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## Simple Resistive Circuits

## Assessment Problems

AP 3.1



Start from the right hand side of the circuit and make series and parallel combinations of the resistors until one equivalent resistor remains. Begin by combining the  $6\Omega$  resistor and the  $10\Omega$  resistor in series:

 $6\,\Omega+10\,\Omega=16\,\Omega$ 

Now combine this  $16 \Omega$  resistor in parallel with the  $64 \Omega$  resistor:

$$16\,\Omega \| 64\,\Omega = \frac{(16)(64)}{16+64} = \frac{1024}{80} = 12.8\,\Omega$$

This equivalent  $12.8 \Omega$  resistor is in series with the  $7.2 \Omega$  resistor:

 $12.8\,\Omega+7.2\,\Omega=20\,\Omega$ 

Finally, this equivalent  $20 \Omega$  resistor is in parallel with the  $30 \Omega$  resistor:

$$20\,\Omega \| 30\,\Omega = \frac{(20)(30)}{20+30} = \frac{600}{50} = 12\,\Omega$$

Thus, the simplified circuit is as shown:



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[a] With the simplified circuit we can use Ohm's law to find the voltage across both the current source and the  $12\Omega$  equivalent resistor:

 $v = (12 \Omega)(5 A) = 60 V$ 

[b] Now that we know the value of the voltage drop across the current source, we can use the formula p = -vi to find the power associated with the source:

p = -(60 V)(5 A) = -300 W

Thus, the source delivers 300 W of power to the circuit.

[c] We now can return to the original circuit, shown in the first figure. In this circuit, v = 60 V, as calculated in part (a). This is also the voltage drop across the 30  $\Omega$  resistor, so we can use Ohm's law to calculate the current through this resistor:

$$i_A = \frac{60 \text{ V}}{30 \Omega} = 2 \text{ A}$$

Now write a KCL equation at the upper left node to find the current  $i_B$ :

$$-5 A + i_A + i_B = 0$$
 so  $i_B = 5 A - i_A = 5 A - 2 A = 3 A$ 

Next, write a KVL equation around the outer loop of the circuit, using Ohm's law to express the voltage drop across the resistors in terms of the current through the resistors:

$$-v + 7.2i_B + 6i_C + 10i_C = 0$$
  
So  $16i_C = v - 7.2i_B = 60 \text{ V} - (7.2)(3) = 38.4 \text{ V}$   
Thus  $i_C = \frac{38.4}{16} = 2.4 \text{ A}$ 

Now that we have the current through the  $10 \Omega$  resistor we can use the formula  $p = Ri^2$  to find the power:

$$p_{10\,\Omega} = (10)(2.4)^2 = 57.6 \text{ W}$$





[a] We can use voltage division to calculate the voltage  $v_o$  across the 75 k $\Omega$  resistor:

$$v_o(\text{no load}) = \frac{75,000}{75,000 + 25,000}(200 \text{ V}) = 150 \text{ V}$$

[b] When we have a load resistance of 150 k $\Omega$  then the voltage  $v_o$  is across the parallel combination of the 75 k $\Omega$  resistor and the 150 k $\Omega$  resistor. First, calculate the equivalent resistance of the parallel combination:

75 k
$$\Omega \| 150 \ k\Omega = \frac{(75,000)(150,000)}{75,000 + 150,000} = 50,000 \ \Omega = 50 \ k\Omega$$

Now use voltage division to find  $v_o$  across this equivalent resistance:

$$v_o = \frac{50,000}{50,000 + 25,000} (200 \text{ V}) = 133.3 \text{ V}$$

[c] If the load terminals are short-circuited, the 75 k $\Omega$  resistor is effectively removed from the circuit, leaving only the voltage source and the 25 k $\Omega$ resistor. We can calculate the current in the resistor using Ohm's law:

$$i = \frac{200 \text{ V}}{25 \text{ k}\Omega} = 8 \text{ mA}$$

Now we can use the formula  $p = Ri^2$  to find the power dissipated in the 25 k $\Omega$  resistor:

$$p_{25k} = (25,000)(0.008)^2 = 1.6 \text{ W}$$

[d] The power dissipated in the 75 k $\Omega$  resistor will be maximum at no load since  $v_o$  is maximum. In part (a) we determined that the no-load voltage is 150 V, so be can use the formula  $p = v^2/R$  to calculate the power:

$$p_{75k}(\max) = \frac{(150)^2}{75,000} = 0.3$$
 W

AP 3.3



[a] We will write a current division equation for the current throught the  $80\Omega$  resistor and use this equation to solve for R:

$$i_{80\Omega} = \frac{R}{R + 40\,\Omega + 80\,\Omega} (20 \text{ A}) = 4 \text{ A}$$
 so  $20R = 4(R + 120)$   
Thus  $16R = 480$  and  $R = \frac{480}{16} = 30\,\Omega$ 

[b] With  $R = 30 \Omega$  we can calculate the current through R using current division, and then use this current to find the power dissipated by R, using the formula  $p = Ri^2$ :

$$i_R = \frac{40 + 80}{40 + 80 + 30} (20 \text{ A}) = 16 \text{ A}$$
 so  $p_R = (30)(16)^2 = 7680 \text{ W}$ 

[c] Write a KVL equation around the outer loop to solve for the voltage v, and then use the formula p = -vi to calculate the power delivered by the current source:

 $-v + (60 \Omega)(20 \text{ A}) + (30 \Omega)(16 \text{ A}) = 0$  so v = 1200 + 480 = 1680 VThus,  $p_{\text{source}} = -(1680 \text{ V})(20 \text{ A}) = -33,600 \text{ W}$ 

Thus, the current source generates 33,600 W of power.

AP 3.4



[a] First we need to determine the equivalent resistance to the right of the  $40 \Omega$  and  $70 \Omega$  resistors:

$$R_{\rm eq} = 20\,\Omega \|30\,\Omega\| (50\,\Omega + 10\,\Omega) \qquad \text{so} \qquad \frac{1}{R_{\rm eq}} = \frac{1}{20\,\Omega} + \frac{1}{30\,\Omega} + \frac{1}{60\,\Omega} = \frac{1}{10\,\Omega}$$
  
Thus,  $R_{\rm eq} = 10\,\Omega$ 

Now we can use voltage division to find the voltage  $v_o$ :

$$v_o = \frac{40}{40 + 10 + 70} (60 \text{ V}) = 20 \text{ V}$$

[b] The current through the  $40 \Omega$  resistor can be found using Ohm's law:

$$i_{40\Omega} = \frac{v_o}{40} = \frac{20 \text{ V}}{40 \Omega} = 0.5 \text{ A}$$

1 -

This current flows from left to right through the  $40 \Omega$  resistor. To use current division, we need to find the equivalent resistance of the two parallel branches containing the  $20 \Omega$  resistor and the  $50 \Omega$  and  $10 \Omega$ resistors:

$$20\,\Omega \| (50\,\Omega + 10\,\Omega) = \frac{(20)(60)}{20 + 60} = 15\,\Omega$$

Now we use current division to find the current in the  $30 \Omega$  branch:

$$i_{30\Omega} = \frac{15}{15+30}(0.5 \text{ A}) = 0.16667 \text{ A} = 166.67 \text{ mA}$$

[c] We can find the power dissipated by the  $50 \Omega$  resistor if we can find the current in this resistor. We can use current division to find this current

from the current in the  $40 \Omega$  resistor, but first we need to calculate the equivalent resistance of the  $20 \Omega$  branch and the  $30 \Omega$  branch:

$$20 \,\Omega \| 30 \,\Omega = \frac{(20)(30)}{20 + 30} = 12 \,\Omega$$
  
Current division gives:  
$$i_{50\Omega} = \frac{12}{12 + 50 + 10} (0.5 \text{ A}) = 0.08333 \text{ A}$$
  
Thus,  $p_{50\Omega} = (50)(0.08333)^2 = 0.34722 \text{ W} = 347.22 \text{ mW}$ 

AP 3.5 [a]



We can find the current i using Ohm's law:

$$i = \frac{1 \text{ V}}{100 \Omega} = 0.01 \text{ A} = 10 \text{ mA}$$

[b]



 $R_m = 50 \,\Omega \| 5.555 \,\Omega = 5 \,\Omega$ 

We can use the meter resistance to find the current using Ohm's law:

$$i_{\text{meas}} = \frac{1 \text{ V}}{100 \,\Omega + 5 \,\Omega} = 0.009524 = 9.524 \text{ mA}$$

AP 3.6 [a]



Use voltage division to find the voltage v:

$$v = \frac{75,000}{75,000 + 15,000} (60 \text{ V}) = 50 \text{ V}$$

 $[\mathbf{b}]$ 



The meter resistance is a series combination of resistances:

$$R_m = 149,950 + 50 = 150,000\,\Omega$$

We can use voltage division to find v, but first we must calculate the equivalent resistance of the parallel combination of the 75 k $\Omega$  resistor and the voltmeter:

$$75,000 \,\Omega \| 150,000 \,\Omega = \frac{(75,000)(150,000)}{75,000 + 150,000} = 50 \,\mathrm{k\Omega}$$
  
Thus,  $v_{\mathrm{meas}} = \frac{50,000}{50,000 + 15,000} (60 \,\mathrm{V}) = 46.15 \,\mathrm{V}$ 

AP 3.7 [a] Using the condition for a balanced bridge, the products of the opposite resistors must be equal. Therefore,

$$100R_x = (1000)(150)$$
 so  $R_x = \frac{(1000)(150)}{100} = 1500 \,\Omega = 1.5 \,\mathrm{k\Omega}$ 

[b] When the bridge is balanced, there is no current flowing through the meter, so the meter acts like an open circuit. This places the following branches in parallel: The branch with the voltage source, the branch with the series combination  $R_1$  and  $R_3$  and the branch with the series combination of  $R_2$  and  $R_x$ . We can find the current in the latter two branches using Ohm's law:

$$i_{R_1,R_3} = \frac{5 \text{ V}}{100 \Omega + 150 \Omega} = 20 \text{ mA};$$
  $i_{R_2,R_x} = \frac{5 \text{ V}}{1000 + 1500} = 2 \text{ mA}$ 

We can calculate the power dissipated by each resistor using the formula  $p = Ri^2$ :

$$p_{100\Omega} = (100 \,\Omega)(0.02 \,\mathrm{A})^2 = 40 \,\mathrm{mW}$$

 $p_{150\Omega} = (150 \,\Omega)(0.02 \,\mathrm{A})^2 = 60 \,\mathrm{mW}$ 

 $p_{1000\Omega} = (1000 \,\Omega)(0.002 \,\mathrm{A})^2 = 4 \,\mathrm{mW}$ 

$$p_{1500\Omega} = (1500 \,\Omega)(0.002 \,\mathrm{A})^2 = 6 \,\mathrm{mW}$$

Since none of the power dissipation values exceeds 250 mW, the bridge can be left in the balanced state without exceeding the power-dissipating capacity of the resistors.

