Series-Parallel Circuits

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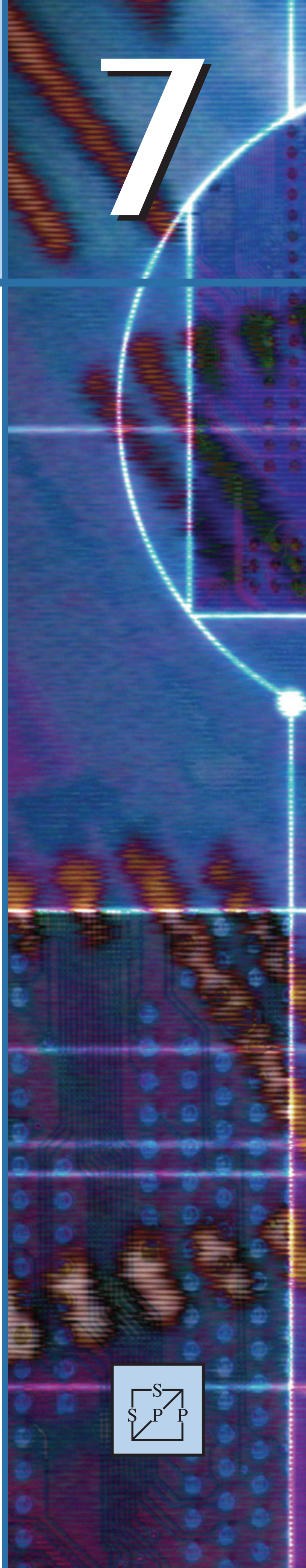


Objectives

- ***Learn about the unique characteristics of series-parallel configurations and how to solve for the voltage, current, or power to any individual element or combination of elements.***
- ***Become familiar with the voltage divider supply and the conditions needed to use it effectively.***
- ***Learn how to use a potentiometer to control the voltage across any given load.***

7.1 INTRODUCTION

Chapters 5 and 6 were dedicated to the fundamentals of series and parallel circuits. In some ways, these chapters may be the most important ones in the text, because they form a foundation for all the material to follow. The remaining network configurations cannot be defined by a strict list of conditions because of the variety of configurations that exists. In broad terms, we can look upon the remaining possibilities as either **series-parallel** or **complex**.

A series-parallel configuration is one that is formed by a combination of series and parallel elements.

A complex configuration is one in which none of the elements are in series or parallel.

In this chapter, we examine the series-parallel combination using the basic laws introduced for series and parallel circuits. There are no new laws or rules to learn—simply an approach that permits the analysis of such structures. In the next chapter, we consider complex networks using methods of analysis that allow us to analyze any type of network.

The possibilities for series-parallel configurations are infinite. Therefore, you need to examine each network as a separate entity and define the approach that provides the best path to determining the unknown quantities. In time, you will find similarities between configurations that make it easier to define the best route to a solution, but this occurs only with exposure, practice, and patience. The best preparation for the analysis of series-parallel networks is a firm understanding of the concepts introduced for series and parallel networks. All the rules and laws to be applied in this chapter have already been introduced in the previous two chapters.

7.2 SERIES-PARALLEL NETWORKS

The network in Fig. 7.1 is a series-parallel network. At first, you must be very careful to determine which elements are in series and which are in parallel. For instance, resistors R_1 and R_2 are *not* in series due to resistor R_3 connected to the common point b between R_1 and R_2. Resistors R_2 and R_4 are *not* in parallel because they are not connected at both ends. They are separated at one end by resistor R_3. The need to be absolutely sure of your definitions from the last two chapters now becomes obvious. In fact, it may be a good idea to refer to those rules as we progress through this chapter.

If we look carefully enough at Fig. 7.1, we do find that the two resistors R_3 and R_4 are in series because they share only point c, and no other element is connected to that point. Further,

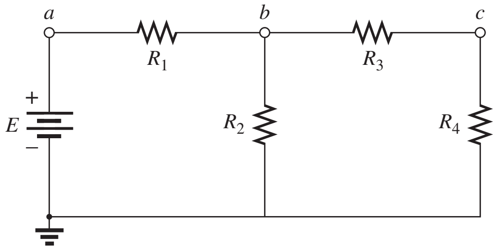


FIG. 7.1
Series-parallel dc network.

the voltage source E and resistor R_1 are in series because they share point *a,* with no other elements connected to the same point. In the entire configuration, there are no two elements in parallel.

How do we analyze such configurations? The approach is one that requires us to first identify elements that can be combined. Since there are no parallel elements, we must turn to the possibilities with series elements. The voltage source and the series resistor cannot be combined because they are different types of elements. However, resistors R_3 and R_4 can be combined to form a single resistor. The total resistance of the two is their sum as defined by series circuits. The resulting resistance is then in parallel with resistor R_2, and they can be combined using the laws for parallel elements. The process has begun: We are slowly reducing the network to one that will be represented by a single resistor equal to the total resistance "seen" by the source.

The source current can now be determined using Ohm's law, and we can work back through the network to find all the other currents and voltages. The ability to define the first step in the analysis can sometimes be difficult. However, combinations can be made only by using the rules for series or parallel elements, so naturally the first step may simply be to define which elements are in series or parallel. You must then define how to find such things as the total resistance and the source current and proceed with the analysis. In general, the following steps will provide some guidance for the wide variety of possible combinations that you might encounter.

General Approach:

1. Take a moment to study the problem "in total" and make a brief mental sketch of the overall approach you plan to use. The result may be time- and energy-saving shortcuts.
2. Examine each region of the network independently before tying them together in series-parallel combinations. This usually simplifies the network and possibly reveals a direct approach toward obtaining one or more desired unknowns. It also eliminates many of the errors that may result due to the lack of a systematic approach.
3. Redraw the network as often as possible with the reduced branches and undisturbed unknown quantities to maintain clarity and provide the reduced networks for the trip back to unknown quantities from the source.
4. When you have a solution, check that it is reasonable by considering the magnitudes of the energy source and the elements in the network. If it does not seem reasonable, either solve the circuit using another approach or review your calculations.

7.3 REDUCE AND RETURN APPROACH

The network of Fig. 7.1 is redrawn as Fig. 7.2(a). For this discussion, let us assume that voltage V_4 is desired. As described in Section 7.2, first combine the series resistors R_3 and R_4 to form an equivalent resistor R' as shown in Fig. 7.2(b). Resistors R_2 and R' are then in parallel and can be combined to establish an equivalent resistor R'_T as shown in Fig. 7.2(c). Resistors R_1 and R'_T are then in series and can be combined to establish the total resistance of the network as shown in Fig. 7.2(d). The **reduction phase** of the analysis is now complete. The network cannot be put in a simpler form.

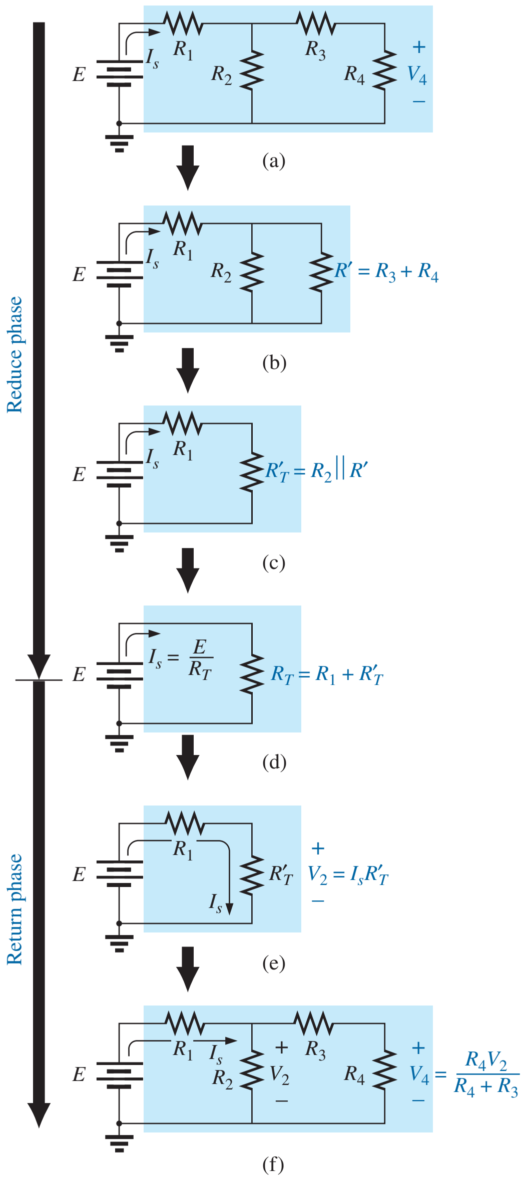


FIG. 7.2

Introducing the reduce and return approach.

