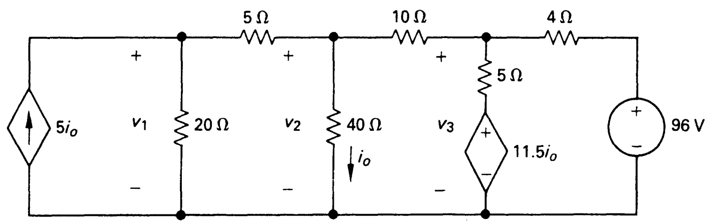

FIGURE P4.21

4.22 Assume you are a project engineer and one of your staff is assigned to analyze the circuit shown in Fig. P4.22. The reference node and node numbers given on the figure were assigned by the analyst. Her solution gives the values of v_3 and v_4 as 108 V and 81.60 V respectively.
Test these values by checking the total power developed in the circuit against the total power dissipated. Do you agree with the solution submitted by the analyst?

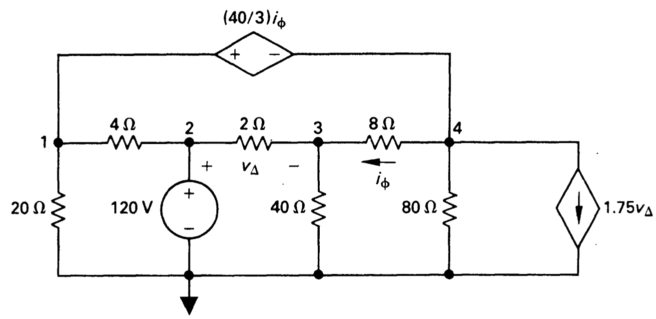

FIGURE P4.22

4.23 Show that when Eqs. (4.16), (4.17), and (4.19) are solved for i_B, the result is identical to Eq. (2.27).

4.24 Use the node-voltage method to find the power developed by the 20-V source in the circuit in Fig. P4.24.

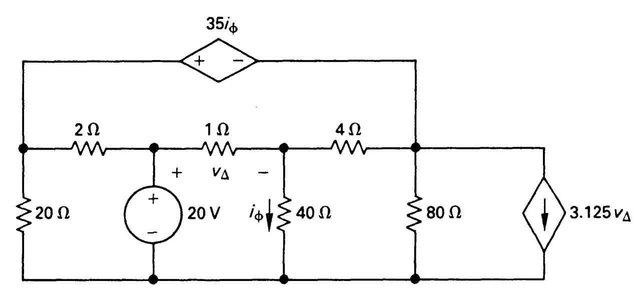

FIGURE P4.24

4.25 a) Use the node-voltage method to show that the output voltage v_o in the circuit in Fig. P4.25 is equal to the average value of the source voltages.

b) Find v_o if $v_1 = 100$ V, $v_2 = 80$ V, and $v_3 = -60$ V.

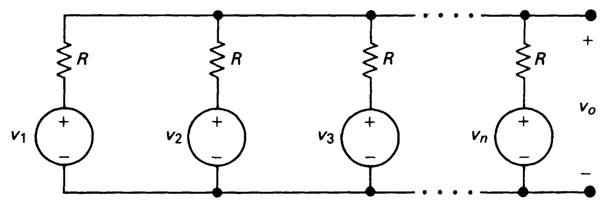

FIGURE P4.25

4.26 a) Use the mesh-current method to find the branch currents i_a, i_b, and i_c in the circuit in Fig. P4.26.

b) Repeat part (a) if the polarity of the 64-V source is reversed.

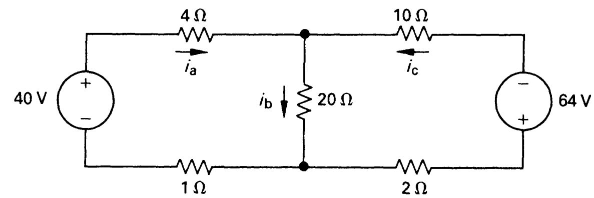

FIGURE P4.26

4.27 a) Use the mesh-current method to find the total power developed in the circuit in Fig. P4.27.

b) Check your answer by showing that the total power developed equals the total power dissipated.

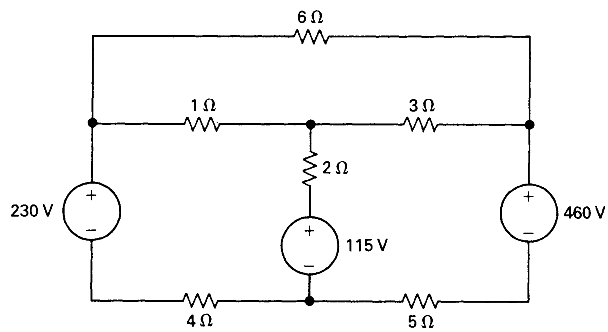

FIGURE P4.27

4.28 a) Use the mesh-current method to find how much power the 4-A current source delivers to the circuit in Fig. P4.28.

b) Find the total power delivered to the circuit.

c) Check your calculations by showing that the total power developed in the circuit equals the total power dissipated.

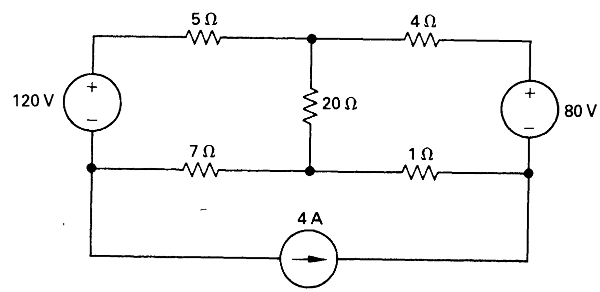

FIGURE P4.28

4.29 Use the mesh-current method to find the total power dissipated in the circuit in Fig. P4.29.

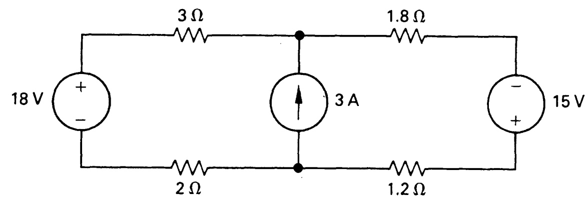

FIGURE P4.29

4.30 Assume the 18-V source in the circuit in Fig. P4.29 is reduced to 6 V. Find the total power dissipated in the circuit.

4.31 a) Assume the 18-V source in the circuit in Fig. P4.29 is reduced to 10 V. Find the total power dissipated in the circuit.

b) Repeat part (a) if the 3-A current source is replaced by a short circuit.

c) Explain why the answers to parts (a) and (b) are the same.

4.32 a) Use the mesh-current method to find the branch currents i_a through i_e in the circuit in Fig. P4.32.

b) Check your solution by showing the total power developed in the circuit equals the total power dissipated.

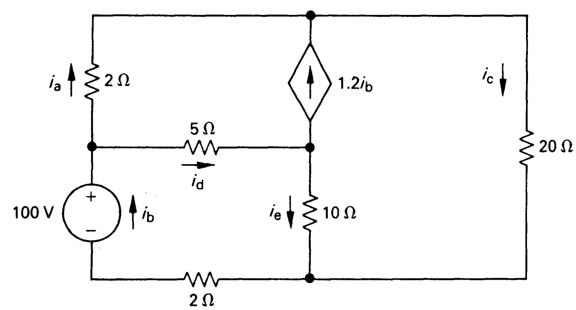

FIGURE P4.32

4.33 Use the mesh-current method to find the power delivered by the dependent voltage source in the circuit seen in Fig. P4.33.

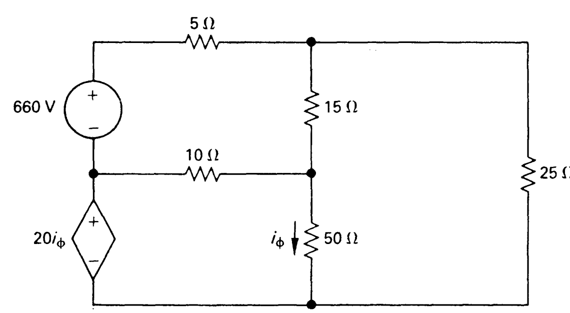

FIGURE P4.33

4.34 a) Use the mesh-current method to find v_o in the circuit in Fig. P4.34.

b) Find the power delivered by the dependent source.

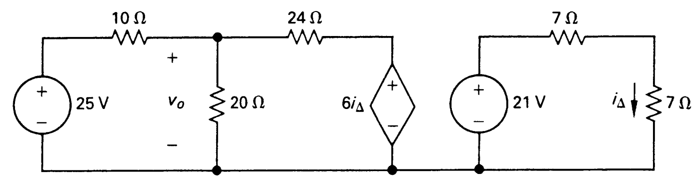

FIGURE P4.34

4.35 a) Use the mesh-current method to solve for i_Δ in the circuit in Fig. P4.35.

b) Find the power delivered by the independent current source.

c) Find the power delivered by the dependent voltage source.

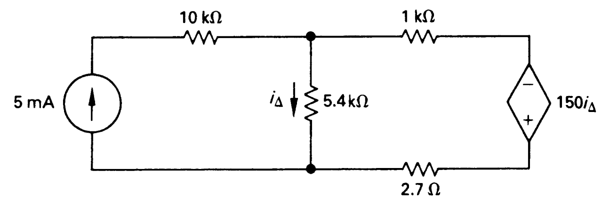

FIGURE P4.35

4.36 a) Use the mesh-current method to determine which sources in the circuit in Fig. P4.36 are generating power.

b) Find the total power dissipated in the circuit.

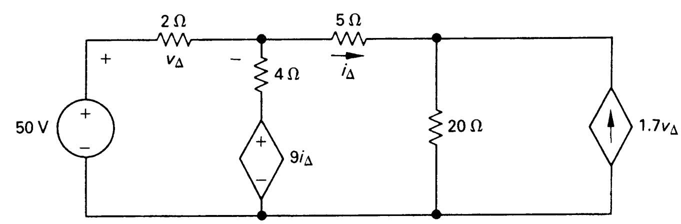

FIGURE P4.36

4.37 Use the mesh-current method to find the total power developed in the circuit in Fig. P4.37.

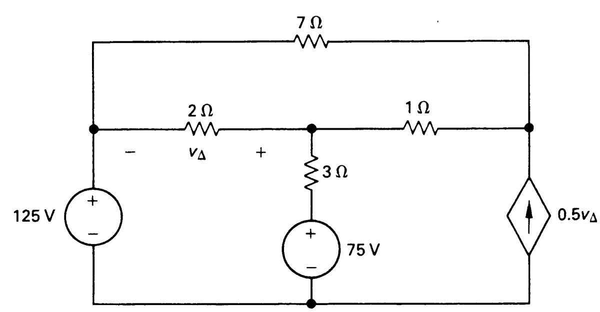

FIGURE P4.37

4.38 Use the mesh-current method to find the power dissipated in the 20-Ω resistor in the circuit in Fig. P4.38.

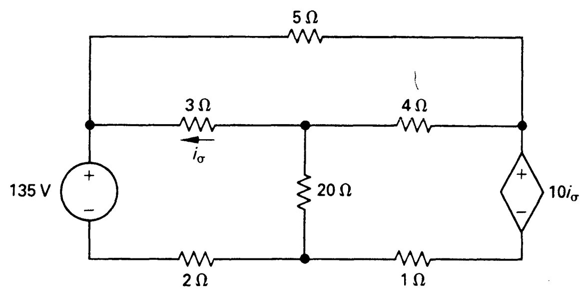

FIGURE P4.38

4.39 a) Use the mesh-current method to find the power delivered to the 25-Ω resistor in the circuit in Fig. P4.39.

b) What percent of the total power developed in the circuit is delivered to the 25-Ω resistor?