AP 3.8 Convert the three Y-connected resistors,  $20 \Omega$ ,  $10 \Omega$ , and  $5 \Omega$  to three  $\Delta$ -connected resistors  $R_{\rm a}, R_{\rm b}$ , and  $R_{\rm c}$ . To assist you the figure below has both the Y-connected resistors and the  $\Delta$ -connected resistors  $_{28 \Omega}$ 



$$R_{\rm a} = \frac{(5)(10) + (5)(20) + (10)(20)}{20} = 17.5\,\Omega$$
$$R_{\rm b} = \frac{(5)(10) + (5)(20) + (10)(20)}{10} = 35\,\Omega$$
$$R_{\rm c} = \frac{(5)(10) + (5)(20) + (10)(20)}{5} = 70\,\Omega$$

The circuit with these new  $\Delta$ -connected resistors is shown below:



From this circuit we see that the 70  $\Omega$  resistor is parallel to the 28  $\Omega$  resistor:

$$70\,\Omega \|28\,\Omega = \frac{(70)(28)}{70+28} = 20\,\Omega$$

Also, the  $17.5 \Omega$  resistor is parallel to the  $105 \Omega$  resistor:

$$17.5\,\Omega \| 105\,\Omega = \frac{(17.5)(105)}{17.5+105} = 15\,\Omega$$

Once the parallel combinations are made, we can see that the equivalent  $20 \Omega$  resistor is in series with the equivalent  $15 \Omega$  resistor, giving an equivalent resistance of  $20 \Omega + 15 \Omega = 35 \Omega$ . Finally, this equivalent  $35 \Omega$  resistor is in parallel with the other  $35 \Omega$  resistor:

$$35\,\Omega \| 35\,\Omega = \frac{(35)(35)}{35+35} = 17.5\,\Omega$$

Thus, the resistance seen by the 2 A source is  $17.5 \Omega$ , and the voltage can be calculated using Ohm's law:

 $v = (17.5 \,\Omega)(2 \,\mathrm{A}) = 35 \,\mathrm{V}$ 

## Problems

P 3.1 [a] The 6 k $\Omega$  and 12 k $\Omega$  resistors are in series, as are the 9 k $\Omega$  and 7 k $\Omega$  resistors. The simplified circuit is shown below:



**[b]** The 3 k $\Omega$ , 5 k $\Omega$ , and 7 k $\Omega$  resistors are in series. The simplified circuit is shown below:



[c] The  $300 \Omega$ ,  $400 \Omega$ , and  $500 \Omega$  resistors are in series. The simplified circuit is shown below:



P 3.2 [a] The  $10 \Omega$  and  $40 \Omega$  resistors are in parallel, as are the  $100 \Omega$  and  $25 \Omega$  resistors. The simplified circuit is shown below:



[b] The 9 k $\Omega$ , 18 k $\Omega$ , and 6 k $\Omega$  resistors are in parallel. The simplified circuit is shown below:



[c] The  $600 \Omega$ ,  $200 \Omega$ , and  $300 \Omega$  resistors are in parallel. The simplified circuit is shown below:



- P 3.3 Always work from the side of the circuit furthest from the source. Remember that the current in all series-connected circuits is the same, and that the voltage drop across all parallel-connected resistors is the same.
  - [a]  $R_{eq} = 6 + 12 + [4||(9+7)] = 6 + 12 + 4||16 = 6 + 12 + 3.2 = 21.2 \Omega$
  - $[\mathbf{b}] \ R_{\mathrm{eq}} = 4 \ \mathrm{k} + [10 \ \mathrm{k} \| (3 \ \mathrm{k} + 5 \ \mathrm{k} + 7 \ \mathrm{k})] = 4 \ \mathrm{k} + 10 \ \mathrm{k} \| 15 \ \mathrm{k} = 4 \ \mathrm{k} + 6 \ \mathrm{k} = 10 \ \mathrm{k} \Omega$
  - [c]  $R_{eq} = 300 + 400 + 500 + (600||1200) = 300 + 400 + 500 + 400 = 1600 \Omega$
- P 3.4 Always work from the side of the circuit furthest from the source. Remember that the current in all series-connected circuits is the same, and that the voltage drop across all parallel-connected resistors is the same.

[a] 
$$R_{eq} = 18 + [100||25||(10||40 + 22)] = 18 + [100||25||(8 + 22)]$$
  
=  $18 + [100||25||30] = 18 + 12 = 30 \Omega$ 

**[b]**  $R_{eq} = 10 \text{ k} \| [5 \text{ k} + 2 \text{ k} + (9 \text{ k} \| 18 \text{ k} \| 6 \text{ k})] = 10 \text{ k} \| [5 \text{ k} + 2 \text{ k} + 3 \text{ k}]$ 

$$= 10 \text{ k} \| 10 \text{ k} = 5 \text{ k} \Omega$$

[c] 
$$R_{eq} = 600 \|200\|300\|(250 + 150) = 600\|200\|300\|400 = 80 \Omega$$

P 3.5 [a]  $R_{ab} = 10 + (5||20) + 6 = 10 + 4 + 6 = 20 \Omega$ [b]  $R_{ab} = 30 k||60 k||[20 k + (200 k||50 k)] = 30 k||60 k||(20 k + 40 k)$  $= 30 k||60 k||60 k = 15 k\Omega$ 

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[a]  $60||20| = 1200/80| = 15 \Omega$   $12||24| = 288/36| = 8 \Omega$ P 3.6  $15 + 8 + 7 = 30 \Omega$  $30||120 = 3600/150 = 24 \Omega$  $R_{\rm ab} = 15 + 24 + 25 = 64\,\Omega$ 

**[b]**
$$35 + 40 = 75 \Omega$$
 $75 ||50 = 3750/125 = 30 \Omega$  $30 + 20 = 50 \Omega$  $50 ||75 = 3750/125 = 30 \Omega$  $30 + 10 = 40 \Omega$  $40 ||60 + 9||18 = 24 + 6 = 30 \Omega$  $30 ||30 = 15 \Omega$  $R_{ab} = 10 + 15 + 5 = 30 \Omega$ 

 $[c] \quad 50 + 30 = 80\,\Omega \qquad 80||20 = 16\,\Omega$  $16 + 14 = 30 \,\Omega$   $30 + 24 = 54 \,\Omega$  $54||27 = 18\,\Omega \qquad 18 + 12 = 30\,\Omega$  $30||30 = 15 \Omega$   $R_{ab} = 3 + 15 + 2 = 20 \Omega$ 

P 3.7 **[a]** For circuit (a)

 $R_{\rm ab} = 4 \| (3+7+2) = 4 \| 12 = 3 \,\Omega$ 

For circuit (b)

 $R_{\rm ab} = 6 + 2 + [8\|(7+5\|2.5\|7.5\|5\|(9+6))] = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\|(9+6)\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 2 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 6 + 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|5\| = 8\|(7+1)\|$  $= 6 + 2 + 4 = 12 \Omega$ For circuit (c)

$$144 ||(4 + 12) = 14.4 \Omega$$

$$14.4 + 5.6 = 20 \Omega$$

$$20 ||12 = 7.5 \Omega$$

$$7.5 + 2.5 = 10 \Omega$$

$$10 ||15 = 6 \Omega$$

$$14 + 6 + 10 = 30 \Omega$$

$$R_{ab} = 30 ||60 = 20 \Omega$$

$$[b] P_a = \frac{15^2}{3} = 75 W$$

$$P_b = \frac{48^2}{12} = 192 W$$

$$P_c = 5^2(20) = 500 W$$

P 3.8 [a] 
$$p_{4\Omega} = i_s^2 4 = (12)^2 4 = 576 \text{ W}$$
  $p_{18\Omega} = (4)^2 18 = 288 \text{ W}$   
 $p_{3\Omega} = (8)^2 3 = 192 \text{ W}$   $p_{6\Omega} = (8)^2 6 = 384 \text{ W}$   
[b]  $p_{120V}(\text{delivered}) = 120i_s = 120(12) = 1440 \text{ W}$   
[c]  $p_{\text{diss}} = 576 + 288 + 192 + 384 = 1440 \text{ W}$   
P 3.9 [a] From Ex. 3-1:  $i_1 = 4 \text{ A}$ ,  $i_2 = 8 \text{ A}$ ,  $i_s = 12 \text{ A}$   
at node b:  $-12 + 4 + 8 = 0$ , at node d:  $12 - 4 - 8 = 0$   
 $4\Omega$   $3\Omega$   
 $i_s \uparrow + v_1 - v_2 \rightarrow 18\Omega$   $v_4 \rightarrow 6\Omega$   
 $120 \sqrt{40} + \sqrt{14} + \sqrt{14}$ 

 $v_2 = 18i_1 = 72 \text{ V}$   $v_4 = 6i_2 = 48 \text{ V}$ loop abda: -120 + 48 + 72 = 0, loop bcdb: -72 + 24 + 48 = 0, loop abcda: -120 + 48 + 24 + 48 = 0

P 3.10 
$$R_{eq} = 10 ||[6+5||(8+12)]| = 10 ||(6+5||20)| = 10 ||(6+4)| = 5 \Omega$$

 $v_{10A} = v_{10\Omega} = (10 \text{ A})(5 \Omega) = 50 \text{ V}$ 

Using voltage division:

$$v_{5\Omega} = \frac{5\|(8+12)}{6+5\|(8+12)}(50) = \frac{4}{6+4}(50) = 20 \text{ V}$$