We can now proceed with the **return phase** whereby we work our way back to the desired voltage V_4. Due to the resulting series configuration, the source current is also the current through R_1 and R'_T. The voltage across R'_T (and therefore across R_2) can be determined using Ohm's law as shown in Fig. 7.2(e). Finally, the desired voltage V_4 can be determined by an application of the voltage divider rule as shown in Fig. 7.2(f).

The *reduce and return approach* has now been introduced. This process enables you to reduce the network to its simplest form across the source and then determine the source current. In the return phase, you use the resulting source current to work back to the desired unknown. For most single-source series-parallel networks, the above approach provides a viable option toward the solution. In some cases, shortcuts can be applied that save some time and energy. Now for a few examples.

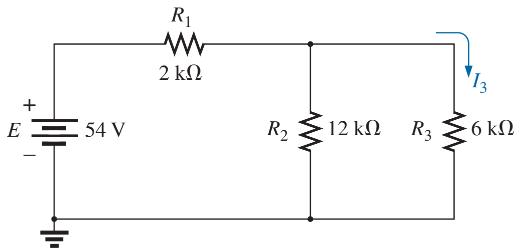


FIG. 7.3
Series-parallel network for Example 7.1.

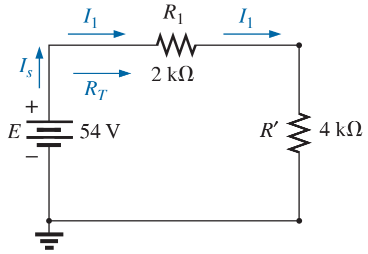


FIG. 7.4
Substituting the parallel equivalent resistance for resistors R_2 and R_3 in Fig. 7.3.

EXAMPLE 7.1 Find current I_3 for the series-parallel network in Fig. 7.3.

Solution: Checking for series and parallel elements, we find that resistors R_2 and R_3 are in parallel. Their total resistance is

$$R' = R_2 \parallel R_3 = \frac{R_2 R_3}{R_2 + R_3} = \frac{(12\text{ k}\Omega)(6\text{ k}\Omega)}{12\text{ k}\Omega + 6\text{ k}\Omega} = 4\text{ k}\Omega$$

Replacing the parallel combination with a single equivalent resistance results in the configuration in Fig. 7.4. Resistors R_1 and R' are then in series, resulting in a total resistance of

$$R_T = R_1 + R' = 2\text{ k}\Omega + 4\text{ k}\Omega = 6\text{ k}\Omega$$

The source current is then determined using Ohm's law:

$$I_s = \frac{E}{R_T} = \frac{54\text{ V}}{6\text{ k}\Omega} = 9\text{ mA}$$

In Fig. 7.4, since R_1 and R' are in series, they have the same current I_s. The result is

$$I_1 = I_s = 9\text{ mA}$$

Returning to Fig. 7.3, we find that I_1 is the total current entering the parallel combination of R_2 and R_3. Applying the current divider rule results in the desired current:

$$I_3 = \left(\frac{R_2}{R_2 + R_3}\right)I_1 = \left(\frac{12\text{ k}\Omega}{12\text{ k}\Omega + 6\text{ k}\Omega}\right)9\text{ mA} = \mathbf{6\text{ mA}}$$

Note in the solution for Example 7.1 that all of the equations used were introduced in the last two chapters—nothing new was introduced except how to approach the problem and use the equations properly.

EXAMPLE 7.2 For the network in Fig. 7.5:

a. Determine currents I_4 and I_s and voltage V_2.
b. Insert the meters to measure current I_4 and voltage V_2.

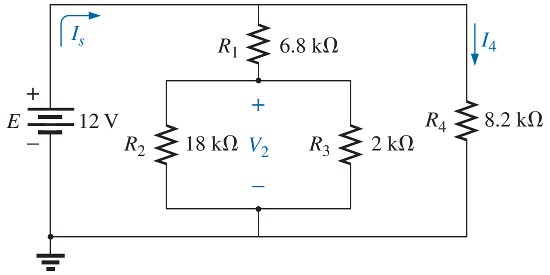


FIG. 7.5
Series-parallel network for Example 7.2.

Solutions:

a. Checking out the network, we find that there are no two resistors in series and the only parallel combination is resistors R_2 and R_3. Combining the two parallel resistors results in a total resistance of

$$R' = R_2 \parallel R_3 = \frac{R_2 R_3}{R_2 + R_3} = \frac{(18\ \text{k}\Omega)(2\ \text{k}\Omega)}{18\ \text{k}\Omega + 2\ \text{k}\Omega} = 1.8\ \text{k}\Omega$$

Redrawing the network with resistance R' inserted results in the configuration in Fig. 7.6.

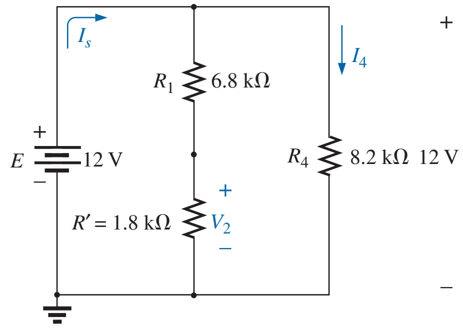


FIG. 7.6

Schematic representation of the network in Fig. 7.5 after substituting the equivalent resistance R' for the parallel combination of R_2 and R_3.

You may now be tempted to combine the series resistors R_1 and R' and redraw the network. However, a careful examination of Fig. 7.6 reveals that since the two resistive branches are in parallel, the voltage is the same across each branch. That is, the voltage across the series combination of R_1 and R' is 12 V and that across resistor R_4 is 12 V. The result is that I_4 can be determined directly using Ohm's law as follows:

$$I_4 = \frac{V_4}{R_4} = \frac{E}{R_4} = \frac{12\ \text{V}}{8.2\ \text{k}\Omega} = \mathbf{1.46\ mA}$$

In fact, for the same reason, I_4 could have been determined directly from Fig. 7.5. Because the total voltage across the series combination of R_1 and R'_T is 12 V, the voltage divider rule can be applied to determine voltage V_2 as follows:

$$V_2 = \left(\frac{R'}{R' + R_1}\right)E = \left(\frac{1.8\ \text{k}\Omega}{1.8\ \text{k}\Omega + 6.8\ \text{k}\Omega}\right)12\ \text{V} = \mathbf{2.51\ V}$$

The current I_s can be found one of two ways. Find the total resistance and use Ohm's law or find the current through the other parallel branch and apply Kirchhoff's current law. Since we already have the current I_4, the latter approach will be applied:

$$I_1 = \frac{E}{R_1 + R'} = \frac{12\ \text{V}}{6.8\ \text{k}\Omega + 1.8\ \text{k}\Omega} = 1.40\ \text{mA}$$

and $\quad I_s = I_1 + I_4 = 1.40\ \text{mA} + 1.46\ \text{mA} = \mathbf{2.86\ mA}$

b. The meters have been properly inserted in Fig. 7.7. Note that the voltmeter is across both resistors since the voltage across parallel

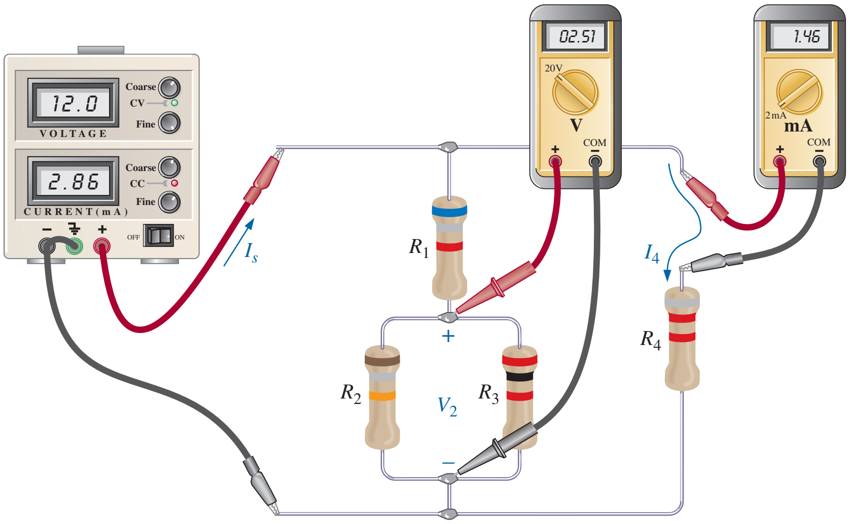


FIG. 7.7

Inserting an ammeter and a voltmeter to measure I_4 and V_2, respectively.

elements is the same. In addition, note that the ammeter is in series with resistor R_4, forcing the current through the meter to be the same as that through the series resistor. The power supply is displaying the source current.