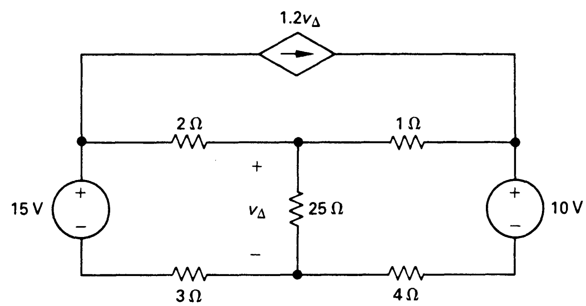

FIGURE P4.39

4.40 Use the mesh-current method to find the power developed in the dependent voltage source in the circuit in Fig. P4.40.

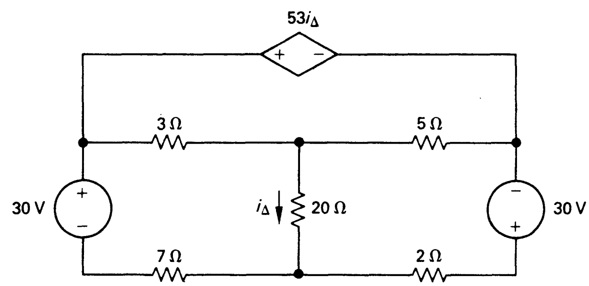

FIGURE P4.40

4.41 Assume you have been asked to find the power dissipated in the 5-Ω resistor in the circuit in Fig. P4.41.

a) Which method of circuit analysis would you recommend? Explain why.

b) Use your recommended method of analysis

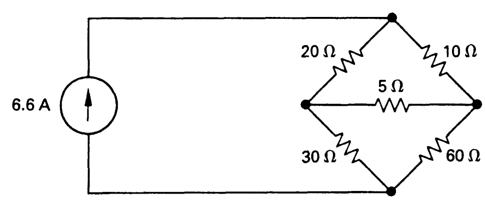

FIGURE P4.41

(continued)

to find the power dissipated in the 5-Ω resistor.

c) Would you change your recommendation if the problem had been to find the power developed by the 6.6-A current source? Explain.

d) Find the power developed by the 6.6-A current source.

4.42 A 160-Ω resistor is placed in parallel with the 6.6-A current source in the circuit in Fig. P4.41. Assume you have been asked to calculate the power developed by the current source.

a) Which method of circuit analysis, node-voltage or mesh-current, would you recommend? Explain why.

b) Find the power developed by the current source.

4.43 a) Would you use the node-voltage or mesh-current method to find the power absorbed by the 5-V source in the circuit in Fig. P4.43? Explain your choice.

b) Use the method you selected in part (a) to find the power.

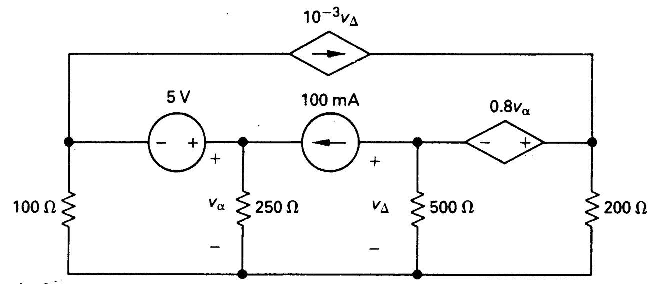

FIGURE P4.43

4.44 a) Find the branch currents i_a through i_e for the circuit shown in Fig. P4.44.

b) Check your answers by showing that the total power generated equals the total power dissipated.

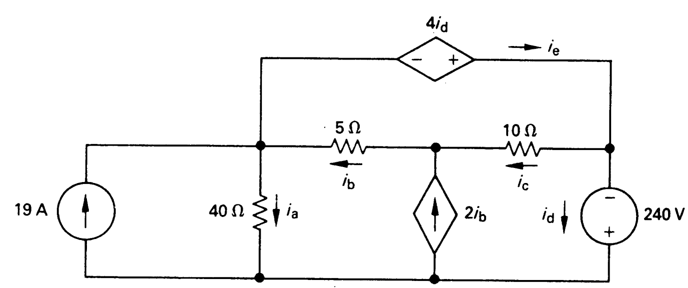

FIGURE P4.44

4.45 The circuit in Fig. P4.45 is a direct-current version of a typical three-wire distribution system. The resistors R_a, R_b, and R_c represent the resistances of the three conductors that connect the three loads R_1, R_2, and R_3 to the 125/250-V voltage supply. The resistors R_1 and R_2 represent loads connected to the 125-V circuits, and R_3 represents a load connected to the 250-V circuit.

a) Calculate v_1, v_2, and v_3.

b) Calculate the power delivered to R_1, R_2, and R_3.

c) What percentage of the total power developed by the sources is delivered to the loads?

d) The R_b branch represents the neutral conductor in the distribution circuit. What adverse effect occurs if the neutral conductor is opened? (*Hint:* Calculate v_1 and v_2 and note that appliances or loads designed for use in this circuit would have a nominal voltage rating of 125 V.)

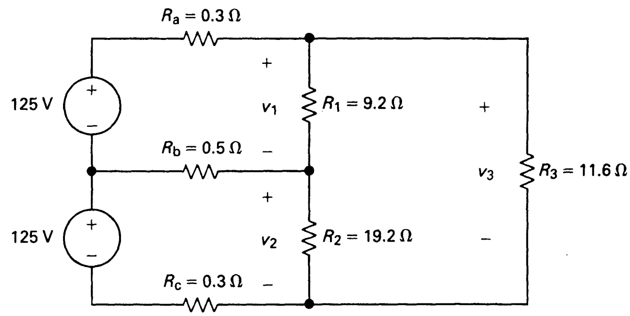

FIGURE P4.45

4.46 Show that whenever $R_1 = R_2$ in the circuit in Fig. P4.45 the current in the neutral conductor is zero. (*Hint:* Solve for the neutral conductor current as a function of R_1 and R_2.)

4.47 The variable dc-voltage source in the circuit in Fig. P4.47 is adjusted so that the power developed by the 5-A current source is zero. Find the value of the dc voltage.

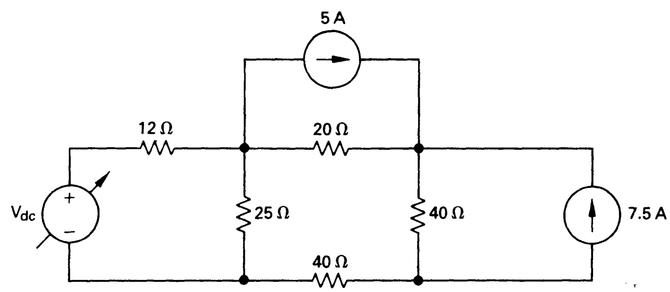

FIGURE P4.47

4.48 The variable dc-voltage source in the circuit in Fig. P4.48 is adjusted so that i_o is zero. Find the value of V_{dc}.

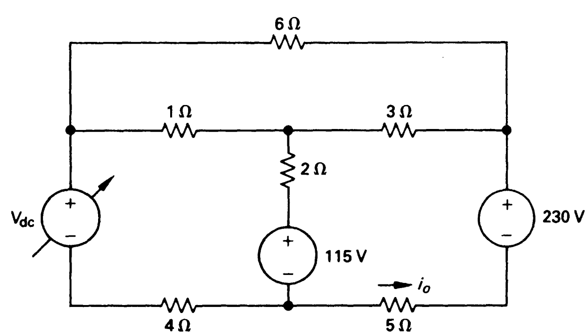

FIGURE P4.48

4.49 The variable resistor (R_o) in the circuit in Fig. P4.49 is adjusted until the power dissipated in the resistor (R_o) is 250 W. Find the values of R_o which satisfy this condition.

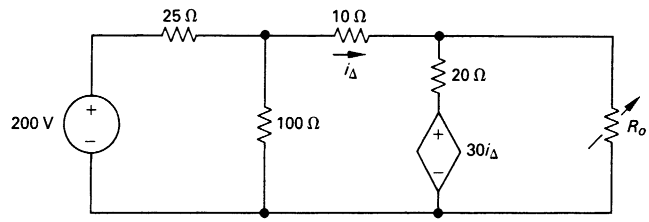

FIGURE P4.49

4.50 a) Use a series of source transformations to find the current i_o in the circuit in Fig. P4.50.

b) Verify your solution by using the node-voltage method to find i_o.

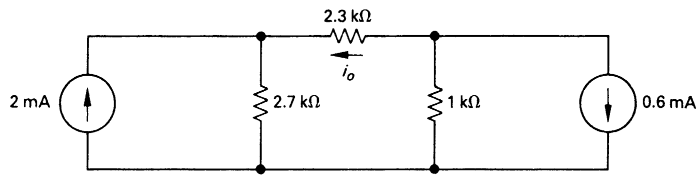

FIGURE P4.50

4.51 a) Use a series of source transformations to find i_o in the circuit in Fig. P4.51.

b) Verify your solution by using the mesh-current method to find i_o.

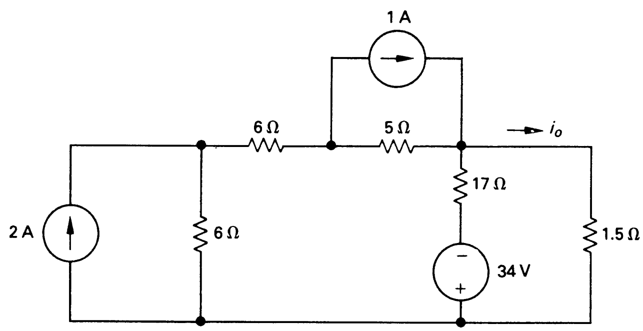

FIGURE P4.51

4.52 a) Find the current in the 5-kΩ resistor in the circuit in Fig. P4.52 by making a succession of appropriate source transformations.

b) Using the result obtained in part (a) work back through the circuit to find the power developed by the 120-V source.

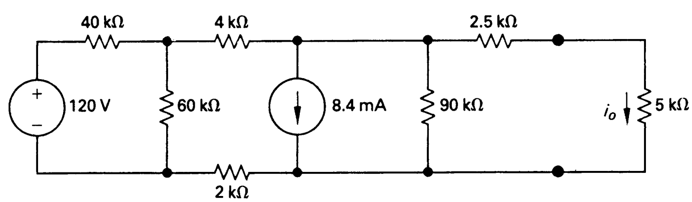

FIGURE P4.52

4.53 a) Use source transformations to find v_o in the circuit in Fig. P4.53.

b) Find the power developed by the 520-V source.

c) Find the power developed by the 1-A current source.

d) Verify that the total power developed equals the total power dissipated.