Thus, 
$$p_{5\Omega} = \frac{v_{5\Omega}^2}{5} = \frac{20^2}{5} = 80$$
 W

P 3.11 [a]



$$\begin{aligned} v_o &= v_{201} = \frac{20}{10+20} (24) = 16 \text{ V} \\ v_{001} &= \frac{90||10}{6+(90||10)} (24) = \frac{9}{15} (24) = 14.4 \text{ V} \\ i_o &= \frac{14.4}{90} = 0.16 \text{ A} \end{aligned}$$

$$\begin{aligned} \text{[b]} & p_{60} = \frac{(v_{2.4A} - v_{901})^2}{6} = \frac{(24-14.4)^2}{6} = 15.36 \text{ W} \\ \text{[c]} & p_{2.4A} = -(2.4) (24) = -57.6 \text{ W} \\ \text{Thus the power developed by the current source is 57.6 W.} \end{aligned}$$

$$\begin{aligned} \text{P 3.12} \quad [\textbf{a}] & R + R = 2R \\ \text{[b]} & R + R + R + \cdots + R = nR \\ \text{[c]} & R + R = 2R = 3000 \quad \text{so} \quad R = 1500 = 1.5 \text{ k}\Omega \\ \text{This is a resistor from Appendix II.} \\ \text{[d]} & nR = 4000; \qquad \text{so in } n = 4, \quad R = 1 \text{ k}\Omega \\ \text{This is a resistor from Appendix H.} \end{aligned}$$

$$\begin{aligned} \text{P 3.13} \quad [\textbf{a}] & R_{eq} = R ||R = \frac{R^2}{2R} = \frac{R}{2} \\ \text{[b]} & R_{eq} = R ||R ||R ||R|| \cdots ||R \quad (n R^*s) \\ &= R ||\frac{R}{n-1} \\ &= \frac{R^2/(n-1)}{R + R/(n-1)} = \frac{R^2}{nR} = \frac{R}{n} \end{aligned}$$

$$\begin{aligned} \text{[c]} & \frac{R}{2} = 5000 \text{ so } R = 10 \text{ k}\Omega \\ \text{This is a resistor from Appendix H.} \end{aligned}$$

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$$\begin{aligned} \text{[c]} & \frac{R}{2} = 4000 \text{ so } R = 4000n \\ \text{If } n = 3 \quad r = 4000(3) = 12 \text{ k}\Omega \\ \text{This is a resistor from Appendix H. So put three 12k resistors in parallel to get 4k\Omega.} \end{aligned}$$

$$\begin{aligned} \text{P 3.14} & 4 = \frac{20R_2}{R_2 + 40} \text{ so } R_2 = 10\Omega \\ 3 = \frac{20R_e}{40 + R_e} \text{ so } R_e = \frac{120}{17} \Omega \\ \text{Thus, } \quad \frac{120}{17} = \frac{10R_L}{10 + R_L} \text{ so } R_L = 24\Omega \end{aligned}$$

P 3.15 [a] 
$$v_o = \frac{160(3300)}{(4700 + 3300)} = 66 \text{ V}$$
  
[b]  $i = 160/8000 = 20 \text{ mA}$   
 $P_{R_1} = (400 \times 10^{-6})(4.7 \times 10^3) = 1.88 \text{ W}$   
 $P_{R_2} = (400 \times 10^{-6})(3.3 \times 10^3) = 1.32 \text{ W}$ 

[c] Since  $R_1$  and  $R_2$  carry the same current and  $R_1 > R_2$  to satisfy the voltage requirement, first pick  $R_1$  to meet the 0.5 W specification

$$i_{R_1} = \frac{160 - 66}{R_1}$$
, Therefore,  $\left(\frac{94}{R_1}\right)^2 R_1 \le 0.5$   
Thus,  $R_1 \ge \frac{94^2}{0.5}$  or  $R_1 \ge 17,672 \,\Omega$ 

Now use the voltage specification:

$$\frac{R_2}{R_2 + 17,672}(160) = 66$$

Thus,  $R_2 = 12,408 \,\Omega$ 

P 3.16 [a] 
$$v_o = \frac{40R_2}{R_1 + R_2} = 8$$
 so  $R_1 = 4R_2$   
Let  $R_e = R_2 || R_L = \frac{R_2 R_L}{R_2 + R_L}$   
 $v_o = \frac{40R_e}{R_1 + R_e} = 7.5$  so  $R_1 = 4.33R_e$   
Then,  $4R_2 = 4.33R_e = \frac{4.33(3600R_2)}{3600 + R_2}$   
Thus,  $R_2 = 300 \Omega$  and  $R_1 = 4(300) = 1200 \Omega$ 

[b] The resistor that must dissipate the most power is  $R_1$ , as it has the largest resistance and carries the same current as the parallel combination of  $R_2$  and the load resistor. The power dissipated in  $R_1$  will be maximum when the voltage across  $R_1$  is maximum. This will occur when the voltage divider has a resistive load. Thus,

$$v_{R_1} = 40 - 7.5 = 32.5 \text{ V}$$
  
 $p_{R_1} = \frac{32.5^2}{1200} = 880.2 \text{ m W}$ 

Thus the minimum power rating for all resistors should be 1 W.

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P 3.17 Refer to the solution to Problem 3.16. The voltage divider will reach the maximum power it can safely dissipate when the power dissipated in  $R_1$  equals 1 W. Thus,

$$\frac{v_{R_1}^2}{1200} = 1 \quad \text{so} \quad v_{R_1} = 34.64 \text{ V}$$

$$v_o = 40 - 34.64 = 5.36 \text{ V}$$

$$\text{So, } \frac{40R_e}{1200 + R_e} = 5.36 \quad \text{and} \quad R_e = 185.68 \Omega$$

$$\text{Thus, } \frac{(300)R_L}{300 + R_L} = 185.68 \quad \text{and} \quad R_L = 487.26 \Omega$$

The minimum value for  $R_{\rm L}$  from Appendix H is 560  $\Omega$ .

P 3.18 Begin by using the relationships among the branch currents to express all branch currents in terms of  $i_4$ :

$$i_1 = 2i_2 = 2(2i_3) = 4(2i_4)$$
  
 $i_2 = 2i_3 = 2(2i_4)$   
 $i_3 = 2i_4$ 

Now use KCL at the top node to relate the branch currents to the current supplied by the source.

$$i_1 + i_2 + i_3 + i_4 = 1 \text{ mA}$$

Express the branch currents in terms of  $i_4$  and solve for  $i_4$ :

1 mA = 
$$8i_4 + 4i_4 + 2i_4 + i_4 = 15i_4$$
 so  $i_4 = \frac{0.001}{15}$  A

Since the resistors are in parallel, the same voltage, 1 V appears across each of them. We know the current and the voltage for  $R_4$  so we can use Ohm's law to calculate  $R_4$ :

$$R_4 = \frac{v_g}{i_4} = \frac{1 \text{ V}}{(1/15) \text{ mA}} = 15 \text{ k}\Omega$$

Calculate  $i_3$  from  $i_4$  and use Ohm's law as above to find  $R_3$ :

$$i_3 = 2i_4 = \frac{0.002}{15} \text{ A}$$
  $\therefore$   $R_3 = \frac{v_g}{i_3} = \frac{1 \text{ V}}{(2/15) \text{ mA}} = 7.5 \text{ k}\Omega$ 

Calculate  $i_2$  from  $i_4$  and use Ohm's law as above to find  $R_2$ :

$$i_2 = 4i_4 = \frac{0.004}{15} \text{ A}$$
  $\therefore$   $R_2 = \frac{v_g}{i_2} = \frac{1 \text{ V}}{(4/15) \text{ mA}} = 3750 \Omega$ 

Calculate  $i_1$  from  $i_4$  and use Ohm's law as above to find  $R_1$ :

$$i_1 = 8i_4 = \frac{0.008}{15} \text{ A}$$
  $\therefore$   $R_1 = \frac{v_g}{i_1} = \frac{1 \text{ V}}{(8/15) \text{ mA}} = 1875 \Omega$ 

The resulting circuit is shown below:

$$1_{mA} +$$

$$-$$

$$1_{875\Omega} +$$

$$3750\Omega + 7.5k\Omega + 15k\Omega$$

P 3.19 [a]



$$40~\mathrm{k}\Omega+60~\mathrm{k}\Omega=100~\mathrm{k}\Omega$$

25 kΩ||100 kΩ = 20 kΩ  
$$v_{o1} = \frac{20,000}{(75,000 + 20,000)} (380) = 80$$

$$v_o = \frac{60,000}{(100,000)}(v_{o1}) = 48 \text{ V}$$

[b ]



$$v_o = \frac{60,000}{100,000}(95) = 57 \text{ V}$$

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V

[c] It removes loading effect of second voltage divider on the first voltage divider. Observe that the open circuit voltage of the first divider is

$$v_{o1}' = \frac{25,000}{(100,000)}(380) = 95 \text{ V}$$

Now note this is the input voltage to the second voltage divider when the current controlled voltage source is used.

P 3.22 [a] At no load: 
$$v_o = kv_s = \frac{R_2}{R_1 + R_2}v_s$$
.  
At full load:  $v_o = \alpha v_s = \frac{R_e}{R_1 + R_e}v_s$ , where  $R_e = \frac{R_oR_2}{R_o + R_2}$ 

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Therefore 
$$k = \frac{R_2}{R_1 + R_2}$$
 and  $R_1 = \frac{(1-k)}{k}R_2$   
 $\alpha = \frac{R_e}{R_1 + R_e}$  and  $R_1 = \frac{(1-\alpha)}{\alpha}R_e$   
Thus  $\left(\frac{1-\alpha}{\alpha}\right) \left[\frac{R_2R_o}{R_o + R_2}\right] = \frac{(1-k)}{k}R_2$   
Solving for  $R_2$  yields  $R_2 = \frac{(k-\alpha)}{\alpha(1-k)}R_o$   
Also,  $R_1 = \frac{(1-k)}{k}R_2$   $\therefore$   $R_1 = \frac{(k-\alpha)}{\alpha k}R_o$   
[b]  $R_1 = \left(\frac{0.05}{0.68}\right)R_o = 2.5 \text{ k}\Omega$   
 $R_2 = \left(\frac{0.05}{0.12}\right)R_o = 14.167 \text{ k}\Omega$   
[c]

Maximum dissipation in  $R_2$  occurs at no load, therefore,

$$P_{R_2(\text{max})} = \frac{[(60)(0.85)]^2}{14,167} = 183.6 \text{ mW}$$

Maximum dissipation in  $R_1$  occurs at full load.

$$P_{R_1(\text{max})} = \frac{[60 - 0.80(60)]^2}{2500} = 57.60 \text{ mW}$$

[d ]

+  

$$E0 \vee$$
  
 $P_{R_1} = \frac{(60)^2}{2500} = 1.44 \text{ W} = 1440 \text{ mW}$   
 $P_{R_2} = \frac{(0)^2}{14,167} = 0 \text{ W}$ 

P 3.23 [a] The equivalent resistance of the circuit to the right of the  $18 \Omega$  resistor is  $100||25||[(40||10) + 22] = 100||25||30 = 12 \Omega$ 