Clearly, Example 7.2 revealed how a careful study of a network can eliminate unnecessary steps toward the desired solution. It is often worth the extra time to sit back and carefully examine a network before trying every equation that seems appropriate.

7.4 BLOCK DIAGRAM APPROACH

In the previous example, we used the reduce and return approach to find the desired unknowns. The direction seemed fairly obvious and the solution relatively easy to understand. However, occasionally the approach is not as obvious, and you may need to look at groups of elements rather than the individual components. Once the grouping of elements reveals the most direct approach, you can examine the impact of the individual components in each group. This grouping of elements is called the *block diagram approach* and is used in the following examples.

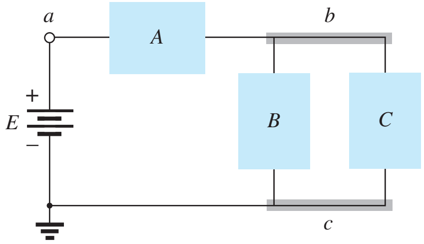


FIG. 7.8
Introducing the block diagram approach.

In Fig. 7.8, blocks *B* and *C* are in parallel (points *b* and *c* in common), and the voltage source *E* is in series with block *A* (point *a* in common). The parallel combination of *B* and *C* is also in series with *A* and the voltage source *E* due to the common points *b* and *c*, respectively.

To ensure that the analysis to follow is as clear and uncluttered as possible, the following notation is used for series and parallel combinations of elements. For series resistors R_1 and R_2, a comma is inserted between their subscript notations, as shown here:

$$R_{1,2} = R_1 + R_2$$

For parallel resistors R_1 and R_2, the parallel symbol is inserted between their subscripted notations, as follows:

$$R_{1\|2} = R_1 \parallel R_2 = \frac{R_1 R_2}{R_1 + R_2}$$

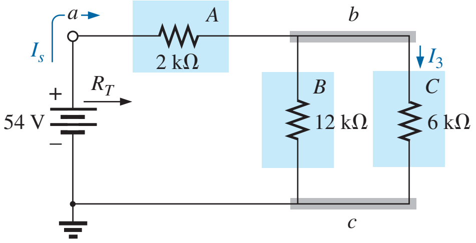


FIG. 7.9
Block diagram format of Fig. 7.3.

If each block in Fig. 7.8 were a single resistive element, the network in Fig. 7.9 would result. Note that it is an exact replica of Fig. 7.3 in Example 7.1. Blocks *B* and *C* are in parallel, and their combination is in series with block *A*.

However, as shown in the next example, the same block configuration can result in a totally different network.

EXAMPLE 7.3 Determine all the currents and voltages of the network in Fig. 7.10.

Solution: Blocks *A, B,* and *C* have the same relative position, but the internal components are different. Note that blocks *B* and *C* are still in parallel and block *A* is in series with the parallel combination. First, reduce each block into a single element and proceed as described for Example 7.1.

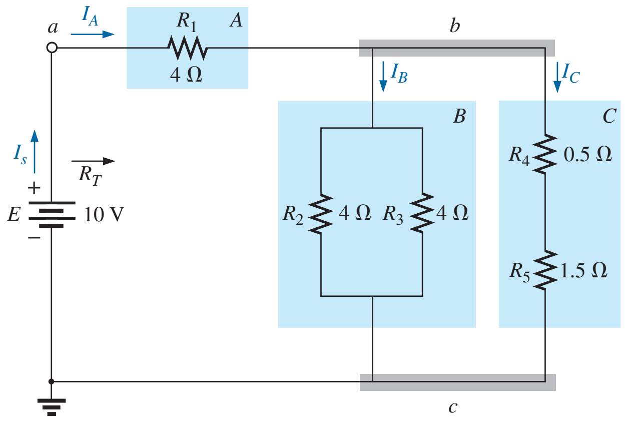


FIG. 7.10
Example 7.3.

In this case:

$$A\colon R_A = 4\ \Omega$$

$$B\colon R_B = R_2 \parallel R_3 = R_{2\parallel 3} = \frac{R}{N} = \frac{4\ \Omega}{2} = 2\ \Omega$$

$$C\colon R_C = R_4 + R_5 = R_{4,5} = 0.5\ \Omega + 1.5\ \Omega = 2\ \Omega$$

Blocks *B* and *C* are still in parallel, and

$$R_{B\parallel C} = \frac{R}{N} = \frac{2\ \Omega}{2} = 1\ \Omega$$

with

$$\begin{aligned} R_T &= R_A + R_{B\parallel C} \\ &= 4\ \Omega + 1\ \Omega = \mathbf{5\ \Omega} \end{aligned}$$

(Note the similarity between this equation and that obtained for Example 7.1.)

and
$$I_s = \frac{E}{R_T} = \frac{10\ \text{V}}{5\ \Omega} = \mathbf{2\ A}$$

We can find the currents I_A, I_B, and I_C using the reduction of the network in Fig. 7.10 (recall Step 3) as found in Fig. 7.11. Note that I_A, I_B, and I_C are the same in Figs. 7.10 and Fig. 7.11 and therefore also appear in Fig. 7.11. In other words, the currents I_A, I_B, and I_C in Fig. 7.11 have the same magnitude as the same currents in Fig. 7.10.

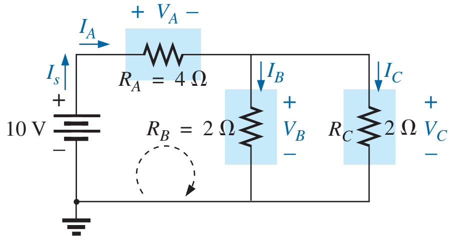


FIG. 7.11
Reduced equivalent of Fig. 7.10.

$$I_A = I_s = \mathbf{2\ A}$$

and
$$I_B = I_C = \frac{I_A}{2} = \frac{I_s}{2} = \frac{2\ \text{A}}{2} = \mathbf{1\ A}$$

Returning to the network in Fig. 7.10, we have

$$I_{R_2} = I_{R_3} = \frac{I_B}{2} = \mathbf{0.5\ A}$$

The voltages V_A, V_B, and V_C from either figure are

$$\begin{aligned} V_A &= I_A R_A = (2\ \text{A})(4\ \Omega) = \mathbf{8\ V} \\ V_B &= I_B R_B = (1\ \text{A})(2\ \Omega) = \mathbf{2\ V} \\ V_C &= V_B = \mathbf{2\ V} \end{aligned}$$

Applying Kirchhoff's voltage law for the loop indicated in Fig. 7.11, we obtain

$$\Sigma_{\circlearrowright} V = E - V_A - V_B = 0$$
$$E = V_A + V_B = 8\text{ V} + 2\text{ V}$$

or

$$10\text{ V} = 10\text{ V} \quad \text{(checks)}$$

EXAMPLE 7.4 Another possible variation of Fig. 7.8 appears in Fig. 7.12. Determine all the currents and voltages.

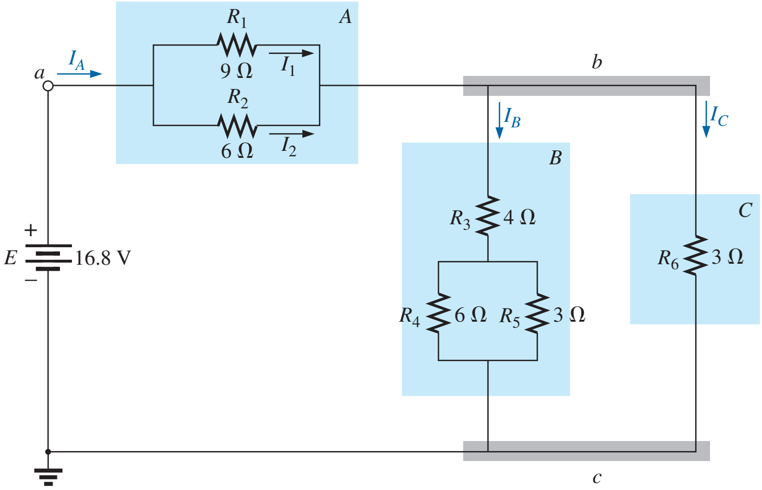


FIG. 7.12
Example 7.4.