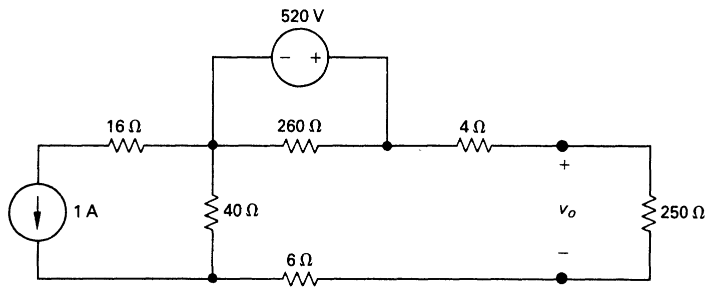

FIGURE P4.53

4.54 Find the Thévenin equivalent with respect to the terminals a,b for the circuit in Fig. P4.54.

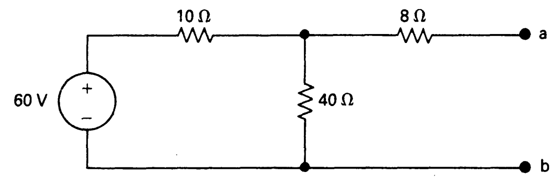

FIGURE P4.54

4.55 Find the Thévenin equivalent with respect to the terminals a,b for the circuit in Fig. P4.55.

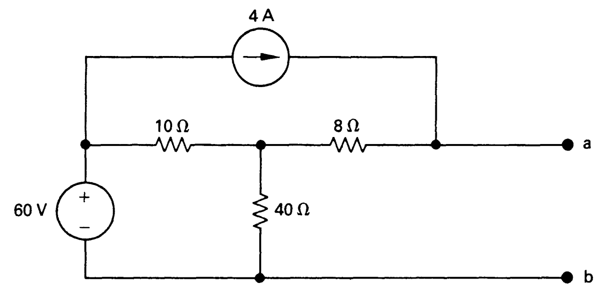

FIGURE P4.55

4.56 Find the Thévenin equivalent with respect to the terminals a,b for the circuit in Fig. P4.56.

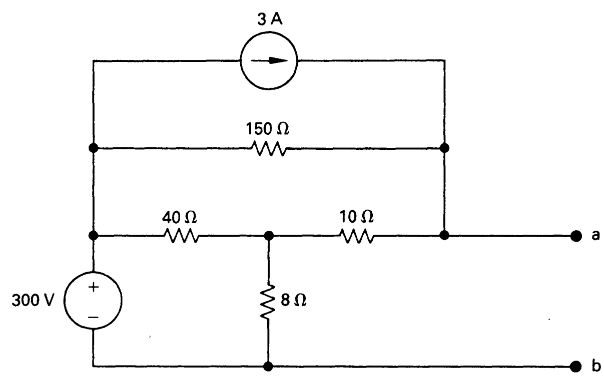

FIGURE P4.56

4.57 a) Find the Thévenin equivalent with respect to the terminals a,b for the circuit in Fig. P4.57 by finding the open-circuit voltage and the short-circuit current.

b) Solve for the Thévenin resistance by removing the independent sources. Compare your result to the Thévenin resistance found in part (a).

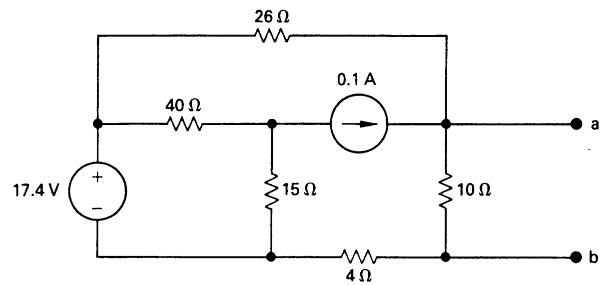

FIGURE P4.57

4.58 Find the Norton equivalent with respect to the terminals a,b in the circuit in Fig. P4.58.

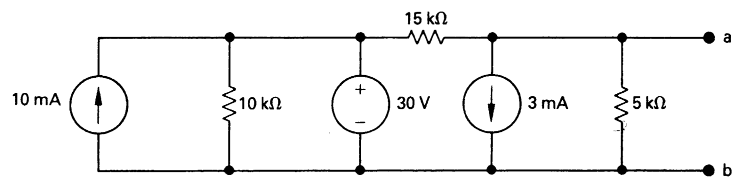

FIGURE P4.58

4.59 Determine i_o and v_o in the circuit shown in Fig. P4.59 when R_o is 0, 1, 3, 5, 10, 15, 25, 40, 55, 70, 85, and 95-Ω.

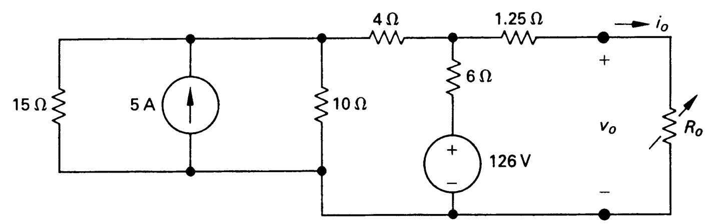

FIGURE P4.59

4.60 A voltmeter with a resistance of 85.5 kΩ is used to measure the voltage v_{ab} in the circuit in Fig. P4.60.

a) What is the voltmeter reading?

b) What is the percent error in the voltmeter reading if percent error is defined as [(measured − actual)/actual] × 100?

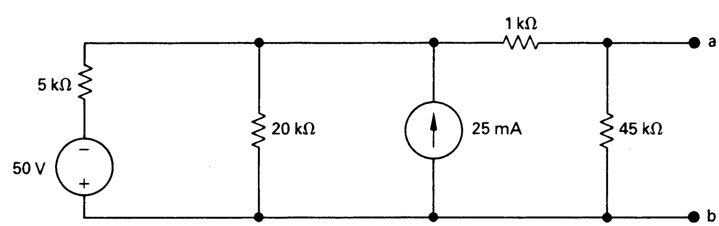

FIGURE P4.60

4.61 The Wheatstone bridge in the circuit shown in Fig. P4.61 is balanced when R_2 equals 3000 Ω. If the galvanometer has a resistance of 50 Ω, how much current will the galvanometer detect when the bridge is unbalanced by setting R_2 to 3003 Ω? (*Hint:* Find the Thévenin equivalent with respect to the galvanometer terminals when $R_2 = 3003$ Ω.) Note that once we have found the Thévenin equivalent with respect to the galvanometer terminals, it is easy to find the amount of unbalanced current in the galvanometer branch for different galvanometer movements.

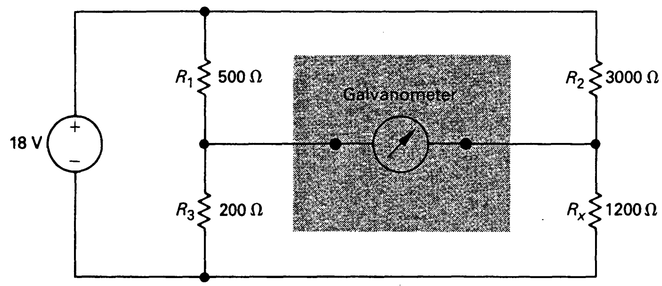

FIGURE P4.61

4.62 Determine the Thévenin equivalent with respect to the terminals a,b for the circuit shown in Fig. P4.62.

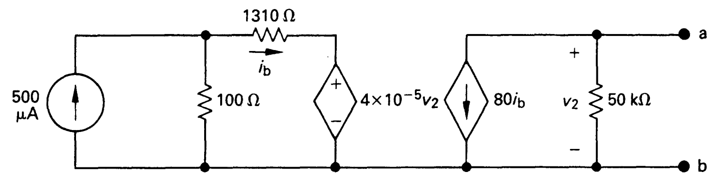

FIGURE P4.62

4.63 Find the Thévenin equivalent with respect to the terminals a,b for the circuit shown in Fig. P4.63.

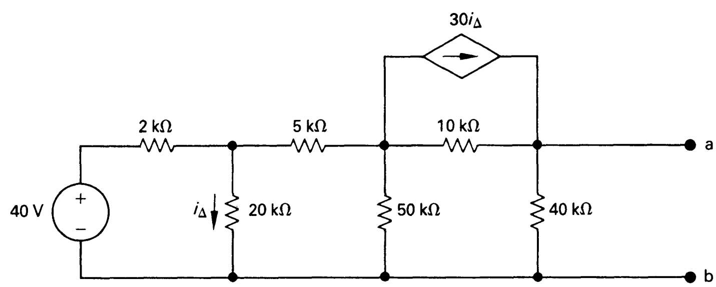

FIGURE P4.63

4.64 When a voltmeter is used to measure the voltage v_e in Fig. P4.64 it reads 5.5 V.

a) What is the resistance of the voltmeter?

b) What is the percent error in the voltage measurement?

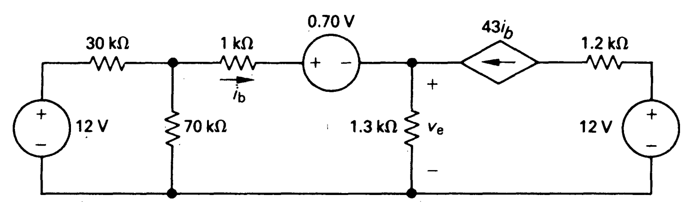

FIGURE P4.64

4.65 When an ammeter is used to measure the current i_ϕ in the circuit shown in Fig. P4.65 it reads 6 A.

a) What is the resistance of the ammeter?

b) What is the percent error in the current measurement?

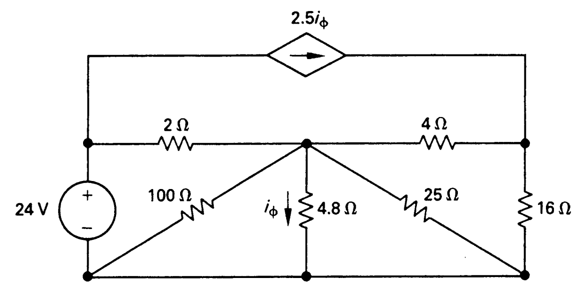

FIGURE P4.65

4.66 Find the Thévenin equivalent with respect to the terminals a,b for the circuit shown in Fig. P4.66.

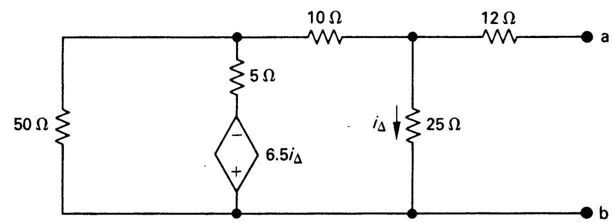

FIGURE P4.66

4.67 Find the Thévenin equivalent with respect to the terminals a,b in the circuit in Fig. P4.67.

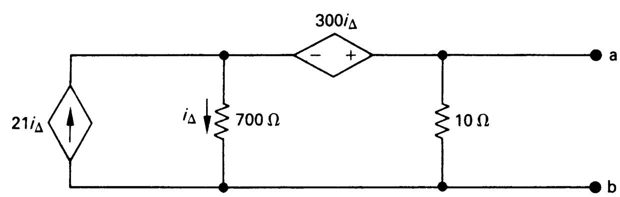

FIGURE P4.67

4.68 A Thévenin equivalent can also be determined from measurements made at the pair of terminals of interest. Assume the following measurements were made at the terminals a,b in the circuit in Fig. P4.68.

When a 20-Ω resistor is connected to the terminals a,b the voltage v_{ab} is measured and found to be 100 V.

When a 50-Ω resistor is connected to the terminals a,b the voltage is measured and found to be 200 V.

Find the Thévenin equivalent of the network with respect to the terminals a,b.

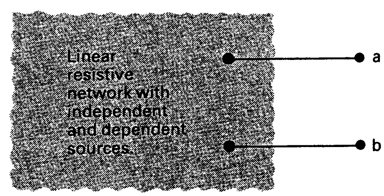

FIGURE P4.68

4.69 An automobile battery, when connected to a car radio, provides 12.5 V to the radio. When connected to a set of headlights it provides 11.8 V to the headlights. Assume the radio can be modeled as a 6-Ω resistor and the headlights can be modeled as a 0.75-Ω resistor. What are the Thévenin and Norton equivalents for the battery?

4.70 a) Calculate the power delivered to each resistor in Problem 4.59.

b) Plot the power delivered versus the resistance.

c) At what value of R is the power maximum?

4.71 The variable resistor in the circuit in Fig. P4.71 is adjusted for maximum power transfer to R_o.

a) Find the value of R_o.

b) Find the maximum power that can be delivered to R_o.

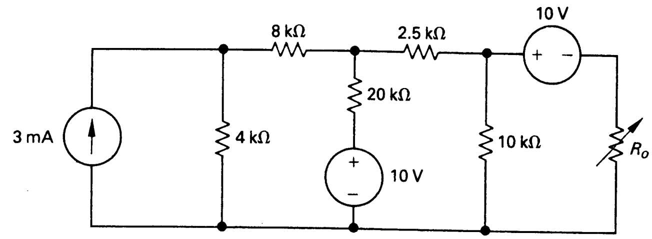

FIGURE P4.71

4.72 The variable resistor in the circuit in Fig. P4.72 is adjusted for maximum power transfer to R_o. What percentage of the total power developed in the circuit is delivered to R_o?