Thus by voltage division,

$$v_{18} = \frac{18}{18 + 12}(60) = 36 \text{ V}$$

[b] The current in the  $18 \Omega$  resistor can be found from its voltage using Ohm's law:

$$i_{18} = \frac{36}{18} = 2$$
 A

[c] The current in the  $18 \Omega$  resistor divides among three branches – one containing  $100 \Omega$ , one containing  $25 \Omega$  and one containing  $(22 + 40||10) = 30 \Omega$ . Using current division,

$$i_{25} = \frac{100||25||30}{25}(i_{18}) = \frac{12}{25}(2) = 0.96$$
 A

[d] The voltage drop across the  $25 \Omega$  resistor can be found using Ohm's law:

$$v_{25} = 25i_{25} = 25(0.96) = 24 \text{ V}$$

[e] The voltage  $v_{25}$  divides across the  $22 \Omega$  resistor and the equivalent resistance  $40||10 = 8 \Omega$ . Using voltage division,

$$v_{10} = \frac{8}{8+22}(24) = 6.4 \text{ V}$$

P 3.24 [a] The equivalent resistance to the right of the 10 k $\Omega$  resistor is 5 k + 2 k + [9 k||18 k||6 k)] = 10 k $\Omega$ . Therefore,

$$i_{10k} = \frac{10 \text{ k} \| 10 \text{ k}}{10 \text{ k}} (0.050) = 25 \text{ mA}$$

[b] The voltage drop across the 10 k $\Omega$  resistor can be found using Ohm's law:

$$v_{10k} = (10,000)i_{10k} = (10,000)(0.025) = 250 \text{ V}$$

[c] The voltage  $v_{10k}$  drops across the 5 k $\Omega$  resistor, the 2 k $\Omega$  resistor and the equivalent resistance of the 9 k $\Omega$ , 18 k $\Omega$  and 6 k $\Omega$  resistors in parallel. Thus, using voltage division,

$$v_{6k} = \frac{2 \text{ k}}{5 \text{ k} + 2 \text{ k} + [9 \text{ k} \| 18 \text{ k} \| 6 \text{ k}]} (250) = \frac{2}{10} (250) = 50 \text{ V}$$

[d] The current through the 2  $k\Omega$  resistor can be found from its voltage using Ohm's law:

$$i_{2\mathbf{k}} = \frac{v_{2\mathbf{k}}}{2000} = \frac{50}{2000} = 25 \text{ mA}$$

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[e] The current through the 2 k $\Omega$  resistor divides among the 9 k $\Omega$ , 18 k $\Omega$ , and 6 k $\Omega$ . Using current division,

$$i_{18k} = \frac{9 \text{ k} \|18 \text{ k}\|6 \text{ k}}{18 \text{ k}} (0.025) = \frac{3}{18} (0.025) = 4.167 \text{ mA}$$

P 3.25 The equivalent resistance of the circuit to the right of the 90  $\Omega$  resistor is

$$R_{\rm eq} = [(150||75) + 40] ||(30 + 60) = 90||90 = 45\,\Omega$$

Use voltage division to find the voltage drop between the top and bottom nodes:

$$v_{\text{Req}} = \frac{45}{45 + 90}(3) = 1 \text{ V}$$

Use voltage division again to find  $v_1$  from  $v_{\text{Req}}$ :

$$v_1 = \frac{150 \| 75}{150 \| 75 + 40} (1) = \frac{50}{90} (1) = \frac{5}{9} V$$

Use voltage division one more time to find  $v_2$  from  $v_{\text{Req}}$ :

$$v_{2} = \frac{30}{30+60}(1) = \frac{1}{3} \text{ V}$$
P 3.26  $i_{10k} = \frac{(18)(15 \text{ k})}{40 \text{ k}} = 6.75 \text{ mA}$   
 $v_{15k} = -(6.75 \text{ m})(15 \text{ k}) = -101.25 \text{ V}$   
 $i_{3k} = 18 \text{ m} - 6.75 \text{ m} = 11.25 \text{ mA}$   
 $v_{12k} = -(12 \text{ k})(11.25 \text{ m}) = -135 \text{ V}$   
 $v_{o} = -101.25 - (-135) = 33.75 \text{ V}$   
P 3.27 [a]  $v_{6k} = \frac{6}{6+2}(18) = 13.5 \text{ V}$   
 $v_{3k} = \frac{3}{3+9}(18) = 4.5 \text{ V}$ 

$$v_x = v_{6k} - v_{3k} = 13.5 - 4.5 = 9 \text{ V}$$

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**[b]** 
$$v_{6k} = \frac{6}{8}(V_s) = 0.75V_s$$
  
 $v_{3k} = \frac{3}{12}(V_s) = 0.25V_s$   
 $v_x = (0.75V_s) - (0.25V_s) = 0.5V_s$ 

P 3.28  $5\Omega \| 20\Omega = 4\Omega;$   $4\Omega + 6\Omega = 10\Omega;$   $10\| (15 + 12 + 13) = 8\Omega;$ 

Therefore, 
$$i_g = \frac{125}{2+8} = 12.5 \text{ A}$$

$$i_{6\Omega} = \frac{8}{6+4}(12.5) = 10 \text{ A}; \quad i_o = \frac{5||20}{20}(10) = 2 \text{ A}$$

P 3.29 [a] The equivalent resistance seen by the voltage source is  

$$60 \| [8 + 30\| (4 + 80\| 20)] = 60 \| [8 + 30\| 20] = 60\| 20 = 15 \Omega$$
  
Thus,  
200

$$i_g = \frac{300}{15} = 20 \text{ A}$$

**[b]** Use current division to find the current in the  $8\Omega$  division:

$$\frac{15}{20}(20) = 15$$
 A

Use current division again to find the current in the  $30\,\Omega$  resistor:

$$i_{30} = \frac{12}{30}(15) = 6$$
 A

Thus,

 $p_{30} = (6)^2 (30) = 1080 \text{ W}$ 

P 3.30 [a] The voltage across the 9  $\Omega$  resistor is 1(12 + 6) = 18 V. The current in the 9  $\Omega$  resistor is 18/9 = 2 A. The current in the 2  $\Omega$  resistor is 1 + 2 = 3 A. Therefore, the voltage across the 24  $\Omega$  resistor is (2)(3) + 18 = 24 V. The current in the 24  $\Omega$  resistor is 1 A. The current in the 3  $\Omega$  resistor is 1 + 2 + 1 = 4 A. Therefore, the voltage across the 72  $\Omega$  resistor is 24 + 3(4) = 36 V. The current in the 72  $\Omega$  resistor is 36/72 = 0.5 A. The 20  $\Omega \parallel 5 \Omega$  resistors are equivalent to a 4  $\Omega$  resistor. The current in this equivalent resistor is 36 + 4.5(4) = 54 V. The current in the 108  $\Omega$  resistor is 54/108 = 0.5 A. The current in the  $1.2 \Omega$  resistor is 4.5 + 0.5 = 5 A. Therefore,

$$v_g = (1.2)(5) + 54 = 60 \text{ V}$$

**[b]** The current in the  $20 \Omega$  resistor is

$$i_{20} = \frac{(4.5)(4)}{20} = \frac{18}{20} = 0.9 \text{ A}$$

Thus, the power dissipated by the  $20 \Omega$  resistor is

$$p_{20} = (0.9)^2 (20) = 16.2 \text{ W}$$

P 3.31 For all full-scale readings the total resistance is

$$R_V + R_{\text{movement}} = \frac{\text{full-scale reading}}{10^{-3}}$$

We can calculate the resistance of the movement as follows:

$$R_{\rm movement} = \frac{20 \text{ mV}}{1 \text{ mA}} = 20 \,\Omega$$

Therefore,  $R_V = 1000$  (full-scale reading) -20

- $[\mathbf{a}] \ R_V = 1000(50) 20 = 49,980\,\Omega$
- **[b]**  $R_V = 1000(5) 20 = 4980 \,\Omega$
- [c]  $R_V = 1000(0.25) 20 = 230\,\Omega$
- $[\mathbf{d}] \ R_V = 1000(0.025) 20 = 5\,\Omega$

P 3.32 [a] 
$$v_{\text{meas}} = (50 \times 10^{-3})[15||45||(4980 + 20)] = 0.5612 \text{ V}$$
  
[b]  $v_{\text{true}} = (50 \times 10^{-3})(15||45) = 0.5625 \text{ V}$   
% error  $= \left(\frac{0.5612}{0.5625} - 1\right) \times 100 = -0.224\%$ 

P 3.33 The measured value is  $60||20.1 = 15.05618 \Omega$ .

$$i_g = \frac{50}{(15.05618 + 10)} = 1.995526 \text{ A};$$
  $i_{\text{meas}} = \frac{60}{80.1}(1.996) = 1.494768 \text{ A}$ 

The true value is  $60||20 = 15 \Omega$ .

$$i_g = \frac{50}{(15+10)} = 2$$
 A;  $i_{true} = \frac{60}{80}(2) = 1.5$  A

% error = 
$$\left[\frac{1.494768}{1.5} - 1\right] \times 100 = -0.34878\% \approx -0.35\%$$

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P 3.34 Begin by using current division to find the actual value of the current  $i_o$ :

$$i_{\text{true}} = \frac{15}{15 + 45} (50 \text{ mA}) = 12.5 \text{ mA}$$
$$i_{\text{meas}} = \frac{15}{15 + 45 + 0.1} (50 \text{ mA}) = 12.4792 \text{ mA}$$
$$\% \text{ error } = \left[\frac{12.4792}{12.5} - 1\right] 100 = -0.166389\% \approx -0.17\%$$

P 3.35 [a] The model of the ammeter is an ideal ammeter in parallel with a resistor whose resistance is given by

$$R_m = \frac{100 \,\mathrm{mV}}{2 \,\mathrm{mA}} = 50 \,\Omega.$$

We can calculate the current through the real meter using current division:

$$i_m = \frac{(25/12)}{50 + (25/12)}(i_{\text{meas}}) = \frac{25}{625}(i_{\text{meas}}) = \frac{1}{25}i_{\text{meas}}$$

[b] At full scale,  $i_{\text{meas}} = 5$  A and  $i_{\text{m}} = 2$  mA so 5 - 0.002 = 4998 mA flows throught the resistor  $R_{\text{A}}$ :

$$R_{\rm A} = \frac{100 \text{ mV}}{4998 \text{ mA}} = \frac{100}{4998} \Omega$$
$$i_m = \frac{(100/4998)}{50 + (100/4998)} (i_{\rm meas}) = \frac{1}{2500} (i_{\rm meas})$$