Solution:

$$R_A = R_{1\|2} = \frac{(9\ \Omega)(6\ \Omega)}{9\ \Omega + 6\ \Omega} = \frac{54\ \Omega}{15} = 3.6\ \Omega$$

$$R_B = R_3 + R_{4\|5} = 4\ \Omega + \frac{(6\ \Omega)(3\ \Omega)}{6\ \Omega + 3\ \Omega} = 4\ \Omega + 2\ \Omega = 6\ \Omega$$

$$R_C = 3\ \Omega$$

The network in Fig. 7.12 can then be redrawn in reduced form, as shown in Fig. 7.13. Note the similarities between this circuit and the circuits in Figs. 7.9 and 7.11.

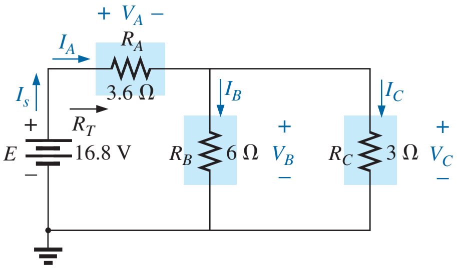


FIG. 7.13
Reduced equivalent of Fig. 7.12.

$$R_T = R_A + R_{B\|C} = 3.6\ \Omega + \frac{(6\ \Omega)(3\ \Omega)}{6\ \Omega + 3\ \Omega}$$
$$= 3.6\ \Omega + 2\ \Omega = \mathbf{5.6\ \Omega}$$
$$I_s = \frac{E}{R_T} = \frac{16.8\text{ V}}{5.6\ \Omega} = \mathbf{3\ A}$$
$$I_A = I_s = \mathbf{3\ A}$$

Applying the current divider rule yields

$$I_B = \frac{R_C I_A}{R_C + R_B} = \frac{(3\ \Omega)(3\text{ A})}{3\ \Omega + 6\ \Omega} = \frac{9\text{ A}}{9} = \mathbf{1\ A}$$

By Kirchhoff's current law,

$$I_C = I_A - I_B = 3\text{ A} - 1\text{ A} = \mathbf{2\ A}$$

By Ohm's law,

$$V_A = I_A R_A = (3\text{ A})(3.6\ \Omega) = \mathbf{10.8\ V}$$
$$V_B = I_B R_B = V_C = I_C R_C = (2\text{ A})(3\ \Omega) = \mathbf{6\ V}$$

Returning to the original network (Fig. 7.12) and applying the current divider rule,

$$I_1 = \frac{R_2 I_A}{R_2 + R_1} = \frac{(6\ \Omega)(3\text{ A})}{6\ \Omega + 9\ \Omega} = \frac{18\text{ A}}{15} = \mathbf{1.2\ A}$$

By Kirchhoff's current law,

$$I_2 = I_A - I_1 = 3\text{ A} - 1.2\text{ A} = \mathbf{1.8\ A}$$

Figs. 7.9, 7.10, and 7.12 are only a few of the infinite variety of configurations that the network can assume starting with the basic arrangement in Fig. 7.8. They were included in our discussion to emphasize the importance of considering each region of the network independently before finding the solution for the network as a whole.

The blocks in Fig. 7.8 can be arranged in a variety of ways. In fact, there is no limit on the number of series-parallel configurations that can appear within a given network. In reverse, the block diagram approach can be used effectively to reduce the apparent complexity of a system by identifying the major series and parallel components of the network. This approach is demonstrated in the next few examples.

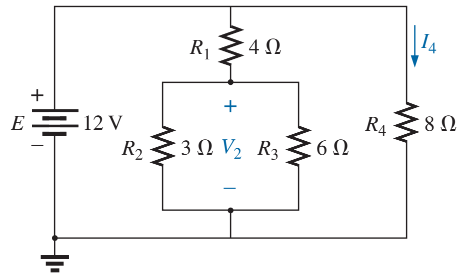


FIG. 7.14
Example 7.5.

7.5 DESCRIPTIVE EXAMPLES

EXAMPLE 7.5 Find the current I_4 and the voltage V_2 for the network in Fig. 7.14 using the block diagram approach.

Solution: Note the similarities with the network in Fig. 7.5. In this case, particular unknowns are requested instead of a complete solution. It would, therefore, be a waste of time to find all the currents and voltages of the network. The method used should concentrate on obtaining only the unknowns requested. With the block diagram approach, the network has the basic structure in Fig. 7.15, clearly indicating that the three branches are in parallel and the voltage across A and B is the supply voltage. The current I_4 is now immediately obvious as simply the supply voltage divided by the resultant resistance for B. If desired, block A can be broken down further, as shown in Fig. 7.16, to identify C and D as series elements, with the voltage V_2 capable of being determined using the voltage divider rule once the resistance of C and D is reduced to a single value. This is an example of how making a mental sketch of the approach before applying laws, rules, and so on, can help avoid dead ends and frustration.

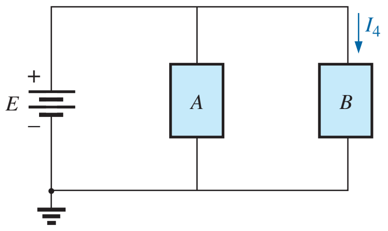


FIG. 7.15
Block diagram of Fig. 7.14.

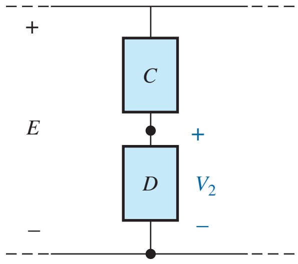


FIG. 7.16
Alternative block diagram for the first parallel branch in Fig. 7.14.

Applying Ohm's law,

$$I_4 = \frac{E}{R_B} = \frac{E}{R_4} = \frac{12\text{ V}}{8\ \Omega} = \mathbf{1.5\ A}$$

Combining the resistors R_2 and R_3 in Fig. 7.14 results in

$$R_D = R_2 \parallel R_3 = 3\ \Omega \parallel 6\ \Omega = \frac{(3\ \Omega)(6\ \Omega)}{3\ \Omega + 6\ \Omega} = \frac{18\ \Omega}{9} = 2\ \Omega$$

and, applying the voltage divider rule,

$$V_2 = \frac{R_D E}{R_D + R_C} = \frac{(2\ \Omega)(12\ \text{V})}{2\ \Omega + 4\ \Omega} = \frac{24\ \text{V}}{6} = \mathbf{4\ V}$$

EXAMPLE 7.6 Find the indicated currents and voltages for the network in Fig. 7.17.

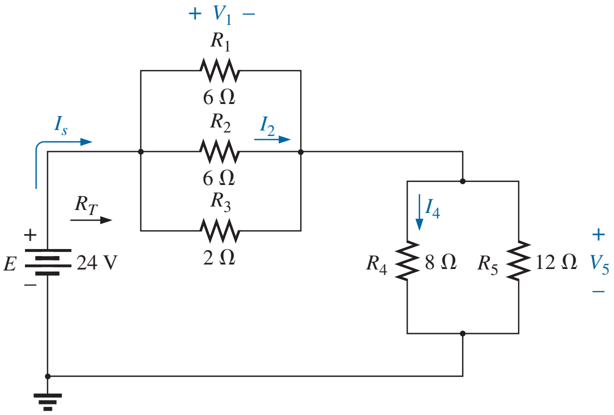


FIG. 7.17
Example 7.6.

Solution: Again, only specific unknowns are requested. When the network is redrawn, be sure to note which unknowns are preserved and which have to be determined using the original configuration. The block diagram of the network may appear as shown in Fig. 7.18, clearly revealing that A and B are in series. Note in this form the number of unknowns that have been preserved. The voltage V_1 is the same across the three parallel branches in Fig. 7.17, and V_5 is the same across R_4 and R_5. The unknown currents I_2 and I_4 are lost since they represent the currents through only one of the parallel branches. However, once V_1 and V_5 are known, you can find the required currents using Ohm's law.