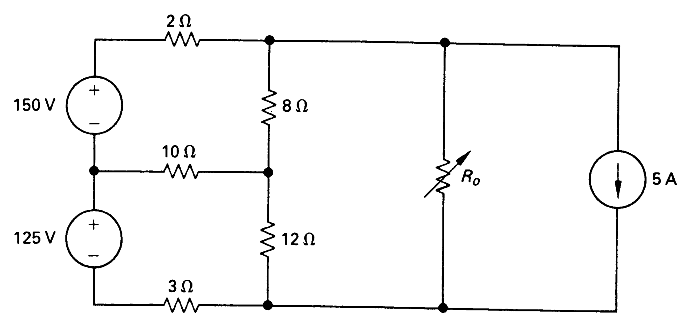

FIGURE P4.72

4.73 The variable resistor (R_L) in the circuit in Fig. P4.73 is adjusted for maximum power transfer to R_L.

a) Find the numerical value of R_L.

b) Find the maximum power transfered to R_L.

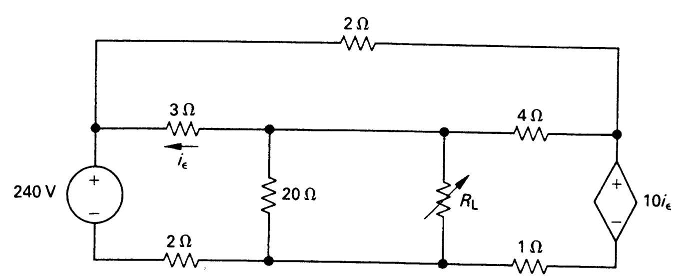

FIGURE P4.73

4.74 The variable resistor (R_o) in the circuit in Fig. P4.74 is adjusted for maximum power transfer to R_o.

a) Find the value of R_o.

b) Find the maximum power that can be delivered to R_o.

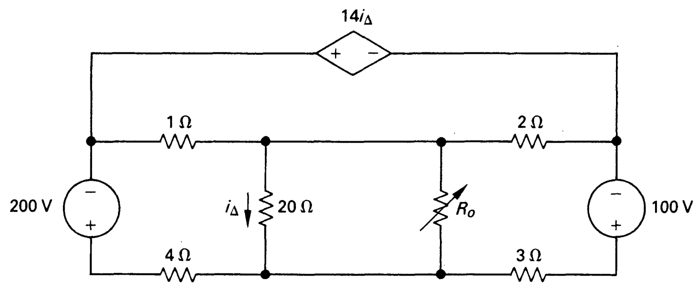

FIGURE P4.74

4.75 What percentage of the total power developed in the circuit in Fig. P4.74 is delivered to R_o?

4.76 The variable resistor (R_o) in the circuit in Fig. P4.76 is adjusted until it absorbs maximum power from the circuit. Find:

a) the value of R_o;

b) the maximum power; and

c) the percent of the total power developed in the circuit that is delivered to R_o.

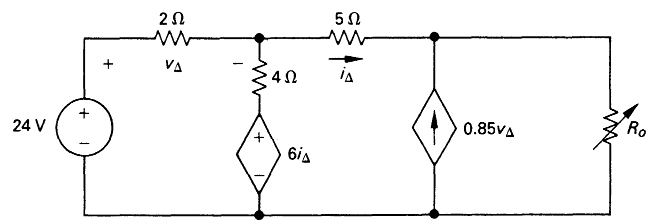

FIGURE P4.76

4.77 The variable resistor (R_o) in the circuit in Fig. P4.77 is adjusted for maximum power transfer to R_o. What percent of the total power developed in the circuit is delivered to R_o?

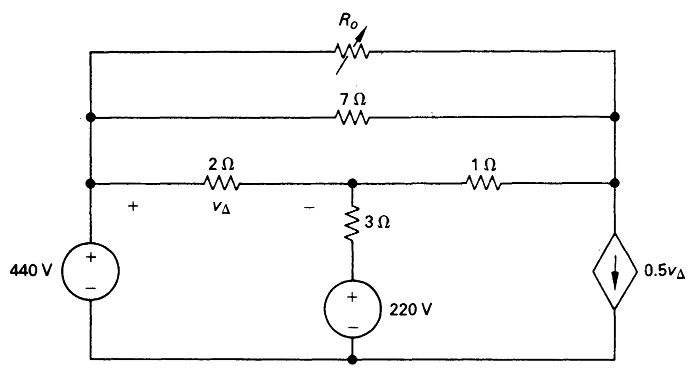

FIGURE P4.77

4.78 The 40-Ω resistor in the circuit in Fig. P4.24 is replaced with a variable resistor R_o. R_o is adjusted for maximum power transfer to R_o.

a) Find the numerical value of R_o.

b) Find the maximum power delivered to R_o.

c) How much power does the 20-V source deliver to the circuit when R_o is adjusted to the value found in part (a)?

4.79 A variable resistor R_o is connected across the terminals a,b in the circuit in Fig. P4.63. The variable resistor is adjusted until maximum power is transferred to R_o. Find:

a) the value of R_o;

b) the maximum power delivered to R_o; and

c) the percentage of the total power developed in the circuit that is delivered to R_o.

4.80 a) Find the value of the variable resistor R_o in the circuit in Fig. P4.80 that will result in maximum power dissipation in the 8-Ω resistor.

b) What is the maximum power that can be delivered to the 8-Ω resistor.

(*Hint:* Hasty conclusions could be hazardous to your career.)

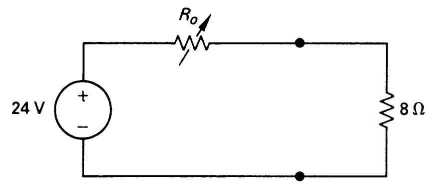

FIGURE P4.80

4.81 Use superposition to solve for i_o and v_o in the circuit in Fig. P4.81.

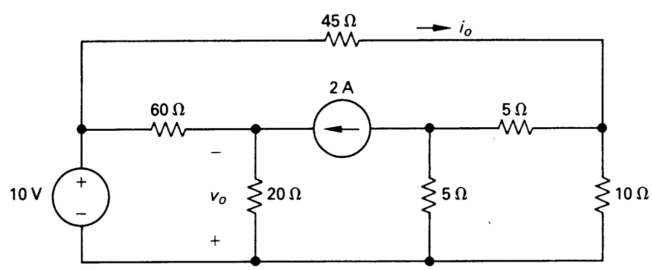

FIGURE P4.81

4.82 Use the principle of superposition to find the current i_o in the circuit shown in Fig. P4.82.

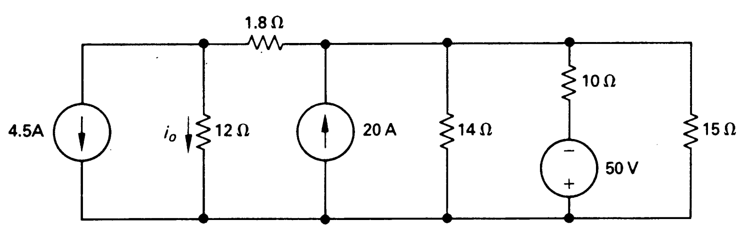

FIGURE P4.82

4.83 Use the principle of superposition to find v_o in the circuit in Fig. P4.83.

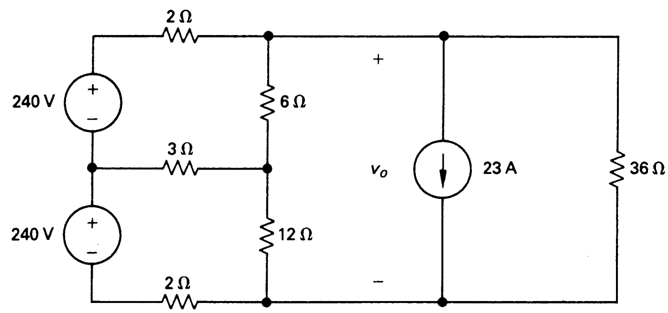

FIGURE P4.83

4.84 Use the principle of superposition to find the voltage v_o in the circuit in Fig. P4.84.

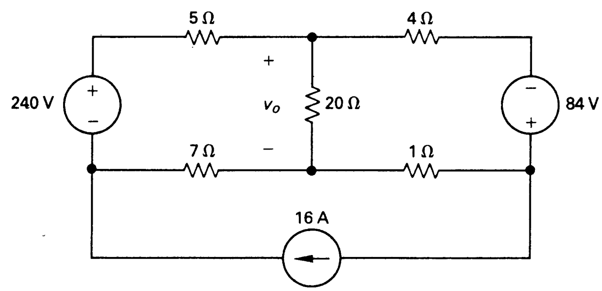

FIGURE P4.84

4.85 a) In the circuit in Fig. P4.85, before the 5-mA current source is attached to the terminals a,b the current i_o was calculated and found to be 3.5 mA. Use superposition to find the value of i_o after the current source is attached.

b) Verify your solution by finding i_o when all three sources are acting simultaneously.

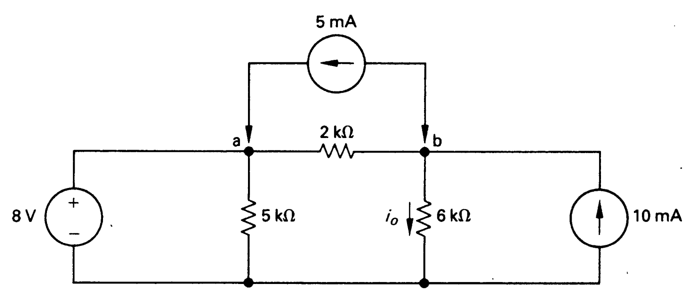

FIGURE P4.85

4.86 Use the principle of superposition to find v_o in the circuit in Fig. P4.86.

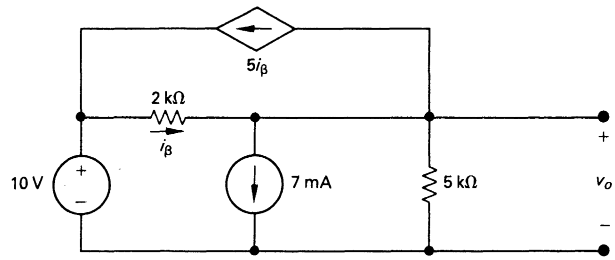

FIGURE P4.86

4.87 Use the principle of superposition to find the current entering the positive terminal of the 75-V source in the circuit in Fig. P4.37.

4.88 Use the principle of superposition to find the current i_Δ in the circuit in Fig. P4.40.

4.89 Use the principle of superposition to find v_Δ in the circuit in Fig. P4.39.

4.90 Use the principle of superposition to find the voltage across the dependent current source in the circuit in Fig. P4.44. Use the upper terminal of the dependent current source as the positive reference for the voltage.

4.91 Laboratory measurements on a dc voltage source yield a terminal voltage of 75 V with no load connected to the source and 60 V when loaded with a 20-Ω resistor.

a) What is the Thévenin equivalent with respect to the terminals of the dc voltage source?

b) Show that the Thévenin resistance of the source is given by the expression

$$R_{Th} = \left(\frac{V_{Th}}{V_o} - 1\right)R_L,$$

where

V_{Th} = the Thévenin voltage,

V_o = the terminal voltage corresponding to the load resistance R_L.