Original meter: 
$$R_{\rm e} = \frac{50 \times 10^{-3}}{5} = 0.01 \,\Omega$$

Modified meter: 
$$R_{\rm e} = \frac{(0.02)(0.01)}{0.03} = 0.00667 \,\Omega$$
  
 $\therefore \ (I_{\rm fs})(0.00667) = 50 \times 10^{-3}$   
 $\therefore \ I_{\rm fs} = 7.5 \,\mathrm{A}$ 



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**[b]**  $R_{\rm A} = \frac{50}{1000 - 2} = 50.1 \text{ m}\Omega$ 

[c]  $R_{\rm A} = \frac{50}{50-2} = 1.042 \text{ m}\Omega$ 

$$[\mathbf{d}] \ R_{\mathbf{A}} = \frac{50}{2-2} = \infty \qquad \text{(open circuit)}$$

P 3.39 At full scale the voltage across the shunt resistor will be 50 mV; therefore the power dissipated will be

$$P_{\rm A} = \frac{(50 \times 10^{-3})^2}{R_{\rm A}}$$

Therefore  $R_{\rm A} \ge \frac{(50 \times 10^{-3})^2}{0.5} = 5 \text{ m}\Omega$ 

Otherwise the power dissipated in  $R_A$  will exceed its power rating of 0.5 W When  $R_A = 5 \text{ m}\Omega$ , the shunt current will be

$$i_{\rm A} = \frac{50 \times 10^{-3}}{5 \times 10^{-3}} = 10 \ {\rm A}$$

The measured current will be  $i_{\text{meas}} = 10 + 0.001 = 10.001 \text{ A}$  $\therefore$  Full-scale reading for practical purposes is 10 A.

P 3.40 
$$R_{\text{meter}} = R_m + R_{\text{movement}} = \frac{750 \text{ V}}{1.5 \text{ mA}} = 500 \text{ k}\Omega$$
  
 $v_{\text{meas}} = (25 \text{ k}\Omega \| 125 \text{ k}\Omega \| 50 \text{ k}\Omega)(30 \text{ mA}) = (20 \text{ k}\Omega)(30 \text{ mA}) = 600 \text{ V}$   
 $v_{\text{true}} = (25 \text{ k}\Omega \| 125 \text{ k}\Omega)(30 \text{ mA}) = (20.83 \text{ k}\Omega)(30 \text{ mA}) = 625 \text{ V}$   
 $\% \text{ error } = \left(\frac{600}{625} - 1\right) 100 = -4\%$ 

P 3.41 [a] Since the unknown voltage is greater than either voltmeter's maximum reading, the only possible way to use the voltmeters would be to connect them in series.

$$i_{1 \max} = \frac{300}{270} \times 10^{-3} = 1.11 \text{ mA};$$
  $i_{2 \max} = \frac{150}{180} \times 10^{-3} = 0.833 \text{ mA}$   
 $\therefore \quad i_{\max} = 0.833 \text{ mA} \text{ since meters are in series}$   
 $v_{\max} = (0.833 \times 10^{-3})(270 + 180)10^3 = 375 \text{ V}$ 

Thus the meters can be used to measure the voltage.

[c] 
$$i_m = \frac{320}{450 \times 10^3} = 0.711 \text{ mA}$$
  
 $v_{m1} = (0.711)(270) = 192 \text{ V}; \qquad v_{m2} = (0.711)(180) = 128 \text{ V}$ 

P 3.42 The current in the series-connected voltmeters is

$$i_m = \frac{205.2}{270,000} = \frac{136.8}{180,000} = 0.76 \text{ mA}$$
  
 $v_{50 \text{ k}\Omega} = (0.76 \times 10^{-3})(50,000) = 38 \text{ V}$   
 $V_{50 \text{ k}\Omega} = (0.76 \times 10^{-3})(50,000) = 38 \text{ V}$ 

 $V_{\text{power supply}} = 205.2 + 136.8 + 38 = 380 \text{ V}$ 

P 3.43 [a] 
$$v_{\text{meter}} = 180 \text{ V}$$
  
[b]  $R_{\text{meter}} = (100)(200) = 20 \text{ k}\Omega$   
 $20||70 = 15.555556 \text{ k}\Omega$   
 $v_{\text{meter}} = \frac{180}{35.55556} \times 15.555556 = 78.75 \text{ V}$   
[c]  $20||20 = 10 \text{ k}\Omega$   
 $v_{\text{meter}} = \frac{180}{80}(10) = 22.5 \text{ V}$   
[d]  $v_{\text{meter a}} = 180 \text{ V}$ 

 $v_{\rm meter~b} + v_{\rm meter~c} = 101.26~{\rm V}$ 

No, because of the loading effect.

P 3.44 From the problem statement we have  

$$50 = \frac{V_s(10)}{10 + R_s} \qquad (1) \quad V_s \text{ in mV}; R_s \text{ in M}\Omega$$

$$48.75 = \frac{V_s(6)}{6 + R_s} \qquad (2)$$

$$[a] \text{ From Eq } (1) \quad 10 + R_s = 0.2V_s$$
  

$$\therefore R_s = 0.2V_s - 10$$
Substituting into Eq (2) yields  

$$48.75 = \frac{6V_s}{0.2V_s - 4} \quad \text{or} \quad V_s = 52 \text{ mV}$$

$$[b] \text{ From Eq } (1)$$

$$50 = \frac{520}{10 + R_s} \quad \text{or} \quad 50R_s = 20$$
So  $R_s = 400 \text{ k}\Omega$ 

$$P \ 3.45 \quad [a] \quad R_1 = (100/2)10^3 = 50 \text{ k}\Omega$$

$$R_2 = (10/2)10^3 = 50 \Omega$$

$$[b] \text{ Let } i_a = \text{ actual current in the movement}$$

$$i_d = \text{ design current in the movement}$$

$$Then \% \text{ error } = \left(\frac{i_a}{i_d} - 1\right) 100$$
For the 100 V scale:  

$$i_a = \frac{100}{50,020} = 0.9995 \qquad \% \text{ error } = (0.9995 - 1)100 = -0.05\%$$
For the 10 V scale:  

$$\frac{i_a}{i_d} = \frac{5000}{5025} = 0.9995 \qquad \% \text{ error } = (0.995 - 1.0)100 = -0.4975\%$$
For the 1 V scale:  

$$\frac{i_a}{i_d} = \frac{5000}{525} = 0.9524 \qquad \% \text{ error } = (0.9524 - 1.0)100 = -4.76\%$$
P 3.46 [a]  $R_{\text{movement}} = \frac{30}{1 \times 10^{-3}} = 30 \text{ k}\Omega \qquad \therefore R_1 = 29.950 \Omega$ 

$$R_2 + R_1 + R_{\text{movement}} = \frac{150}{1 \times 10^{-3}} = 150 \text{ k}\Omega \qquad \therefore R_2 = 120 \text{ k}\Omega$$

$$R_{3} + R_{2} + R_{1} + R_{\text{movement}} = \frac{300}{1 \times 10^{-3}} = 300 \text{ k}\Omega$$
  

$$\therefore R_{3} = 150 \text{ k}\Omega$$
[b]  

$$\downarrow_{120 \text{ ka}} + \downarrow_{1} + \chi_{3.95 \text{ ka}} + \chi_{1} + \chi_{3.95 \text{ ka}} + \chi_{1} + \chi_{120 \text{ ka}} + \chi_{12$$

% error 
$$= \left(\frac{500}{540} - 1\right) 100 = -7.41\%$$

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P 3.48 Since the bridge is balanced, we can remove the detector without disturbing the voltages and currents in the circuit.



It follows that

$$i_{1} = \frac{i_{g}(R_{2} + R_{x})}{R_{1} + R_{2} + R_{3} + R_{x}} = \frac{i_{g}(R_{2} + R_{x})}{\sum R}$$

$$i_{2} = \frac{i_{g}(R_{1} + R_{3})}{R_{1} + R_{2} + R_{3} + R_{x}} = \frac{i_{g}(R_{1} + R_{3})}{\sum R}$$

$$v_{3} = R_{3}i_{1} = v_{x} = i_{2}R_{x}$$

$$\cdot \frac{R_{3}i_{g}(R_{2} + R_{x})}{R_{3} - \frac{R_{x}i_{g}(R_{1} + R_{3})}{R_{3} - R_{x}}$$

$$\dots \quad \underline{\sum}R = \underline{\sum}R$$

$$\therefore R_3(R_2 + R_x) = R_x(R_1 + R_3)$$

From which  $R_x = \frac{R_2 R_3}{R_1}$ 

P 3.49 Note the bridge structure is balanced, that is  $15 \times 5 = 3 \times 25$ , hence there is no current in the 5 k $\Omega$  resistor. It follows that the equivalent resistance of the circuit is

$$R_{\rm eq} = 750 + (15,000 + 3000) ||(25,000 + 5000) = 750 + 11,250 = 12 \ \rm k\Omega$$

The source current is 192/12,000 = 16 mA. The current down through the branch containing the 15 k $\Omega$  and 3 k $\Omega$  resistors is

$$i_{3k} = \frac{11,250}{18,000}(0.016) = 10 \text{ mA}$$

: 
$$p_{3k} = 3000(0.01)^2 = 0.3$$
 W





$$6 \ \mathbf{k}\Omega \| \mathbf{30} \ \mathbf{k}\Omega = 5 \ \mathbf{k}\Omega$$

12 k $\Omega\|20$ k $\Omega=7.5$ k $\Omega$ 

$$i_s = \frac{75}{12,500} = 6 \text{ mA}$$

$$v_1 = 0.006(5000) = 30 \text{ V}$$

$$v_2 = 0.006(7500) = 45 \text{ V}$$

$$i_1 = \frac{30}{6000} = 5 \text{ mA}$$

$$i_2 = \frac{45}{12,000} = 3.75 \text{ mA}$$

$$i_{\rm d} = i_1 - i_2 = 1.25 \text{ mA}$$

P 3.51 [a]



The condition for a balanced bridge is that the product of the opposite resistors must be equal:

$$(500)(R_x) = (1000)(750)$$
 so  $R_x = \frac{(1000)(750)}{500} = 1500 \,\Omega$ 

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[b] The source current is the sum of the two branch currents. Each branch current can be determined using Ohm's law, since the resistors in each branch are in series and the voltage drop across each branch is 24 V:

$$i_s = \frac{24 \text{ V}}{500 \Omega + 750 \Omega} + \frac{24 \text{ V}}{1000 \Omega + 1500 \Omega} = 28.8 \text{ mA}$$

[c] We can use Ohm's law to find the current in each branch:

$$i_{\text{left}} = \frac{24}{500 + 750} = 19.2 \text{ mA}$$
  
 $i_{\text{right}} = \frac{24}{1000 + 1500} = 9.6 \text{ mA}$ 

Now we can use the formula  $p = Ri^2$  to find the power dissipated by each resistor:

$$p_{500} = (500)(0.0192)^2 = 184.32 \text{ mW} \qquad p_{750} = (750)(0.0192)^2 = 276.18 \text{ mW}$$
$$p_{1000} = (1000)(0.0096)^2 = 92.16 \text{ mW} \qquad p_{1500} = (1500)(0.0096)^2 = 138.24 \text{ mW}$$

Thus, the  $750\,\Omega$  resistor absorbs the most power; it absorbs 276.48 mW of power.