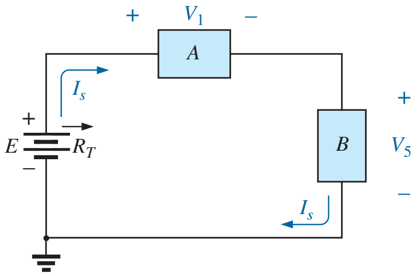


FIG. 7.18
Block diagram for Fig. 7.17.

$$R_{1\|2} = \frac{R}{N} = \frac{6\ \Omega}{2} = 3\ \Omega$$

$$R_A = R_{1\|2\|3} = \frac{(3\ \Omega)(2\ \Omega)}{3\ \Omega + 2\ \Omega} = \frac{6\ \Omega}{5} = 1.2\ \Omega$$

$$R_B = R_{4\|5} = \frac{(8\ \Omega)(12\ \Omega)}{8\ \Omega + 12\ \Omega} = \frac{96\ \Omega}{20} = 4.8\ \Omega$$

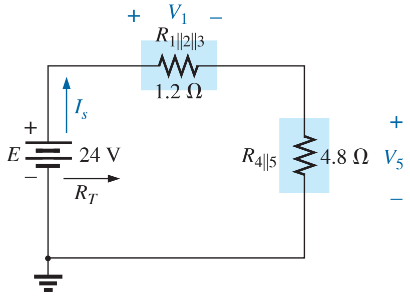


FIG. 7.19
Reduced form of Fig. 7.17.

The reduced form of Fig. 7.17 then appears as shown in Fig. 7.19, and

$$R_T = R_{1\|2\|3} + R_{4\|5} = 1.2\ \Omega + 4.8\ \Omega = \mathbf{6\ \Omega}$$

$$I_s = \frac{E}{R_T} = \frac{24\ \text{V}}{6\ \Omega} = \mathbf{4\ A}$$

with

$$V_1 = I_s R_{1\|2\|3} = (4\ \text{A})(1.2\ \Omega) = \mathbf{4.8\ V}$$
$$V_5 = I_s R_{4\|5} = (4\ \text{A})(4.8\ \Omega) = \mathbf{19.2\ V}$$

Applying Ohm's law,

$$I_4 = \frac{V_5}{R_4} = \frac{19.2\text{ V}}{8\,\Omega} = \mathbf{2.4\text{ A}}$$

$$I_2 = \frac{V_2}{R_2} = \frac{V_1}{R_2} = \frac{4.8\text{ V}}{6\,\Omega} = \mathbf{0.8\text{ A}}$$

The next example demonstrates that unknown voltages do not have to be across elements but can exist between any two points in a network. In addition, the importance of redrawing the network in a more familiar form is clearly revealed by the analysis to follow.

EXAMPLE 7.7

a. Find the voltages V_1, V_3, and V_{ab} for the network in Fig. 7.20.
b. Calculate the source current I_s.

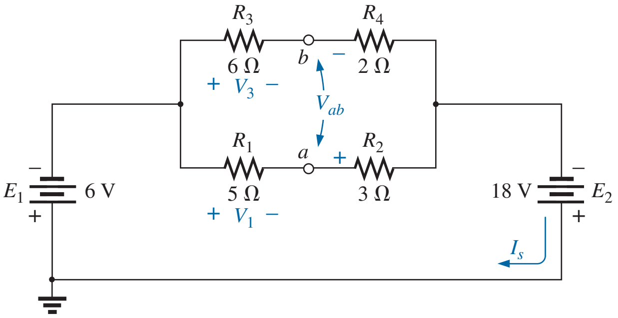


FIG. 7.20
Example 7.7.

Solutions: This is one of those situations where it may be best to redraw the network before beginning the analysis. Since combining both sources will not affect the unknowns, the network is redrawn as shown in Fig. 7.21, establishing a parallel network with the total source voltage across each parallel branch. The net source voltage is the difference between the two with the polarity of the larger.

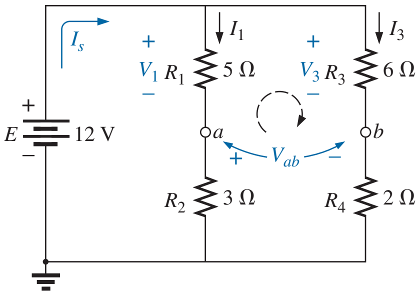


FIG. 7.21
Network in Fig. 7.20 redrawn.

a. Note the similarities with Fig. 7.16, permitting the use of the voltage divider rule to determine V_1 and V_3:

$$V_1 = \frac{R_1E}{R_1 + R_2} = \frac{(5\,\Omega)(12\text{ V})}{5\,\Omega + 3\,\Omega} = \frac{60\text{ V}}{8} = \mathbf{7.5\text{ V}}$$

$$V_3 = \frac{R_3E}{R_3 + R_4} = \frac{(6\,\Omega)(12\text{ V})}{6\,\Omega + 2\,\Omega} = \frac{72\text{ V}}{8} = \mathbf{9\text{ V}}$$

The open-circuit voltage V_{ab} is determined by applying Kirchhoff's voltage law around the indicated loop in Fig. 7.21 in the clockwise direction starting at terminal *a*.

$$+V_1 - V_3 + V_{ab} = 0$$

and $$V_{ab} = V_3 - V_1 = 9\text{ V} - 7.5\text{ V} = \mathbf{1.5\text{ V}}$$

b. By Ohm's law,

$$I_1 = \frac{V_1}{R_1} = \frac{7.5\text{ V}}{5\ \Omega} = 1.5\text{ A}$$

$$I_3 = \frac{V_3}{R_3} = \frac{9\text{ V}}{6\ \Omega} = 1.5\text{ A}$$

Applying Kirchhoff's current law,

$$I_s = I_1 + I_3 = 1.5\text{ A} + 1.5\text{ A} = \mathbf{3\ A}$$

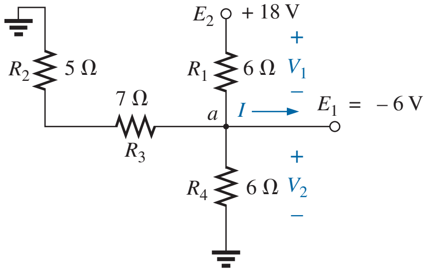


FIG. 7.22

Example 7.8.

EXAMPLE 7.8 For the network in Fig. 7.22, determine the voltages V_1 and V_2 and the current I.

Solution: It would indeed be difficult to analyze the network in the form in Fig. 7.22 with the symbolic notation for the sources and the reference or ground connection in the upper left corner of the diagram. However, when the network is redrawn as shown in Fig. 7.23, the unknowns and the relationship between branches become significantly clearer. Note the common connection of the grounds and the replacing of the terminal notation by actual supplies.

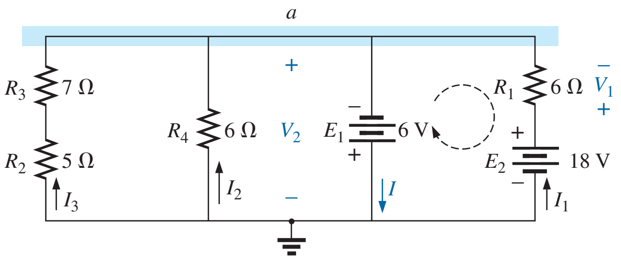


FIG. 7.23

Network in Fig. 7.22 redrawn.

It is now obvious that

$$V_2 = -E_1 = \mathbf{-6\ V}$$

The minus sign simply indicates that the chosen polarity for V_2 in Fig. 7.18 is opposite to that of the actual voltage. Applying Kirchhoff's voltage law to the loop indicated, we obtain

$$-E_1 + V_1 - E_2 = 0$$

and $$V_1 = E_2 + E_1 = 18\text{ V} + 6\text{ V} = \mathbf{24\ V}$$

Applying Kirchhoff's current law to note *a* yields

$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ &= \frac{V_1}{R_1} + \frac{E_1}{R_4} + \frac{E_1}{R_2 + R_3} \\ &= \frac{24\text{ V}}{6\ \Omega} + \frac{6\text{ V}}{6\ \Omega} + \frac{6\text{ V}}{12\ \Omega} \\ &= 4\text{ A} + 1\text{ A} + 0.5\text{ A} \\ I &= \mathbf{5.5\ A} \end{aligned}$$

The next example is clear evidence that techniques learned in the current chapters will have far-reaching applications and will not be dropped for improved methods. Even though we have not studied the **transistor** yet, the dc levels of a transistor network can be examined using the basic rules and laws introduced in earlier chapters.

EXAMPLE 7.9 For the transistor configuration in Fig. 7.24, in which V_B and V_{BE} have been provided:

a. Determine the voltage V_E and the current I_E.
b. Calculate V_1.
c. Determine V_{BC} using the fact that the approximation $I_C = I_E$ is often applied to transistor networks.
d. Calculate V_{CE} using the information obtained in parts (a) through (c).