4.92 Two ideal dc voltage sources are connected by electrical conductors that have a resistance of r ohms/meter as shown in Fig. P4.92. A load having a resistance of R ohms moves between the two voltage sources. Let x equal the distance between the load and the source V_1 and L equal the distance between the sources.

a) Show that

$$v = \frac{V_1RL + R(V_2 - V_1)x}{RL + 2rlx - 2rx^2}.$$

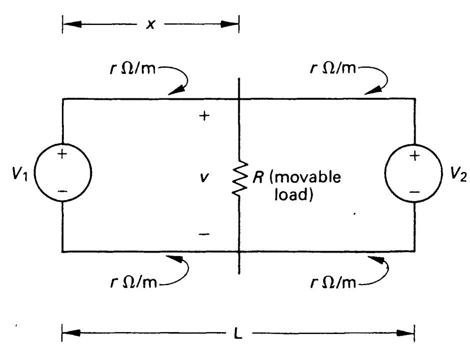

FIGURE P4.92

(continued)

b) Show that the voltage v will be minimum when

$$x = \frac{L}{V_2 - V_1}\left[-V_1 \pm \sqrt{V_1 V_2 - \frac{R}{2rL}(V_1 - V_2)^2}\right].$$

c) Find x when $L = 16$ km, $V_1 = 1000$ V, $V_2 = 1200$ V, $R = 3.9\ \Omega$ and $r = 5 \times 10^{-5}\ \Omega$/m.

d) What is the minimum value of v for the circuit of part (c)?

4.93 Assume your supervisor has asked you to determine the power developed by the 1-V source in the circuit in Fig. P4.93. Before calculating the power developed by the 1-V source the supervisor asks you to submit a proposal describing how you plan to attack the problem. Furthermore he asks you to explain why you have chosen your proposed method of solution.

a) Describe your plan of attack and at the same time explain your reasoning.

b) Use the method you have outlined in (a) to find the power developed by the 1-V source.

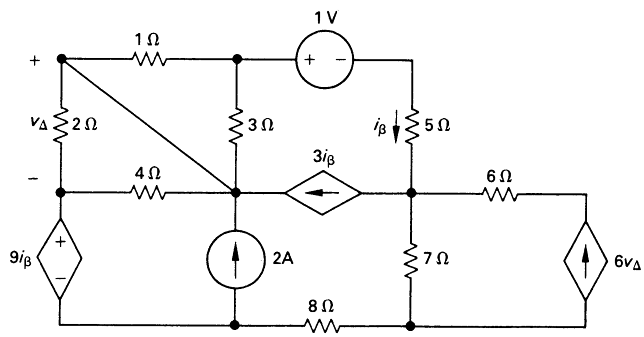

FIGURE P4.93

4.94 Find the power absorbed by the 5-A current source in the circuit in Fig. P4.94.

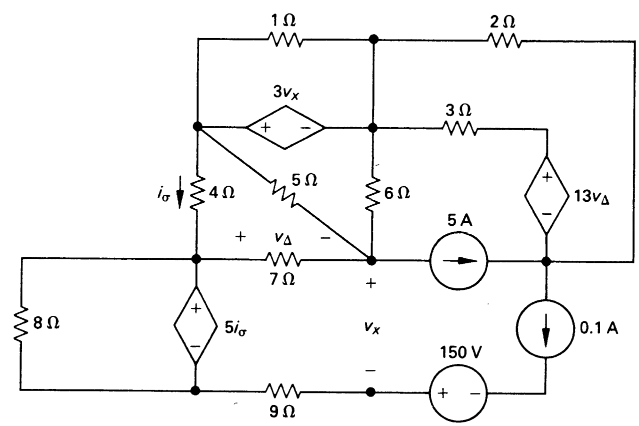

FIGURE P4.94

4.95 Find v_1, v_2, and v_3 in the circuit in Fig. P4.95.

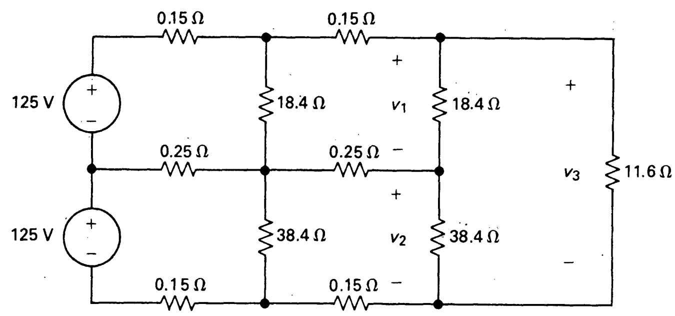

FIGURE P4.95

4.96 Find i_1 in the circuit in Fig. P4.96.

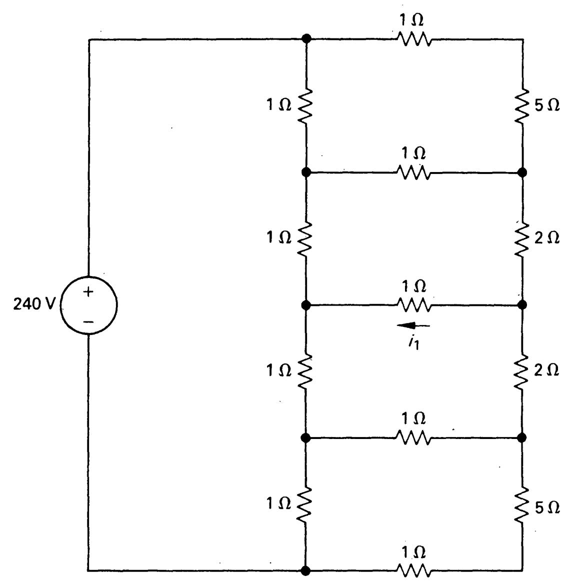

FIGURE P4.96

- *Differential operation:* In this open-loop operation, the high gain of the amplifier is used to amplify a small difference in the input voltages.

We also discussed the

- *common-mode signal*, which is the average value of two signals (either voltage or current);
- *differential-mode signal,* which is the difference between two signals (either voltage or current);
- *common-mode rejection ratio (CMRR),* which is a measure of how effective an operational amplifier is in rejecting the common-mode component of a signal; and
- *Bartlett's bisection theorem,* which is a technique for analyzing symmetric circuits by combining common-mode and differential-mode signal components with the principle of superposition.

PROBLEMS

6.1 The operational amplifier in the circuit in Fig. P6.1 is ideal.

a) Calculate v_o if $v_a = 1.5$ V and $v_b = 0$ V.
b) Calculate v_o if $v_a = 3.0$ V and $v_b = 0$ V.
c) Calculate v_o if $v_a = 1.0$ V and $v_b = 2$ V.
d) Calculate v_o if $v_a = 4.0$ V and $v_b = 2$ V.
e) Calculate v_o if $v_a = 6.0$ V and $v_b = 8$ V.
f) If $v_a = 4.5$ V, specify the range of v_b such that the amplifier does not saturate.

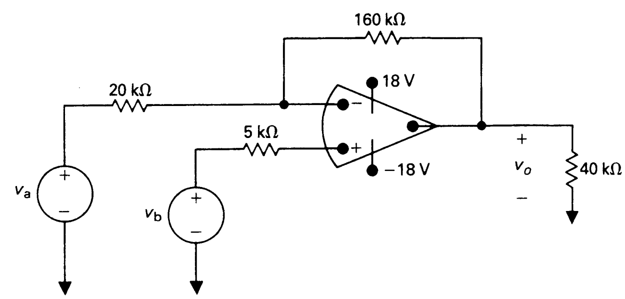

FIGURE P6.1

6.2 The operational amplifier in the circuit in Fig. P6.2 is ideal.

a) Calculate v_o.
b) Calculate i_o.

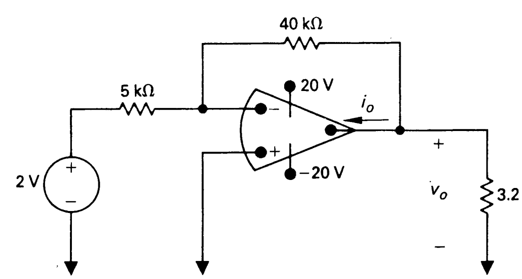

FIGURE P6.2

6.3 A voltmeter with a full-scale reading of 10 V is used to measure the output voltage in the circuit in Fig. P6.3. What is the reading of the voltmeter? Assume the operational amplifier is ideal.

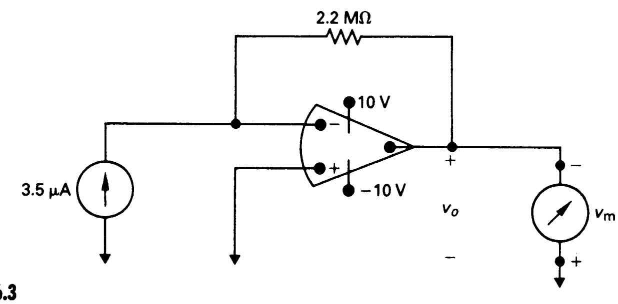

FIGURE P6.3

6.4 Find i_b in the circuit in Fig. P6.4 if the operational amplifier is ideal.

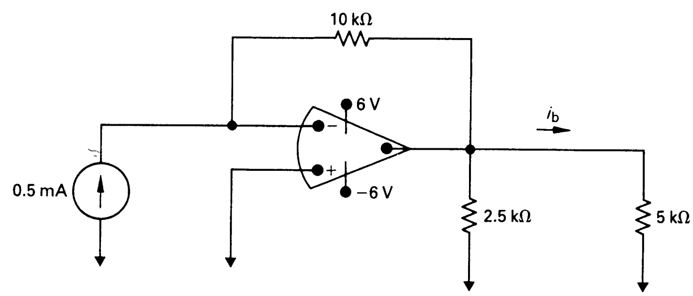

FIGURE P6.4

6.5 A circuit designer claims that the circuit in Fig. P6.5 will produce an output voltage that will vary between ±5 as v_g varies between 0 and 5 V. Assume the operational amplifier is ideal.

a) Draw a graph of the output voltage v_o as a function of the input voltage v_g for $0 \leq v_g \leq 5$ V.

b) Do you agree with the designer's claim?

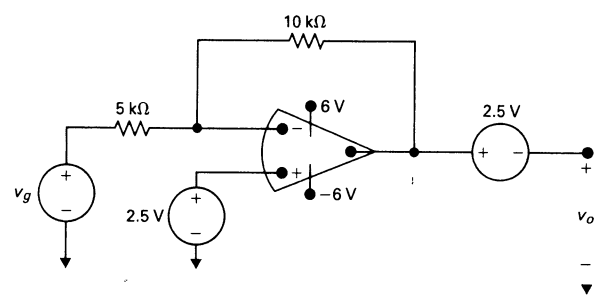

FIGURE P6.5

6.6 The operational amplifier in the circuit in Fig. P6.6 is ideal. Calculate:

a) v_1;

b) v_o;

c) i_2; and

d) i_o when $v_g = 150$ mV.

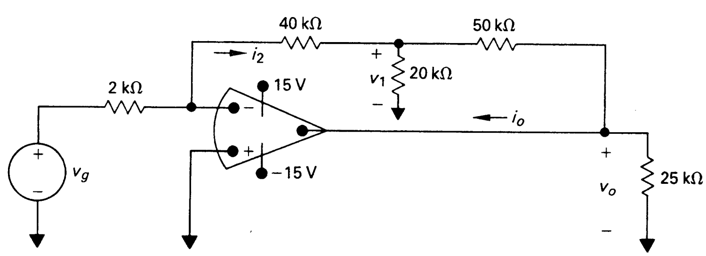

FIGURE P6.6

6.7 a) The operational amplifier in the circuit shown in Fig. P6.7 is ideal. The adjustable resistor R_Δ has a maximum value of 120 kΩ, and α is restricted to the range of $0.25 \leq \alpha \leq 0.8$. Calculate the range of v_o if $v_g = 40$ mV.

b) If α is not restricted, at what value of α will the operational amplifier saturate?