- [d] From the analysis in part (c), the  $1000 \Omega$  resistor absorbs the least power; it absorbs 92.16 mW of power.
- P 3.52 In order that all four decades (1, 10, 100, 1000) that are used to set  $R_3$  contribute to the balance of the bridge, the ratio  $R_2/R_1$  should be set to 0.001.
- P 3.53 Begin by transforming the  $\Delta$ -connected resistors  $(10 \Omega, 40 \Omega, 50 \Omega)$  to Y-connected resistors. Both the Y-connected and  $\Delta$ -connected resistors are shown below to assist in using Eqs. 3.44 – 3.46:



Now use Eqs. 3.44 - 3.46 to calculate the values of the Y-connected resistors:

$$R_1 = \frac{(40)(10)}{10 + 40 + 50} = 4\,\Omega; \quad R_2 = \frac{(10)(50)}{10 + 40 + 50} = 5\,\Omega; \quad R_3 = \frac{(40)(50)}{10 + 40 + 50} = 20\,\Omega$$

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The transformed circuit is shown below:



The equivalent resistance seen by the 24 V source can be calculated by making series and parallel combinations of the resistors to the right of the 24 V source:

$$R_{\rm eq} = (15+5) \| (1+4) + 20 = 20 \| 5+20 = 4+20 = 24 \,\Omega$$

Therefore, the current i in the 24 V source is given by

$$i = \frac{24 \text{ V}}{24 \Omega} = 1 \text{ A}$$

Use current division to calculate the currents  $i_1$  and  $i_2$ . Note that the current  $i_1$  flows in the branch containing the  $15\Omega$  and  $5\Omega$  series connected resistors, while the current  $i_2$  flows in the parallel branch that contains the series connection of the  $1\Omega$  and  $4\Omega$  resistors:

$$i_1 = \frac{4}{15+5}(i) = \frac{4}{20}(1 \text{ A}) = 0.2 \text{ A}, \quad \text{and} \quad i_2 = 1 \text{ A} - 0.2 \text{ A} = 0.8 \text{ A}$$

Now use KVL and Ohm's law to calculate  $v_1$ . Note that  $v_1$  is the sum of the voltage drop across the  $4\Omega$  resistor,  $4i_2$ , and the voltage drop across the  $20\Omega$  resistor, 20i:

$$v_1 = 4i_2 + 20i = 4(0.8 \text{ A}) + 20(1 \text{ A}) = 3.2 + 20 = 23.2 \text{ V}$$

Finally, use KVL and Ohm's law to calculate  $v_2$ . Note that  $v_2$  is the sum of the voltage drop across the  $5\Omega$  resistor,  $5i_1$ , and the voltage drop across the  $20\Omega$  resistor, 20i:

$$v_2 = 5i_1 + 20i = 5(0.2 \text{ A}) + 20(1 \text{ A}) = 1 + 20 = 21 \text{ V}$$

P 3.54 [a] After the  $20 \Omega$ — $100 \Omega$ — $50 \Omega$  wye is replaced by its equivalent delta, the circuit reduces to



Now the circuit can be reduced to  $_{64\ \Omega}$ 



$$i = \frac{96}{400}(1000) = 240 \text{ mA}$$
  
 $i_o = \frac{400}{1000}(240) = 96 \text{ mA}$ 

**[b]** 
$$i_1 = \frac{80}{400}(240) = 48 \text{ mA}$$

 $[\mathbf{c}]$  Now that  $i_o$  and  $i_1$  are known return to the original circuit



$$v_2 = (50)(0.048) + (600)(0.096) = 60 \text{ V}$$
  
 $i_2 = \frac{v_2}{100} = \frac{60}{100} = 600 \text{ mA}$ 

[d]  $v_g = v_2 + 20(0.6 + 0.048) = 60 + 12.96 = 72.96$  V

$$p_g = -(v_g)(1) = -72.96 \text{ W}$$

Thus the current source delivers 72.96 W.

P 3.55 The top of the pyramid can be replaced by a resistor equal to

$$R_1 = \frac{(18)(9)}{27} = 6 \ \mathrm{k}\Omega$$

The lower left and right deltas can be replaced by wyes. Each resistance in the wye equals 3 k $\Omega$ . Thus our circuit can be reduced to



Now the 12 k $\Omega$  in parallel with 6 k $\Omega$  reduces to 4 k $\Omega$ .

$$\therefore R_{ab} = 3 k + 4 k + 3 k = 10 k\Omega$$

P 3.56 [a] Calculate the values of the Y-connected resistors that are equivalent to the  $10 \Omega, 40 \Omega$ , and  $50\Omega \Delta$ -connected resistors:

$$R_X = \frac{(10)(50)}{10 + 40 + 50} = 5\,\Omega; \qquad R_Y = \frac{(50)(40)}{10 + 40 + 50} = 20\,\Omega;$$
$$R_Z = \frac{(10)(40)}{10 + 40 + 50} = 4\,\Omega$$

Replacing the  $R_2$ — $R_3$ — $R_4$  delta with its equivalent Y gives 13  $\Omega$ 



Now calculate the equivalent resistance  $R_{ab}$  by making series and parallel combinations of the resistors:

 $R_{\rm ab} = 13 + 5 + [(8+4)||(20+4)] + 7 = 33\,\Omega$ 

[b] Calculate the values of the  $\Delta$ -connected resistors that are equivalent to the 10  $\Omega$ , 8  $\Omega$ , and 40  $\Omega$  Y-connected resistors:

$$R_X = \frac{(10)(8) + (8)(40) + (10)(40)}{8} = \frac{800}{8} = 100 \,\Omega$$

$$R_Y = \frac{(10)(8) + (8)(40) + (10)(40)}{10} = \frac{800}{10} = 80 \,\Omega$$

$$R_Z = \frac{(10)(8) + (8)(40) + (10)(40)}{40} = \frac{800}{40} = 20 \,\Omega$$

Replacing the  $R_2$ ,  $R_4$ ,  $R_5$  wye with its equivalent  $\Delta$  gives

![](_page_34_Figure_2.jpeg)

Make series and parallel combinations of the resistors to find the equivalent resistance  $R_{ab}$ :

- $100 \Omega \| 50 \Omega = 33.33 \Omega;$   $80 \Omega \| 4 \Omega = 3.81 \Omega$
- $\therefore 20 \| (33.33 + 3.81) = 13 \Omega$
- $\therefore R_{\rm ab} = 13 + 13 + 7 = 33 \,\Omega$
- [c] Convert the delta connection  $R_4 R_5 R_6$  to its equivalent wye. Convert the wye connection  $R_3 - R_4 - R_6$  to its equivalent delta.
- P 3.57 [a] Convert the upper delta to a wye.

$$R_{1} = \frac{(50)(50)}{200} = 12.5 \,\Omega$$
$$R_{2} = \frac{(50)(100)}{200} = 25 \,\Omega$$
$$R_{3} = \frac{(100)(50)}{200} = 25 \,\Omega$$

Convert the lower delta to a wye.

$$R_4 = \frac{(60)(80)}{200} = 24 \,\Omega$$
$$R_5 = \frac{(60)(60)}{200} = 18 \,\Omega$$
$$R_6 = \frac{(80)(60)}{200} = 24 \,\Omega$$

Now redraw the circuit using the wye equivalents.

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![](_page_35_Figure_1.jpeg)

P 3.58 Replace the upper and lower deltas with the equivalent wyes:

$$R_{1U} = \frac{(10)(50)}{100} = 5\,\Omega; R_{2U} = \frac{(50)(40)}{100} = 20\,\Omega; R_{3U} = \frac{(10)(40)}{100} = 4\,\Omega$$

$$R_{1L} = \frac{(10)(60)}{100} = 6\,\Omega; R_{2L} = \frac{(60)(30)}{100} = 18\,\Omega; R_{3L} = \frac{(10)(30)}{100} = 3\,\Omega$$

The resulting circuit is shown below:

Now make series and parallel combinations of the resistors:

$$(4+6) \| (20+32+20+18) = 10 \| 90 = 9 \Omega$$
  
 $R_{\rm ab} = 33+5+9+3+40 = 90 \Omega$ 

P 3.59 
$$8 + 12 = 20 \Omega$$
  
 $20||60 = 15 \Omega$   
 $15 + 20 = 35 \Omega$   
 $35||140 = 28 \Omega$   
 $28 + 22 = 50 \Omega$   
 $50||75 = 30 \Omega$   
 $30 + 10 = 40 \Omega$   
 $i_g = 240/40 = 6 \text{ A}$   
 $i_o = (6)(50)/125 = 2.4 \text{ A}$   
 $i_{140\Omega} = (6 - 2.4)(35)/175 = 0.72 \text{ A}$   
 $p_{140\Omega} = (0.72)^2(140) = 72.576 \text{ W}$ 

P 3.60 [a] Replace the 60–120–20  $\Omega$  delta with a wye equivalent to get  $i_{5} + i_{5} + i_{6} + i_{$ 

P 3.61

![](_page_37_Figure_2.jpeg)

$$25\|6.25 = 5\,\Omega \qquad \qquad 60\|30 = 20\,\Omega$$

![](_page_37_Figure_4.jpeg)

$$i_1 = \frac{(6)(15)}{(40)} = 2.25 \text{ A}; \qquad v_x = 20i_1 = 45 \text{ V}$$

$$v_g = 25i_1 = 56.25 \text{ V}$$

$$v_{6.25} = v_q - v_x = 11.25 \text{ V}$$

$$P_{\text{device}} = \frac{11.25^2}{6.25} + \frac{45^2}{30} + \frac{56.25^2}{15} = 298.6875 \text{ W}$$

P 3.62 [a] Subtracting Eq. 3.42 from Eq. 3.43 gives

$$R_1 - R_2 = (R_c R_b - R_c R_a)/(R_a + R_b + R_c).$$

Adding this expression to Eq. 3.41 and solving for  $R_1$  gives

$$R_1 = R_{\rm c}R_{\rm b}/(R_{\rm a} + R_{\rm b} + R_{\rm c})$$

To find  $R_2$ , subtract Eq. 3.43 from Eq. 3.41 and add this result to Eq. 3.42. To find  $R_3$ , subtract Eq. 3.41 from Eq. 3.42 and add this result to Eq. 3.43.