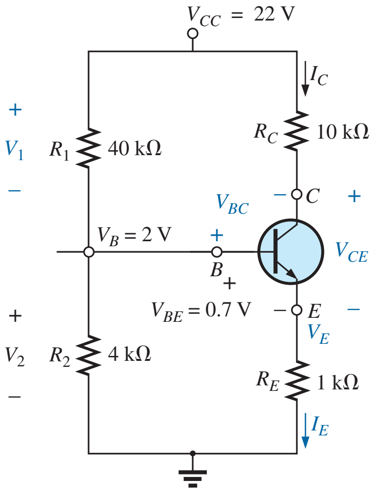


FIG. 7.24
Example 7.9.

Solutions:

a. From Fig. 7.24, we find

$$V_2 = V_B = 2\text{ V}$$

Writing Kirchhoff's voltage law around the lower loop yields

$$V_2 - V_{BE} - V_E = 0$$

or $$V_E = V_2 - V_{BE} = 2\text{ V} - 0.7\text{ V} = \mathbf{1.3\text{ V}}$$

and $$I_E = \frac{V_E}{R_E} = \frac{1.3\text{ V}}{1\text{ k}\Omega} = \mathbf{1.3\text{ mA}}$$

b. Applying Kirchhoff's voltage law to the input side (left region of the network) results in

$$V_2 + V_1 - V_{CC} = 0$$

and $$V_1 = V_{CC} - V_2$$

but $$V_2 = V_B$$

and $$V_1 = V_{CC} - V_2 = 22\text{ V} - 2\text{ V} = \mathbf{20\text{ V}}$$

c. Redrawing the section of the network of immediate interest results in Fig. 7.25, where Kirchhoff's voltage law yields

$$V_C + V_{R_C} - V_{CC} = 0$$

and $$V_C = V_{CC} - V_{R_C} = V_{CC} - I_C R_C$$

but $$I_C = I_E$$

and $$V_C = V_{CC} - I_E R_C = 22\text{ V} - (1.3\text{ mA})(10\text{ k}\Omega) = 9\text{ V}$$

Then $$V_{BC} = V_B - V_C = 2\text{ V} - 9\text{ V} = \mathbf{-7\text{ V}}$$

d. $$V_{CE} = V_C - V_E = 9\text{ V} - 1.3\text{ V} = \mathbf{7.7\text{ V}}$$

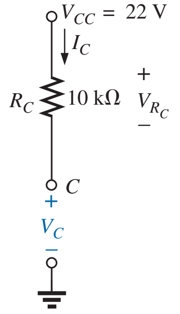


FIG. 7.25
Determining V_C for the network in Fig. 7.24.

EXAMPLE 7.10 Calculate the indicated currents and voltage in Fig. 7.26.

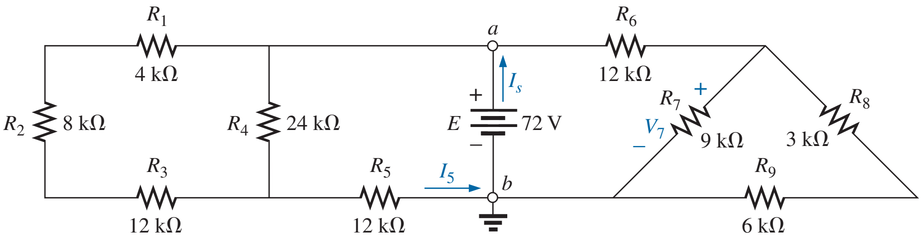


FIG. 7.26
Example 7.10.

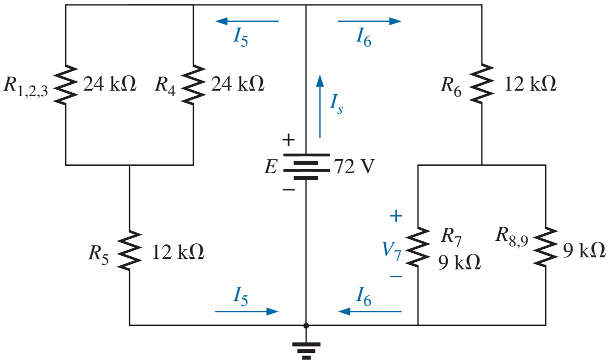


FIG. 7.27
Network in Fig. 7.26 redrawn.

Solution: Redrawing the network after combining series elements yields Fig. 7.27, and

$$I_5 = \frac{E}{R_{(1,2,3)\|4} + R_5} = \frac{72\text{ V}}{12\text{ k}\Omega + 12\text{ k}\Omega} = \frac{72\text{ V}}{24\text{ k}\Omega} = \mathbf{3\text{ mA}}$$

with

$$V_7 = \frac{R_{7\|(8,9)}E}{R_{7\|(8,9)} + R_6} = \frac{(4.5\text{ k}\Omega)(72\text{ V})}{4.5\text{ k}\Omega + 12\text{ k}\Omega} = \frac{324\text{ V}}{16.5} = \mathbf{19.6\text{ V}}$$

$$I_6 = \frac{V_7}{R_{7\|(8,9)}} = \frac{19.6\text{ V}}{4.5\text{ k}\Omega} = \mathbf{4.35\text{ mA}}$$

and $$I_s = I_5 + I_6 = 3\text{ mA} + 4.35\text{ mA} = \mathbf{7.35\text{ mA}}$$

Since the potential difference between points *a* and *b* in Fig. 7.26 is fixed at *E* volts, the circuit to the right or left is unaffected if the network is reconstructed as shown in Fig. 7.28.

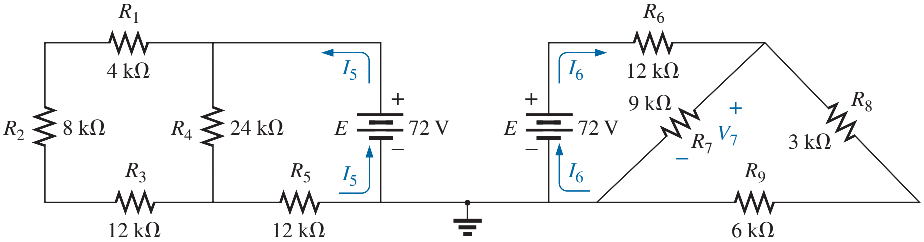


FIG. 7.28
An alternative approach to Example 7.10.

We can find each quantity required, except I_s, by analyzing each circuit independently. To find I_s, we must find the source current for each circuit and add it as in the above solution; that is, $I_s = I_5 + I_6$.

EXAMPLE 7.11 For the network in Fig. 7.29:

a. Determine voltages V_a, V_b, and V_c.
b. Find voltages V_{ac} and V_{bc}.
c. Find current I_2.
d. Find the source current I_{s_3}.
e. Insert voltmeters to measure voltages V_a and V_{bc} and current I_{s_3}.

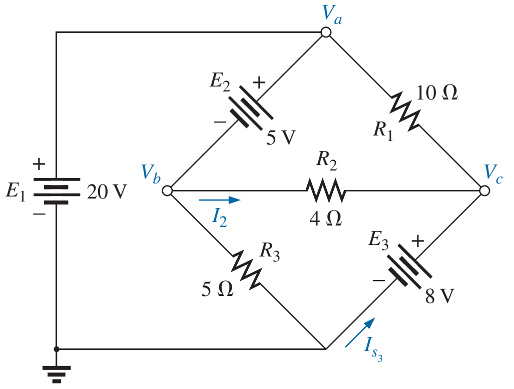


FIG. 7.29
Example 7.11.

Solutions:

a. The network is redrawn in Fig. 7.30 to clearly indicate the arrangement between elements.