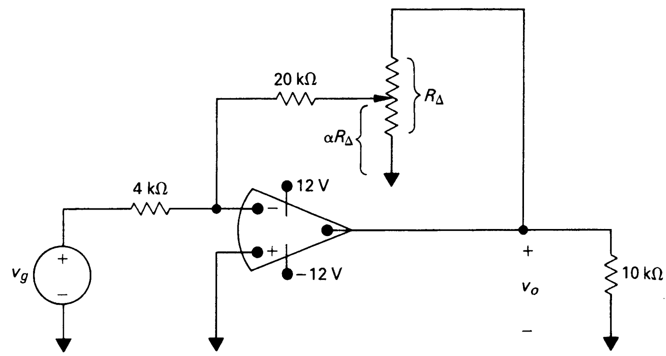

FIGURE P6.7

6.8 The operational amplifier in the circuit in Fig. P6.8 is ideal.

a) Find the range of values for σ for which the operational amplifier does not saturate.

b) Find i_o (in μA) when $\sigma = 0.272$.

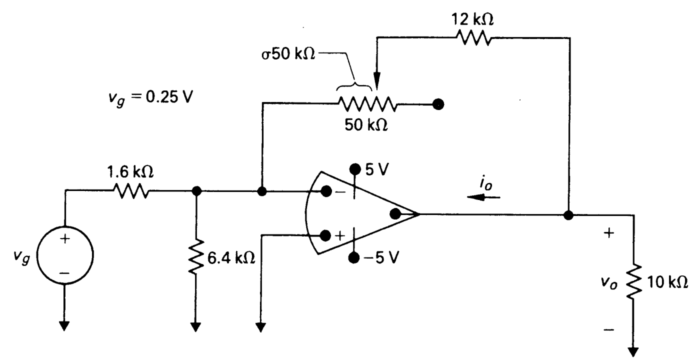

FIGURE P6.8

6.9 The operational amplifier in Fig. P6.9 is ideal.

a) Find v_o if $v_a = 1$ V, $v_b = 1.5$ V and $v_c = -4$ V.

b) The voltages v_a and v_c remain at 1 V and −4 V respectively. What are the limits on v_b if the operational amplifier operates within its linear region?

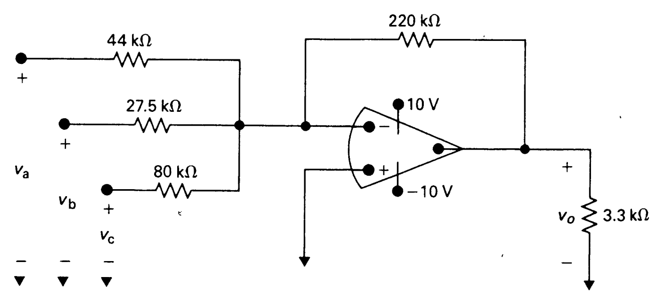

FIGURE P6.9

6.10 a) The operational amplifier in Fig. P6.10 is ideal. Find v_o if $v_a = 15$ V, $v_b = 10$ V, $v_c = 8$ V, and $v_d = 12$ V.

b) Assume v_a, v_c, and v_d retain their values as given in part (a). Specify the range of v_b such that the operational amplifier operates within its linear range.

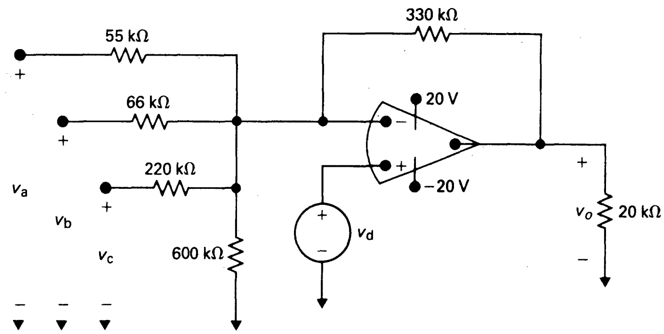

FIGURE P6.10

6.11 The 330-kΩ feedback resistor in the circuit in Fig. P6.10 is replaced by a variable resistor R_f. The voltages v_a through v_d have the same values as given in Problem 6.10(a).

a) What value of R_f will cause the operational amplifier to saturate? Note that $0 \leq R_f \leq \infty$.

b) When R_f has the value found in part (a) what is the current (in microamperes) into the output terminal of the operational amplifier?

6.12 The operational amplifiers in the circuit in Fig. P6.12 are ideal. Find i_a.

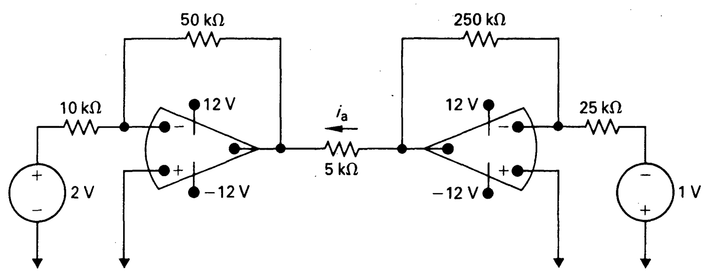

FIGURE P6.12

6.13 The variable resistor R_o in the circuit in Fig. P6.13 is adjusted until the source current i_g is zero. The operational amplifiers are ideal and $0 \leq v_g \leq 1.2$ V.

a) What is the value of R_o?

b) If $v_g = 1.0$ V, how much power (in μW) is dissipated in R_o?

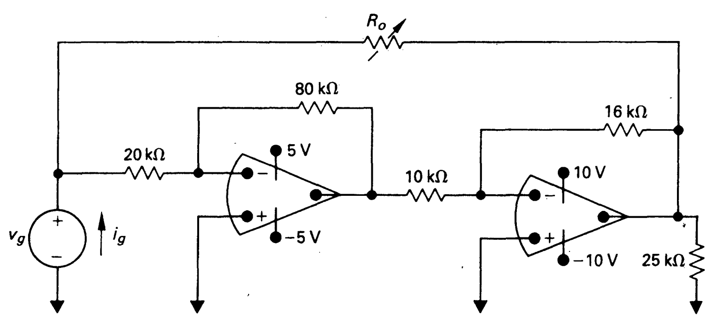

FIGURE P6.13

6.14 The circuit inside the shaded area in Fig. P6.14 is a constant current source for a limited range of values of R_L.

a) Find the value of i_L for $R_L = 4\ \text{k}\Omega$.

b) Find the maximum value for R_L for which i_L will have the value of part (a).

c) Assume that $R_L = 7\ \text{k}\Omega$. Explain the operation of the circuit. You can assume that $i_1 = i_2 \approx 0$ under all operating conditions.

d) Sketch i_L versus R_L for $0 \le R_L \le 7\ \text{k}\Omega$.

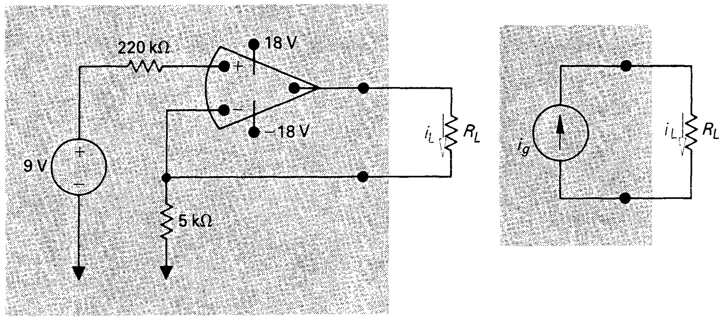

FIGURE P6.14

6.15 a) Find i_a in the circuit in Fig. P6.15 assuming the operational amplifier is ideal and is operating in its linear range.

b) How large can R be before the operational amplifier saturates?

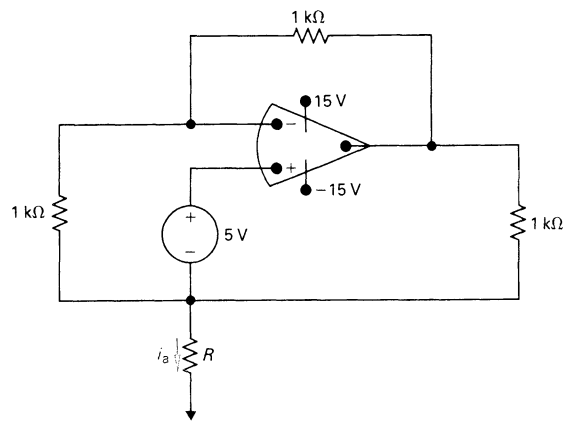

FIGURE P6.15

6.16 Refer to the circuit in Fig. 6.12, where the operational amplifier is assumed to be ideal. Given that $R_a = 3\ \text{k}\Omega$, $R_b = 5\ \text{k}\Omega$, $R_c = 25\ \text{k}\Omega$, $v_a = 150$ mV, $v_b = 100$ mV, $v_c = 250$ mV, and $V_{cc} = \pm 6$ V, specify the range of R_f for which the operational amplifier operates within its linear region.

6.17 The output voltage of a summing amplifier similar to that shown in Fig. 6.12 is to be the inverted weighted sum of the four input signals. Specifically,

$$v_o = -(2v_a + 4v_b + 6v_c + 8v_d).$$

If $R_f = 48\ \text{k}\Omega$, draw a circuit diagram of the amplifier and specify the values of R_a, R_b, R_c, and R_d.

6.18 The operational amplifier in the circuit shown in Fig. P6.18 is ideal.

a) Calculate v_o when v_g equals 4 V.

b) Specify the range of values of v_g so that the operational amplifier operates in a linear mode.

c) Assume that v_g equals 2 V and that the 63-kΩ resistor is replaced with a variable resistor. What value of the variable resistor will cause the operational amplifier to saturate?

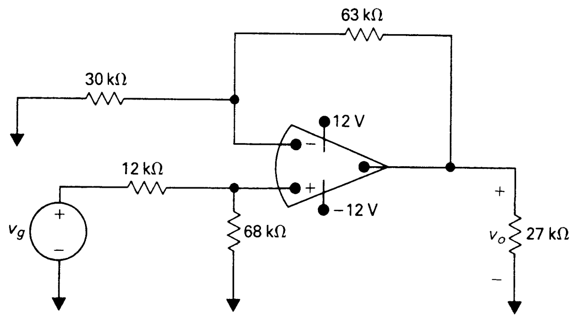

FIGURE P6.18

6.19 Assume that the ideal op amp in the circuit seen in Fig. P6.19 is operating in its linear region.

a) Show that $v_o = [(R_1 + R_2)/R_1]v_s$.

b) What happens if $R_1 \rightarrow \infty$ and $R_2 \rightarrow 0$?

c) Explain why this circuit is referred to as a voltage follower when $R_1 = \infty$ and $R_2 = 0$.

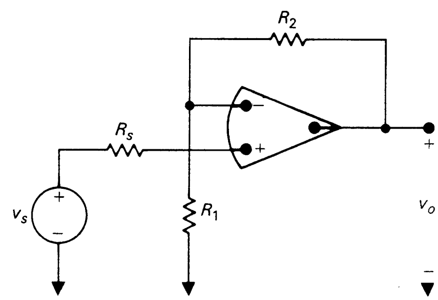

FIGURE P6.19

6.20 Assume that the ideal op amp in the circuit in Fig. P6.20 is operating in its linear region.

a) Calculate the power delivered to the 16-kΩ resistor.

b) Repeat part (a) with the operational amplifier removed from the circuit, that is, with the 16-kΩ resistor connected in the series with the voltage source and the 64-kΩ resistor.

c) Find the ratio of the power found in part (a) to that found in part (b).

d) Does the insertion of the op amp between the source and the load serve a useful purpose? Explain.