[b] Using the hint, Eq. 3.43 becomes

$$R_1 + R_3 = \frac{R_{\rm b}[(R_2/R_3)R_{\rm b} + (R_2/R_1)R_{\rm b}]}{(R_2/R_1)R_{\rm b} + R_{\rm b} + (R_2/R_3)R_{\rm b}} = \frac{R_{\rm b}(R_1 + R_3)R_2}{(R_1R_2 + R_2R_3 + R_3R_1)}$$

Solving for  $R_b$  gives  $R_b = (R_1R_2 + R_2R_3 + R_3R_1)/R_2$ . To find  $R_a$ : First use Eqs. 3.44–3.46 to obtain the ratios  $(R_1/R_3) = (R_c/R_a)$  or

 $R_{\rm c} = (R_1/R_3)R_{\rm a}$  and  $(R_1/R_2) = (R_{\rm b}/R_{\rm a})$  or  $R_{\rm b} = (R_1/R_2)R_{\rm a}$ . Now use these relationships to eliminate  $R_{\rm b}$  and  $R_{\rm c}$  from Eq. 3.42. To find  $R_{\rm c}$ , use Eqs. 3.44–3.46 to obtain the ratios  $R_{\rm b} = (R_3/R_2)R_{\rm c}$  and  $R_{\rm a} = (R_3/R_1)R_{\rm c}$ . Now use the relationships to eliminate  $R_{\rm b}$  and  $R_{\rm a}$  from

Eq. 3.41.

P 3.63 
$$G_{a} = \frac{1}{R_{a}} = \frac{R_{1}}{R_{1}R_{2} + R_{2}R_{3} + R_{3}R_{1}}$$
  

$$= \frac{1/G_{1}}{(1/G_{1})(1/G_{2}) + (1/G_{2})(1/G_{3}) + (1/G_{3})(1/G_{1})}$$

$$= \frac{(1/G_{1})(G_{1}G_{2}G_{3})}{G_{1} + G_{2} + G_{3}} = \frac{G_{2}G_{3}}{G_{1} + G_{2} + G_{3}}$$
Similar manipulations generate the expressions for  $G_{1}$  and

Similar manipulations generate the expressions for  $G_{\rm b}$  and  $G_{\rm c}$ .

P 3.64 [a] 
$$R_{ab} = 2R_1 + \frac{R_2(2R_1 + R_L)}{2R_1 + R_2 + R_L} = R_L$$
  
 $R_2(2R_1 + R_L)$ 

Therefore 
$$2R_1 - R_L + \frac{R_2(2R_1 + R_L)}{2R_1 + R_2 + R_L} = 0$$

 $R_{\rm L}^2 = 4R_1^2 + 4R_1R_2 = 4R_1(R_1 + R_2)$ Thus

When  $R_{\rm ab} = R_{\rm L}$ , the current into terminal a of the attenuator will be  $v_i/R_{\rm L}$ 

Using current division, the current in the  $R_{\rm L}$  branch will be

$$\frac{v_i}{R_L} \cdot \frac{R_2}{2R_1 + R_2 + R_L}$$
Therefore  $v_o = \frac{v_i}{R_L} \cdot \frac{R_2}{2R_1 + R_2 + R_L} R_L$ 
and  $\frac{v_o}{v_i} = \frac{R_2}{2R_1 + R_2 + R_L}$ 
[b]  $(600)^2 = 4(R_1 + R_2)R_1$ 
 $9 \times 10^4 = R_1^2 + R_1R_2$ 
 $\frac{v_o}{v_i} = 0.6 = \frac{R_2}{2R_1 + R_2 + 600}$ 
 $\therefore 1.2R_1 + 0.6R_2 + 360 = R_2$ 
 $0.4R_2 = 1.2R_1 + 360$ 
 $R_2 = 3R_1 + 900$ 
 $\therefore 9 \times 10^4 = R_1^2 + R_1(3R_1 + 900) = 4R_1^2 + 900R_1$ 
 $\therefore R_1^2 + 225R_1 - 22,500 = 0$ 

$$R_1 = -112.5 \pm \sqrt{(112.5)^2 + 22,500} = -112.5 \pm 187.5$$
  
$$\therefore R_1 = 75 \Omega$$
  
$$\therefore R_2 = 3(75) + 900 = 1125 \Omega$$

[c] From Appendix H, choose  $R_1 = 68 \Omega$  and  $R_2 = 1.2 \text{ k}\Omega$ . For these values,

$$R_{\rm ab} = R_{\rm L} = \sqrt{(4)(68)(68 + 1200)} = 587.3\,\Omega$$
  
% error =  $\left(\frac{587.3}{600} - 1\right)100 = -2.1\%$   
 $\frac{v_o}{v_i} = \frac{1200}{2(68) + 1200 + 587.3} = 0.624$   
% error =  $\left(\frac{0.624}{0.6} - 1\right)100 = 4\%$ 

P 3.65 [a] After making the Y-to- $\Delta$  transformation, the circuit reduces to

![](_page_39_Figure_5.jpeg)

Combining the parallel resistors reduces the circuit to

![](_page_39_Figure_7.jpeg)

Now note: 
$$0.75R + \frac{3RR_{\rm L}}{3R + R_{\rm L}} = \frac{2.25R^2 + 3.75RR_{\rm L}}{3R + R_{\rm L}}$$

Therefore 
$$R_{\rm ab} = \frac{3R\left(\frac{2.25R^2 + 3.75RR_{\rm L}}{3R + R_{\rm L}}\right)}{3R + \left(\frac{2.25R^2 + 3.75RR_{\rm L}}{3R + R_{\rm L}}\right)} = \frac{3R(3R + 5R_{\rm L})}{15R + 9R_{\rm L}}$$

If 
$$R = R_{\rm L}$$
, we have  $R_{\rm ab} = \frac{3R_{\rm L}(8R_{\rm L})}{24R_{\rm L}} = R_{\rm L}$ 

Therefore  $R_{\rm ab} = R_{\rm L}$ 

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[b] When 
$$R = R_L$$
, the circuit reduces to  
 $i \to 0^{75R_L} = 0^{15R_L} = 0^{15R_L} = 0^{15R_L} = 1 = \frac{1}{1.5} \frac{v_i}{i_0}$ ,  $v_o = 0.75R_L i_o = \frac{1}{2}v_i$ ,  
Therefore  $\frac{v_o}{v_i} = 0.5$   
P 3.66 [a]  $3.5(3R - R_L) = 3R + R_L$   
 $10.5R - 1050 = 3R + 300$   
 $7.5R = 1350$ ,  $R = 180 \Omega$   
 $R_2 = \frac{2(180)(300)^2}{3(180)^2 - (300)^2} = 4500 \Omega$   
[b]  
 $i \to 0^{100} = \frac{100}{100} = \frac{12}{300} = 40 \text{ mA}$   
 $i_1 = \frac{42 - 12}{4500} = \frac{30}{4500} = 6.67 \text{ mA}$   
 $i_2 = 140 - 6.67 = 133.33 \text{ mA}$   
 $i_3 = 40 - 6.67 = 33.33 \text{ mA}$ 

$$i_4 = 133.33 - 33.33 = 100 \text{ mA}$$

$$p_{4500 \text{ top}} = (6.67 \times 10^{-3})^2 (4500) = 0.2 \text{ W}$$

$$p_{180 \text{ left}} = (133.33 \times 10^{-3})^2 (180) = 3.2 \text{ W}$$

$$p_{180 \text{ right}} = (33.33 \times 10^{-3})^2 (180) = 0.2 \text{ W}$$

$$p_{180 \text{ vertical}} = (100 \times 10^{-3})^2 (180) = 0.48 \text{ W}$$

$$p_{300 \text{ load}} = (40 \times 10^{-3})^2 (300) = 0.48 \text{ W}$$
The 180  $\Omega$  resistor carrying  $i_2$ 

- [c]  $p_{180 \text{ left}} = 3.2 \text{ W}$
- [d] Two resistors dissipate minimum power the 4500  $\Omega$  resistor and the 180  $\Omega$  resistor carrying  $i_3$ .
- [e] They both dissipate 0.2 W.

![](_page_41_Figure_6.jpeg)

When the bridge is balanced,

$$\frac{R_4}{R_o + R_4} v_{\rm in} = \frac{R_3}{R_2 + R_3} v_{\rm in}$$
$$\therefore \quad \frac{R_4}{R_o + R_4} = \frac{R_3}{R_2 + R_3}$$

Thus,

$$v_o = \frac{R_4 v_{\rm in}}{R_o + R_4 + \Delta R} - \frac{R_4 v_{\rm in}}{R_o + R_4}$$
$$= R_4 v_{\rm in} \left[ \frac{1}{R_o + R_4 + \Delta R} - \frac{1}{R_o + R_4} \right]$$
$$= \frac{R_4 v_{\rm in} (-\Delta R)}{(R_o + R_4 + \Delta R)(R_o + R_4)}$$
$$\approx \frac{-(\Delta R) R_4 v_{\rm in}}{(R_o + R_4)^2}, \quad \text{since } \Delta R << R_4$$

$$[\mathbf{b}] \ \Delta R = 0.03R_o$$

$$R_o = \frac{R_2 R_4}{R_3} = \frac{(1000)(5000)}{500} = 10,000 \Omega$$

$$\Delta R = (0.03)(10^4) = 300 \Omega$$

$$\therefore \ v_o \approx \frac{-300(5000)(6)}{(15,000)^2} = -40 \text{ mV}$$

$$[\mathbf{c}] \ v_o = \frac{-(\Delta R)R_4 v_{\text{in}}}{(R_o + R_4 + \Delta R)(R_o + R_4)}$$

$$= \frac{-300(5000)(6)}{(15,300)(15,000)}$$

$$= -39.2157 \text{ mV}$$

$$P \ 3.68 \ [\mathbf{a}] \ \text{approx value} = \frac{-(\Delta R)R_4 v_{\text{in}}}{(R_o + R_4)^2}$$

$$\text{true value} = \frac{-(\Delta R)R_4 v_{\text{in}}}{(R_o + R_4 + \Delta R)(R_o + R_4)}$$

$$\therefore \quad \frac{\text{approx value}}{\text{true value}} = \frac{(R_o + R_4 + \Delta R)}{(R_o + R_4)}$$
$$\therefore \quad \% \text{ error } = \left[\frac{R_o + R_4}{R_o + R_4 + \Delta R} - 1\right] \times 100 = \frac{-\Delta R}{R_o + R_4} \times 100$$

Note that in the above expression, we take the ratio of the true value to the approximate value because both values are negative.