First, note that voltage V_a is directly across voltage source E_1. Therefore,

$$V_a = E_1 = \mathbf{20\ V}$$

The same is true for voltage V_c, which is directly across the voltage source E_3. Therefore,

$$V_c = E_3 = \mathbf{8\ V}$$

To find voltage V_b, which is actually the voltage across R_3, we must apply Kirchhoff's voltage law around loop 1 as follows:

$$+E_1 - E_2 - V_3 = 0$$

and $\quad V_3 = E_1 - E_2 = 20\ \text{V} - 5\ \text{V} = 15\ \text{V}$

and $\quad V_b = V_3 = \mathbf{15\ V}$

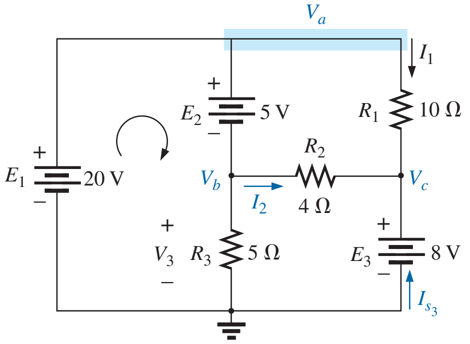


FIG. 7.30
Network in Fig. 7.29 redrawn to better define a path toward the desired unknowns.

b. Voltage V_{ac}, which is actually the voltage across resistor R_1, can then be determined as follows:

$$V_{ac} = V_a - V_c = 20\ \text{V} - 8\ \text{V} = \mathbf{12\ V}$$

Similarly, voltage V_{bc}, which is actually the voltage across resistor R_2, can then be determined as follows:

$$V_{bc} = V_b - V_c = 15\ \text{V} - 8\ \text{V} = \mathbf{7\ V}$$

c. Current I_2 can be determined using Ohm's law:

$$I_2 = \frac{V_2}{R_2} = \frac{V_{bc}}{R_2} = \frac{7\ \text{V}}{4\ \Omega} = \mathbf{1.75\ A}$$

d. The source current I_{s_3} can be determined using Kirchhoff's current law at note c:

$$\Sigma I_i = \Sigma I_o$$
$$I_1 + I_2 + I_{s_3} = 0$$

and $\quad I_{s_3} = -I_1 - I_2 = -\dfrac{V_1}{R_1} - I_2$

with $\quad V_1 = V_{ac} = V_a - V_c = 20\ \text{V} - 8\ \text{V} = 12\ \text{V}$

so that

$$I_{s_3} = -\frac{12\ \text{V}}{10\ \Omega} - 1.75\ \text{A} = -1.2\ \text{A} - 1.75\ \text{A} = \mathbf{-2.95\ A}$$

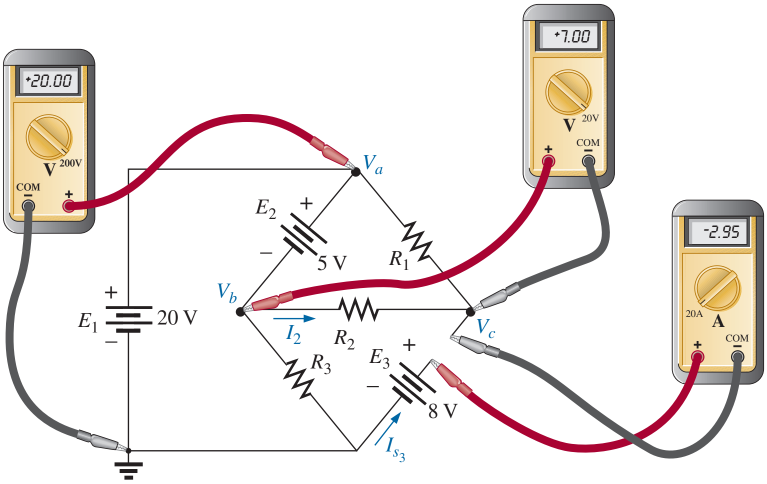


FIG. 7.31
Complex network for Example 7.11.

revealing that current is actually being forced through source E_3 in a direction opposite to that shown in Fig. 7.29.

e. Both voltmeters have a positive reading as shown in Fig. 7.31 while the ammeter has a negative reading.

7.6 LADDER NETWORKS

A three-section **ladder network** appears in Fig. 7.32. The reason for the terminology is quite obvious for the repetitive structure. Basically two approaches are used to solve networks of this type.

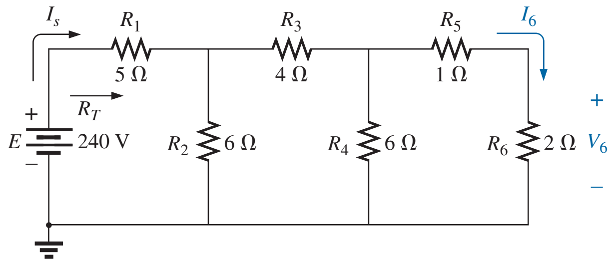


FIG. 7.32
Ladder network.

Method 1

Calculate the total resistance and resulting source current, and then work back through the ladder until the desired current or voltage is obtained. This method is now employed to determine V_6 in Fig. 7.32.

Combining parallel and series elements as shown in Fig. 7.33 results in the reduced network in Fig. 7.34, and

$$R_T = 5\ \Omega + 3\ \Omega = 8\ \Omega$$

$$I_s = \frac{E}{R_T} = \frac{240\ \text{V}}{8\ \Omega} = 30\ \text{A}$$

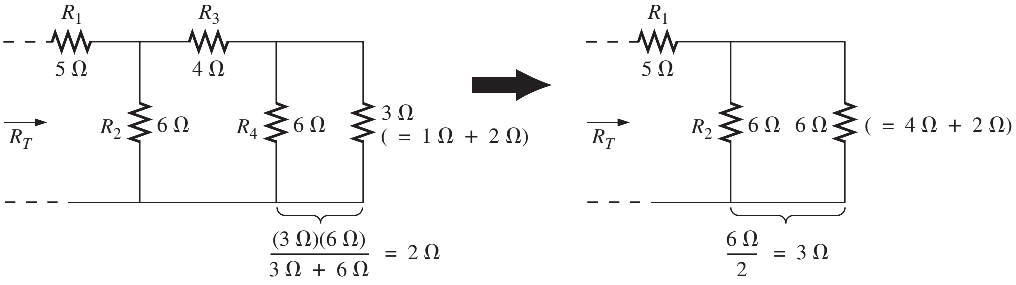


FIG. 7.33
Working back to the source to determine R_T for the network in Fig. 7.32.

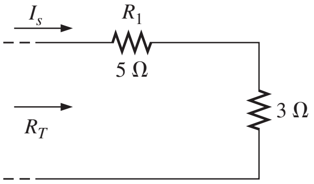


FIG. 7.34
Calculating R_T and I_s.

Working our way back to I_6 (Fig. 7.35), we find that

$$I_1 = I_s$$

and
$$I_3 = \frac{I_s}{2} = \frac{30\text{ A}}{2} = 15\text{ A}$$

and, finally (Fig. 7.36),

$$I_6 = \frac{(6\ \Omega)I_3}{6\ \Omega + 3\ \Omega} = \frac{6}{9}(15\text{ A}) = 10\text{ A}$$

and
$$V_6 = I_6R_6 = (10\text{ A})(2\ \Omega) = \mathbf{20\ V}$$

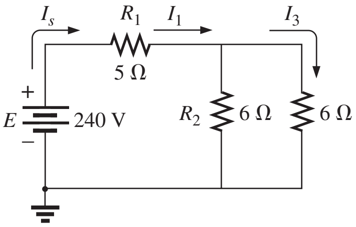


FIG. 7.35
Working back toward I_6.

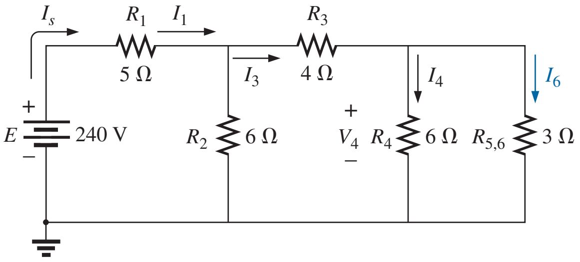


FIG. 7.36
Calculating I_6.

Method 2

Assign a letter symbol to the last branch current and work back through the network to the source, maintaining this assigned current or other current of interest. The desired current can then be found directly. This

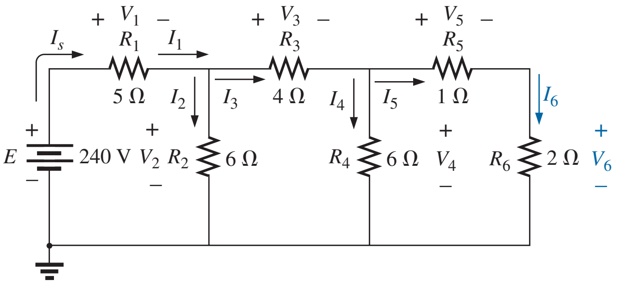


FIG. 7.37

An alternative approach for ladder networks.

method can best be described through the analysis of the same network considered in Fig. 7.32, redrawn in Fig. 7.37.