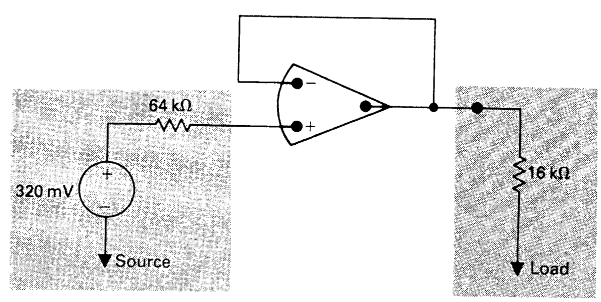

FIGURE P6.20

6.21 The operational amplifier in the noninverting amplifier shown in Fig. P6.21 is ideal. The signal voltages v_a and v_b are 800 mV and 400 mV respectively.

a) Calculate v_o in V.

b) Find i_a and i_b in μA.

c) What are the weighting factors associated with v_a and v_b?

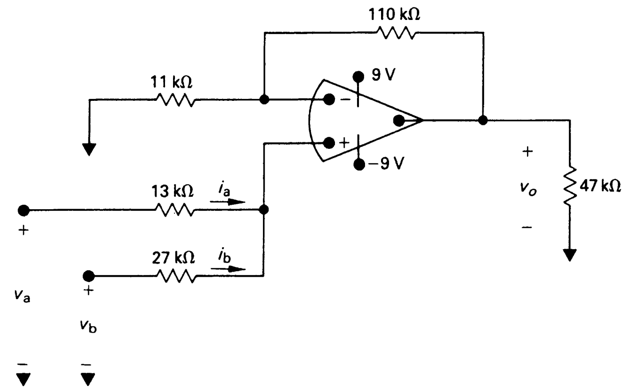

FIGURE P6.21

6.22 The circuit in Fig. P6.22 is a noninverting summing amplifier. The operational amplifier is ideal.

a) Specify the numerical values of R_a and R_c so that

$$v_o = v_a + 2v_b + 3v_c.$$

b) Calculate (in μA) i_a, i_b, and i_c when v_a = 0.7 V, v_b = 0.4 V, and v_c = 1.1 V.

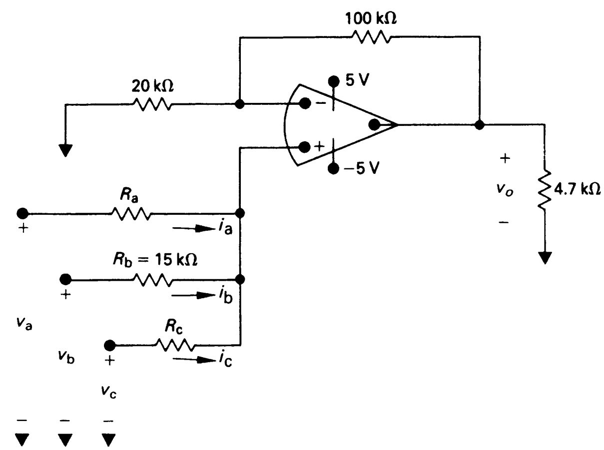

FIGURE P6.22

6.23 The operational amplifier in the noninverting summing amplifier of Fig. P6.23 is ideal.

a) Find the value of R_g so that

$$v_o = 1.8\ v_a + 7.2\ v_b + 14.4\ v_c$$

b) Find (in μA) i_a, i_b, i_c, i_g, and i_h when $v_a = 0.50$ V, $v_b = 0.25$ V, and $v_c = 0.15$ V.

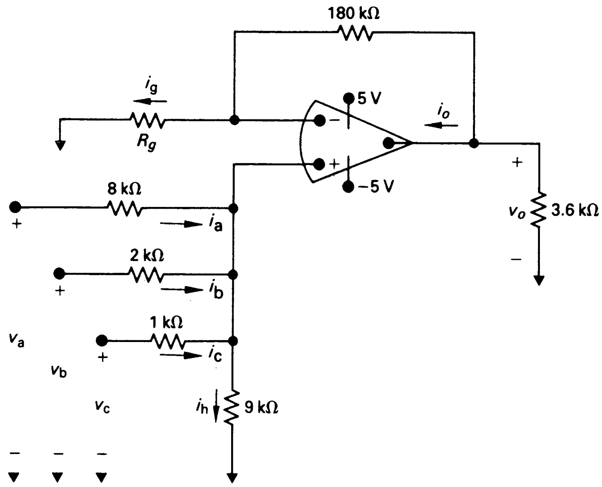

FIGURE P6.23

6.24 The operational amplifier in the circuit of Fig. P6.24 is ideal. Plot v_o versus α when $R_f = 4R_1$ and $v_g = 10$ V. Use increments of 0.1 and note by hypothesis that $0 \le \alpha \le 1.0$.

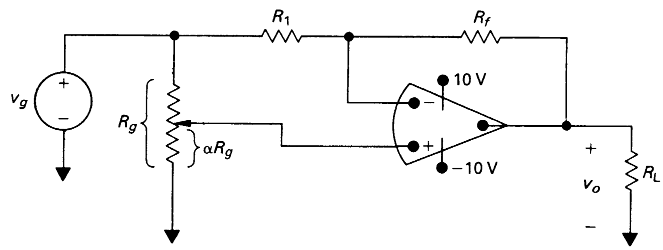

FIGURE P6.24

6.25 Select values of R_a, R_b, and R_f for the amplifier circuit of Fig. P6.25 such that $v_o = 10(v_b - v_a)$ and the voltage source v_b sees an input resistance of 220 kΩ. Use the ideal model for the operational amplifier.

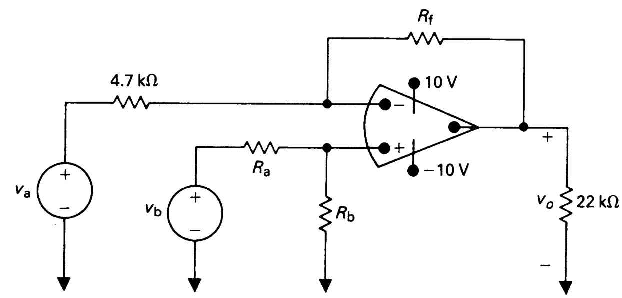

FIGURE P6.25

6.26 The resistors in the difference amplifier shown in Fig. 6.14 are $R_a = 24$ kΩ, $R_b = 75$ kΩ, $R_c = 130$ kΩ, and $R_d = 120$ kΩ. The signal voltages v_a and v_b are 8 and 5 V, respectively, and $V_{CC} = \pm 20$ V.

a) Find v_o.

b) What is the resistance seen by the signal source v_a?

c) What is the resistance seen by the signal source v_b?

6.27 Specify R_a, R_b, R_c, and R_d in the difference amplifier of Fig. 6.14 to meet the following criteria: $v_o = 4.2v_b - 6v_a$; the resistance seen by the signal source v_b is 450 kΩ; and the resistance seen by the signal source v_a is 21 kΩ when the output voltage v_o is zero.

6.28 Select the values of R_1 and R_f in the circuit in Fig. P6.28 so that

$$v_o = 5000(i_b - i_a).$$

The operational amplifier is ideal.

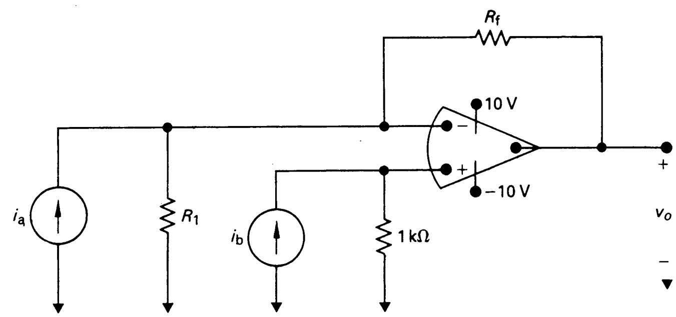

FIGURE P6.28

6.29 The operational amplifier in the adder-subtracter circuit shown in Fig. P6.29 is ideal.

a) Find v_o when $v_a = 1$ V, $v_b = 2$ V, $v_c = 3$ V, and $v_d = 4$ V.

b) If v_a, v_b, and v_d are held constant, what values of v_c will saturate the op amp?

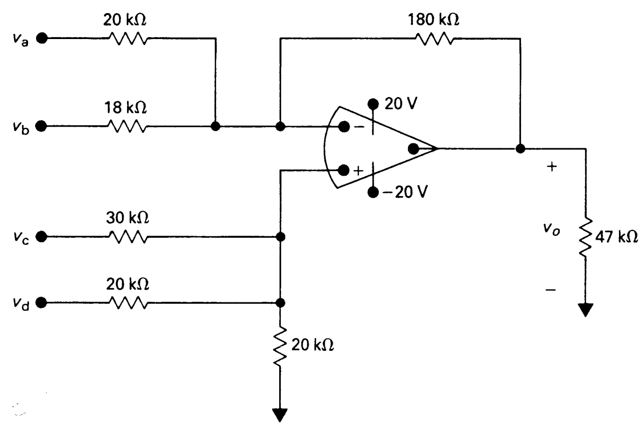

FIGURE P6.29

6.30 The inverting amplifier in the circuit in Fig. P6.30 has an input resistance of 500 kΩ, an output resistance of 5 kΩ, and an open-loop gain of 250,000. Assume that the amplifier is operating in its linear region. Calculate the following:

a) the voltage gain (v_o/v_g) of the amplifier;

b) the value of v_1 in microvolts when v_g = 100 mV;

c) the resistance seen by the signal source (v_g).

d) Repeat parts (a), (b), and (c) using the ideal model for the op amp.

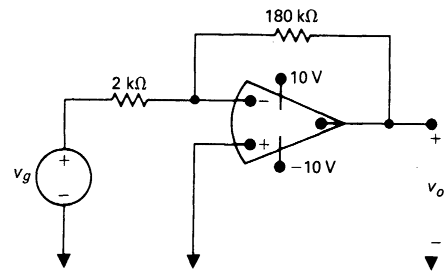

FIGURE P6.30

6.31 Repeat Problem 6.30 given that the inverting amplifier is loaded with a 1600-Ω resistor.

6.32 The operational amplifier in the noninverting amplifier circuit of Fig. P6.32 has an input resistance of 560 kΩ, an output resistance of 8 kΩ, and an open-loop gain of 50,000. Assume that the op amp is operating in its linear region. Calculate the following:

a) the voltage gain (v_o/v_g);

b) the inverting and noninverting input voltages v_1 and v_2 (in mV) if v_g = 1 V;

c) the difference ($v_2 - v_1$) in microvolts when v_g = 1 V;

d) the current drain in picoamperes on the signal source v_g when v_g = 1 V.

e) Repeat parts (a) through (d) assuming an ideal op amp.

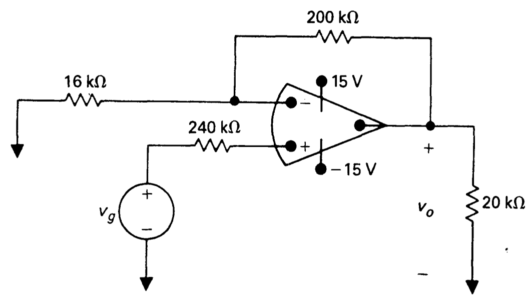

FIGURE P6.32

6.33 Assume the input resistance of the operational amplifier in Fig. P6.33 is infinite and its output resistance is zero.

a) Find v_o as a function of v_g and the open-loop gain A.

b) What is the value of v_o if v_g = 1 V and A = 194?

c) What is the value of v_o if v_g = 1 V and A = ∞?

d) How large does A have to be so that v_o is 99% of its value in part (c)?