But 
$$R_o = \frac{R_2 R_4}{R_3}$$
  
 $\therefore \% \text{ error } = \frac{-R_3 \Delta R}{R_4 (R_2 + R_3)}$   
[b] % error  $= \frac{-(500)(300)}{(5000)(1500)} \times 100 = -2\%$   
P 3.69  $\frac{\Delta R(R_3)(100)}{(R_2 + R_3)R_4} = 0.5$   
 $\frac{\Delta R(500)(100)}{(1500)(5000)} = 0.5$   
 $\therefore \Delta R = 75 \Omega$   
% change  $= \frac{75}{10,000} \times 100 = 0.75\%$ 

P 3.70 [a] From Eq 3.64 we have

$$\left(\frac{i_1}{i_2}\right)^2 = \frac{R_2^2}{R_1^2(1+2\sigma)^2}$$

Substituting into Eq 3.63 yields

$$R_2 = \frac{R_2^2}{R_1^2 (1+2\sigma)^2} R_1$$

Solving for  $R_2$  yields

$$R_2 = (1+2\sigma)^2 R_1$$

 $[\mathbf{b}]$  From Eq 3.67 we have

$$\begin{aligned} \frac{i_1}{i_b} &= \frac{R_2}{R_1 + R_2 + 2R_a} \\ \text{But } R_2 &= (1 + 2\sigma)^2 R_1 \text{ and } R_a = \sigma R_1 \text{ therefore} \\ \frac{i_1}{i_b} &= \frac{(1 + 2\sigma)^2 R_1}{R_1 + (1 + 2\sigma)^2 R_1 + 2\sigma R_1} = \frac{(1 + 2\sigma)^2}{(1 + 2\sigma) + (1 + 2\sigma)^2} \\ &= \frac{1 + 2\sigma}{2(1 + \sigma)} \end{aligned}$$

It follows that

$$\left(\frac{i_1}{i_{\rm b}}\right)^2 = \frac{(1+2\sigma)^2}{4(1+\sigma)^2}$$

Substituting into Eq 3.66 gives

$$R_{\rm b} = \frac{(1+2\sigma)^2 R_{\rm a}}{4(1+\sigma)^2} = \frac{(1+2\sigma)^2 \sigma R_1}{4(1+\sigma)^2}$$

P 3.71 From Eq 3.69

$$\frac{i_1}{i_3} = \frac{R_2 R_3}{D}$$

But  $D = (R_1 + 2R_a)(R_2 + 2R_b) + 2R_bR_2$ 

where 
$$R_{\rm a} = \sigma R_1$$
;  $R_2 = (1+2\sigma)^2 R_1$  and  $R_{\rm b} = \frac{(1+2\sigma)^2 \sigma R_1}{4(1+\sigma)^2}$ 

Therefore D can be written as

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$$D = (R_1 + 2\sigma R_1) \left[ (1 + 2\sigma)^2 R_1 + \frac{2(1 + 2\sigma)^2 \sigma R_1}{4(1 + \sigma)^2} \right] + 2(1 + 2\sigma)^2 R_1 \left[ \frac{(1 + 2\sigma)^2 \sigma R_1}{4(1 + \sigma)^2} \right]$$
$$= (1 + 2\sigma)^3 R_1^2 \left[ 1 + \frac{\sigma}{2(1 + \sigma)^2} + \frac{(1 + 2\sigma)\sigma}{2(1 + \sigma)^2} \right]$$
$$= \frac{(1 + 2\sigma)^3 R_1^2}{2(1 + \sigma)^2} \{ 2(1 + \sigma)^2 + \sigma + (1 + 2\sigma)\sigma \}$$
$$= \frac{(1 + 2\sigma)^3 R_1^2}{(1 + \sigma)^2} \{ 1 + 3\sigma + 2\sigma^2 \}$$

$$D = \frac{(1+2\sigma)^4 R_1^2}{(1+\sigma)}$$
  
$$\therefore \frac{i_1}{i_3} = \frac{R_2 R_3 (1+\sigma)}{(1+2\sigma)^4 R_1^2}$$
  
$$= \frac{(1+2\sigma)^2 R_1 R_3 (1+\sigma)}{(1+2\sigma)^4 R_1^2}$$
  
$$= \frac{(1+\sigma) R_3}{(1+2\sigma)^2 R_1}$$

When this result is substituted into Eq 3.69 we get

$$R_3 = \frac{(1+\sigma)^2 R_3^2 R_1}{(1+2\sigma)^4 R_1^2}$$

Solving for  $R_3$  gives

$$R_3 = \frac{(1+2\sigma)^4 R_1}{(1+\sigma)^2}$$

P 3.72 From the dimensional specifications, calculate  $\sigma$  and  $R_3$ :

$$\sigma = \frac{y}{x} = \frac{0.025}{1} = 0.025;$$
  $R_3 = \frac{V_{\rm dc}^2}{p} = \frac{12^2}{120} = 1.2\,\Omega$ 

Calculate  $R_1$  from  $R_3$  and  $\sigma$ :

$$R_1 = \frac{(1+\sigma)^2}{(1+2\sigma)^4} R_3 = 1.0372\,\Omega$$

Calculate  $R_a$ ,  $R_b$ , and  $R_2$ :

$$R_a = \sigma R_1 = 0.0259\,\Omega \qquad \qquad R_b = \frac{(1+2\sigma)^2 \sigma R_1}{4(1+\sigma)^2} = 0.0068\,\Omega$$

$$R_2 = (1+2\sigma)^2 R_1 = 1.1435\,\Omega$$

Using symmetry,

 $R_4 = R_2 = 1.1435 \,\Omega$   $R_5 = R_1 = 1.0372 \,\Omega$  $R_c = R_b = 0.0068 \,\Omega$   $R_d = R_a = 0.0259 \,\Omega$ 

Test the calculations by checking the power dissipated, which should be 120 W/m. Calculate D, then use Eqs. (3.58)-(3.60) to calculate  $i_b$ ,  $i_1$ , and  $i_2$ :

$$D = (R_1 + 2R_a)(R_2 + 2R_b) + 2R_2R_b = 1.2758$$
$$i_b = \frac{V_{dc}(R_1 + R_2 + 2R_a)}{D} = 21 \text{ A}$$
$$i_1 = \frac{V_{dc}R_2}{D} = 10.7561 \text{ A} \qquad i_2 = \frac{V_{dc}(R_1 + 2R_a)}{D} = 10.2439 \text{ A}$$

It follows that  $i_b^2 R_b = 3$  W and the power dissipation per meter is 3/0.025 = 120 W/m. The value of  $i_1^2 R_1 = 120$  W/m. The value of  $i_2^2 R_2 = 120$  W/m. Finally,  $i_1^2 R_a = 3$  W/m.

P 3.73 From the solution to Problem 3.72 we have  $i_b = 21$  A and  $i_3 = 10$  A. By symmetry  $i_c = 21$  A thus the total current supplied by the 12 V source is 21 + 21 + 10 or 52 A. Therefore the total power delivered by the source is  $p_{12V}$ (del) = (12)(52) = 624 W. We also have from the solution that  $p_a = p_b = p_c = p_d = 3$  W. Therefore the total power delivered to the vertical resistors is  $p_V = (8)(3) = 24$  W. The total power delivered to the five horizontal resistors is  $p_H = 5(120) = 600$  W.

$$\therefore \quad \sum p_{\rm diss} = p_{\rm H} + p_{\rm V} = 624 \text{ W} = \sum p_{\rm del}$$

P 3.74 [a]  $\sigma = 0.03/1.5 = 0.02$ 

Since the power dissipation is 200 W/m the power dissipated in  $R_3$  must be 200(1.5) or 300 W. Therefore

$$R_3 = \frac{12^2}{300} = 0.48\,\Omega$$

From Table 3.1 we have

$$R_{1} = \frac{(1+\sigma)^{2}R_{3}}{(1+2\sigma)^{4}} = 0.4269\,\Omega$$
$$R_{\sigma} = \sigma R_{1} = 0.0085\,\Omega$$

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Problems 3–47

$$\begin{split} R_2 &= (1+2\sigma)^2 R_1 = 0.4617 \, \Omega \\ R_b &= \frac{(1+2\sigma)^2 \sigma R_1}{4(1+\sigma)^2} = 0.0022 \, \Omega \\ \text{Therefore} \\ R_4 &= R_2 = 0.4617 \, \Omega \qquad R_5 = R_1 = 0.4269 \, \Omega \\ R_c &= R_b = 0.0022 \, \Omega \qquad R_d = R_a = 0.0085 \, \Omega \\ \textbf{[b]} \quad D &= [0.4269 + 2(0.0085)][0.4617 + 2(0.0022)] + 2(0.4617)(0.0022) = 0.2090 \\ i_1 &= \frac{V_{dc}R_2}{D} = 26.51 \, \text{A} \\ i_1^2 R_1 &= 300 \, \text{W or } 200 \, \text{W/m} \\ i_2 &= \frac{R_1 + 2R_a}{D} \, V_{dc} = 25.49 \, \text{A} \\ i_2^2 R_2 &= 300 \, \text{W or } 200 \, \text{W/m} \\ i_b &= \frac{R_1 + R_2 + 2R_a}{D} \, V_{dc} = 52 \, \text{A} \\ i_b^2 R_b &= 6 \, \text{W or } 200 \, \text{W/m} \\ i_{source} &= 52 + 52 + \frac{12}{0.48} = 129 \, \text{A} \\ p_{del} &= 12(129) = 1548 \, \text{W} \\ p_H &= 5(300) = 1500 \, \text{W} \\ p_V &= 8(6) = 48 \, \text{W} \\ \sum p_{del} &= \sum p_{diss} = 1548 \, \text{W} \end{split}$$

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