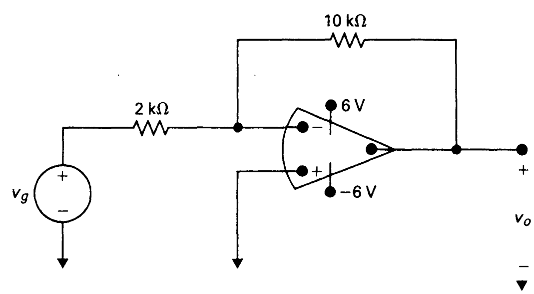

FIGURE P6.33

6.34 a) Find the Thévenin equivalent circuit with respect to the output terminals a,b for the inverting amplifier of Fig. P6.34. The dc signal source has a value of 880 mV. The operational amplifier has an input resistance of 500 kΩ, an output resistance of 2 kΩ, and an open loop gain of 100,000.

b) What is the output resistance of the inverting amplifier?

c) What is the resistance (in ohms) seen by the signal source v_g when the load at the terminals a,b is 330 Ω?

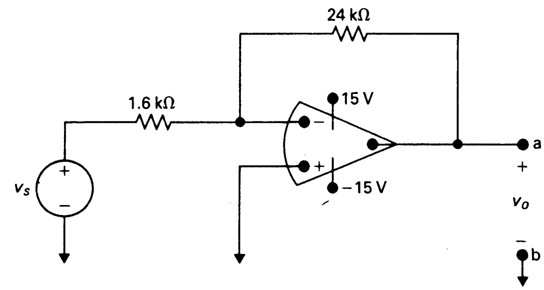

FIGURE P6.34

6.35 Find the Thévenin equivalent with respect to the terminals a,b in the circuit in Fig. P6.35 if the operational amplifier is ideal.

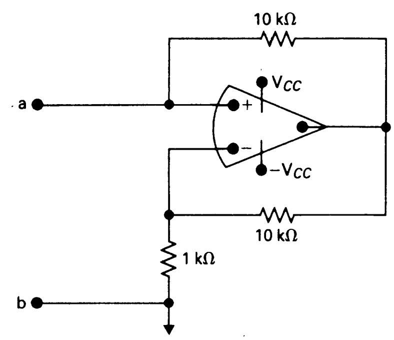

FIGURE P6.35

6.36 a) Derive Eq. (6.37). Note that Eq. (6.37) assumes an ideal operational amplifier and a constant bridge voltage of V_{dc} volts.

b) Verify the approximation given by Eq. (6.38) by using long division to expand

$$\frac{\epsilon}{1 + [R_1/(R_1 + R_4)]\epsilon}$$

into a power series. Simplify the algebra by letting $R_1/(R_1 + R_4) = \alpha$. Note that $\alpha < 1$ by definition. Comment on the significance of higher-order terms for small ϵ.

6.37 The two operational amplifiers in the circuit in Fig. P6.37 are ideal. Calculate v_{o1} and v_{o2}.

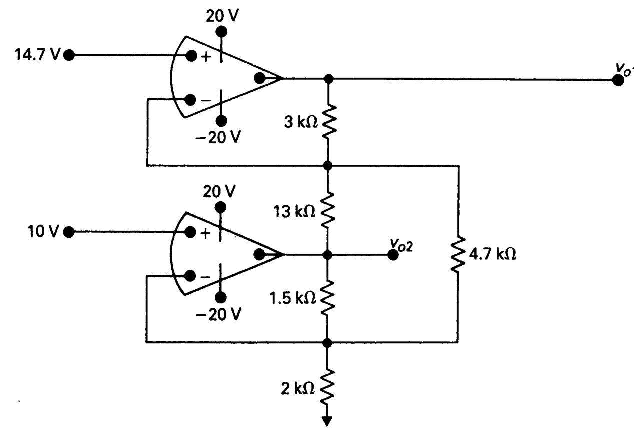

FIGURE P6.37

6.38 The resistor R_f in the circuit seen in Fig. P6.38 is adjusted until the ideal operational amplifier saturates. Specify R_f in kilohms.

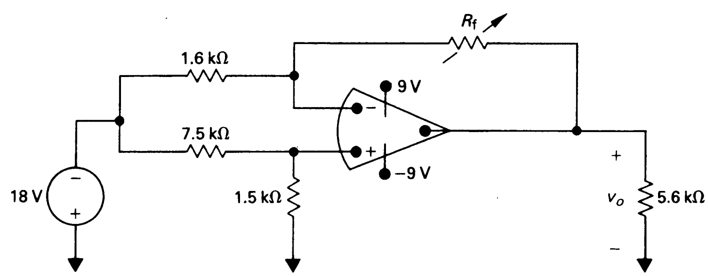

FIGURE P6.38

6.39 The operational amplifiers in the circuit of Fig. P6.39 are ideal. Find v_x, i_a, and i_o.

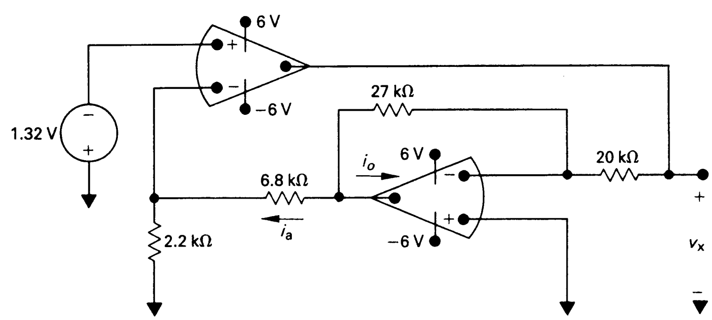

FIGURE P6.39

6.40 Find v_o and i_o in the circuit shown in Fig. P6.40 if the operational amplifiers are ideal.

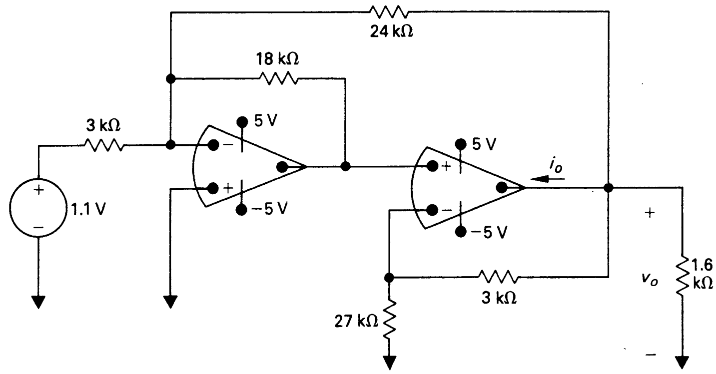

FIGURE P6.40

6.41 The operational amplifiers in the circuit shown in Fig. P6.41 are ideal.

a) Find v_o as a function of α, σ, v_{g1}, and v_{g2} when the op amps operate within their linear range.

b) Describe the behavior of the circuit when $\alpha = \sigma = 1.0$.

c) Describe the behavior of the circuit when $\alpha = \sigma = 0$.

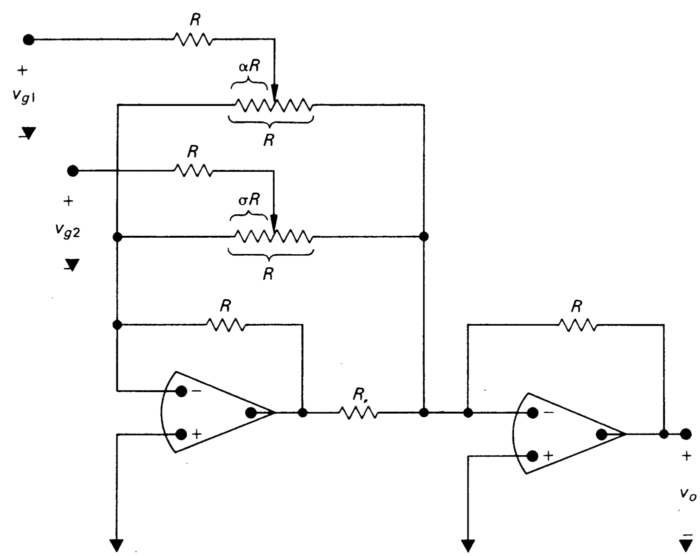

FIGURE P6.41

6.42 The voltage v_g shown in Fig. P6.42(a) is applied to the inverting amplifier shown in Fig. P6.42(b). Sketch v_o vs. t assuming the operational amplifier is ideal.

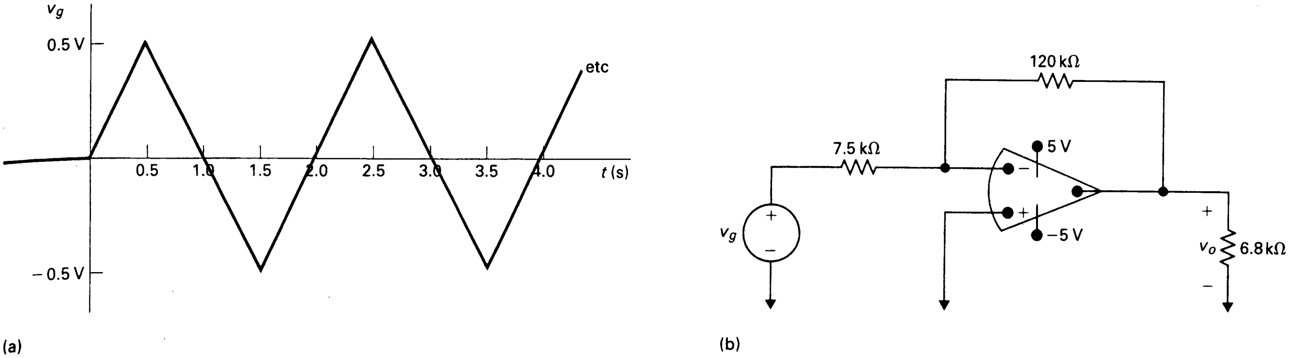

FIGURE P6.42

6.43 The signal voltage v_g in the circuit shown in Fig. P6.43 is described by the following equations:

$$v_g = 0 \qquad t \leq 0$$

$$v_g = 4 \sin (5\pi/3)t \text{ V} \qquad 0 \leq t \leq \infty.$$

Sketch v_o vs. t assuming the operational amplifier is ideal.

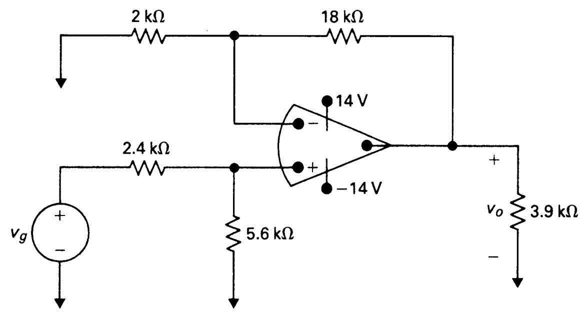

FIGURE P6.43

6.44 Use Bartlett's bisection theorem to find i_a through i_e in the circuit in Fig. P6.44.

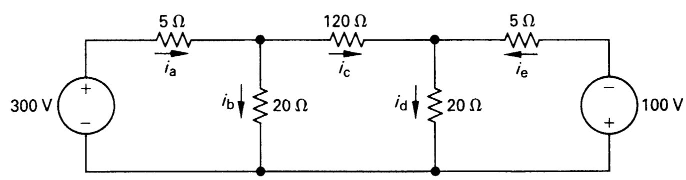

FIGURE P6.44

6.45 Use Bartlett's bisection theorem to find i_1 and i_2 in the circuit in Fig. P6.45. (*Hint:* Observe that $v_2 = 0$).

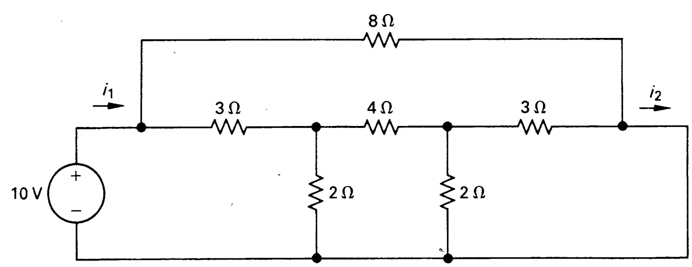

FIGURE P6.45