The assigned notation for the current through the final branch is I_6:

$$I_6 = \frac{V_4}{R_5 + R_6} = \frac{V_4}{1\ \Omega + 2\ \Omega} = \frac{V_4}{3\ \Omega}$$

or $$V_4 = (3\ \Omega)I_6$$

so that $$I_4 = \frac{V_4}{R_4} = \frac{(3\ \Omega)I_6}{6\ \Omega} = 0.5I_6$$

and $$I_3 = I_4 + I_6 = 0.5I_6 + I_6 = 1.5I_6$$

$$V_3 = I_3R_3 = (1.5I_6)(4\ \Omega) = (6\ \Omega)I_6$$

Also, $$V_2 = V_3 + V_4 = (6\ \Omega)I_6 + (3\ \Omega)I_6 = (9\ \Omega)I_6$$

so that $$I_2 = \frac{V_2}{R_2} = \frac{(9\ \Omega)I_6}{6\ \Omega} = 1.5I_6$$

and $$I_s = I_2 + I_3 = 1.5I_6 + 1.5I_6 = 3I_6$$

with $$V_1 = I_1R_1 = I_sR_1 = (5\ \Omega)I_s$$

so that $$E = V_1 + V_2 = (5\ \Omega)I_s + (9\ \Omega)I_6$$

$$= (5\ \Omega)(3I_6) + (9\ \Omega)I_6 = (24\ \Omega)I_6$$

and $$I_6 = \frac{E}{24\ \Omega} = \frac{240\ \text{V}}{24\ \Omega} = 10\ \text{A}$$

with $$V_6 = I_6R_6 = (10\ \text{A})(2\ \Omega) = \mathbf{20\ V}$$

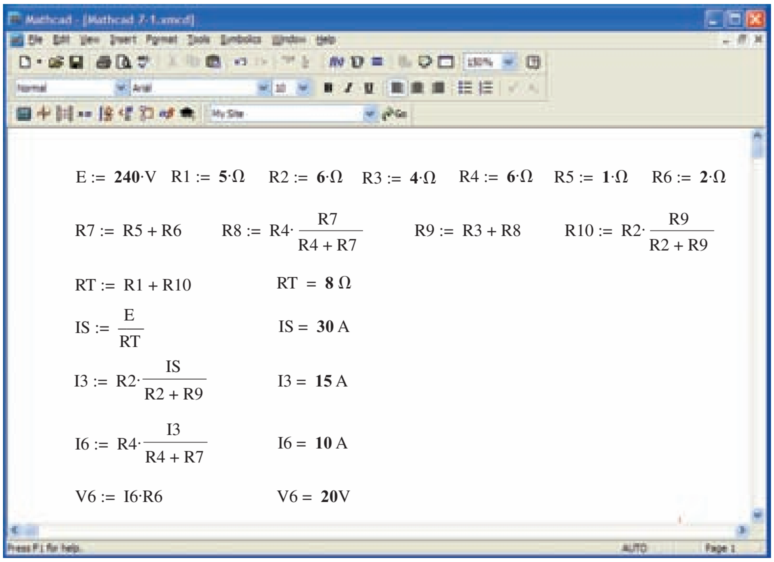
as was obtained using method 1.

Mathcad

We will now use Mathcad to analyze the ladder network in Fig. 7.32 using method 1. It provides an excellent opportunity to practice the basic maneuvers introduced in Sections 3.15 and 6.3.

First, as shown in Fig. 7.38, we define all the parameters of the network. Then we follow the same sequence as included in the text material. For Mathcad, however, we must be sure that the defining sequence for each new variable flows from left to right, as shown in Fig. 7.38, until R_{10} is defined. We are then ready to write the equation for the total resistance and display the result. All the remaining parameters are then defined and displayed as shown. The results are an exact match with the longhand solution.

The wonderful thing about Mathcad is that we can save this sequence in memory and use it as needed for different networks. Simply redefine the parameters of the network, and all the new values for the important parameters of the network will be displayed immediately.



$$E := 240 \cdot V \quad R1 := 5 \cdot \Omega \quad R2 := 6 \cdot \Omega \quad R3 := 4 \cdot \Omega \quad R4 := 6 \cdot \Omega \quad R5 := 1 \cdot \Omega \quad R6 := 2 \cdot \Omega$$

$$R7 := R5 + R6 \qquad R8 := R4 \cdot \frac{R7}{R4 + R7} \qquad R9 := R3 + R8 \qquad R10 := R2 \cdot \frac{R9}{R2 + R9}$$

$$RT := R1 + R10 \qquad RT = 8\,\Omega$$

$$IS := \frac{E}{RT} \qquad IS = 30\,A$$

$$I3 := R2 \cdot \frac{IS}{R2 + R9} \qquad I3 = 15\,A$$

$$I6 := R4 \cdot \frac{I3}{R4 + R7} \qquad I6 = 10\,A$$

$$V6 := I6 \cdot R6 \qquad V6 = 20V$$

FIG. 7.38

Using Mathcad to analyze the ladder network in Fig. 7.32.

7.7 VOLTAGE DIVIDER SUPPLY (UNLOADED AND LOADED)

When the term *loaded* is used to describe voltage divider supply, it refers to the application of an element, network, or system to a supply that draws current from the supply. In other words,

the loading down of a system is the process of introducing elements that will draw current from the system. The heavier the current, the greater the loading effect.

Recall from Section 5.10 that the application of a load can affect the terminal voltage of a supply due to the internal resistance.

No-Load Conditions

Through a voltage divider network such as that in Fig. 7.39, a number of different terminal voltages can be made available from a single supply. Instead of having a single supply of 120 V, we now have terminal voltages of 100 V and 60 V available—a wonderful result for such a simple network. However, there can be disadvantages. One is that the applied resistive loads can have values too close to those making up the voltage divider network.

In general,

for a voltage divider supply to be effective, the applied resistive loads should be significantly larger than the resistors appearing in the voltage divider network.

To demonstrate the validity of the above statement, let us now examine the effect of applying resistors with values very close to those of the voltage divider network.

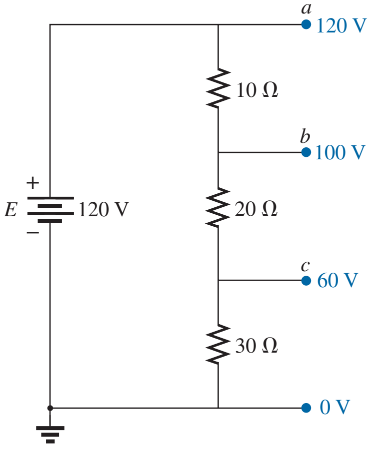


FIG. 7.39

Voltage divider supply.

Loaded Conditions

In Fig. 7.40, resistors of 20 Ω have been connected to each of the terminal voltages. Note that this value is equal to one of the resistors in the voltage divider network and very close to the other two.

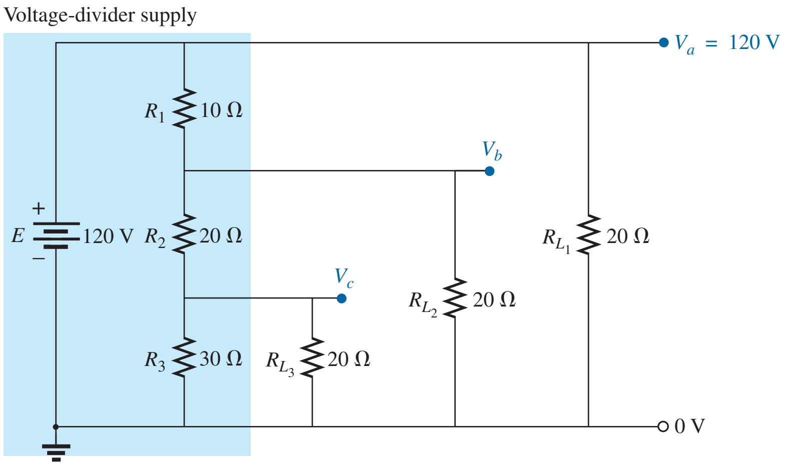


FIG. 7.40

Voltage divider supply with loads equal to the average value of the resistive elements that make up the supply.

Voltage V_a is unaffected by the load R_{L_1} since the load is in parallel with the supply voltage E. The result is $V_a = 120$ V, which is the same as the no-load level. To determine V_b, we must first note that R_3 and R_{L_3} are in parallel and $R'_3 = R_3 \parallel R_{L_3} = 30\ \Omega \parallel 20\ \Omega = 12\ \Omega$. The parallel combination

$$R'_2 = (R_2 + R'_3) \parallel R_{L_2} = (20\ \Omega + 12\ \Omega) \parallel 20\ \Omega$$
$$= 32\ \Omega \parallel 20\ \Omega = 12.31\ \Omega$$

Applying the voltage divider rule gives

$$V_b = \frac{(12.31\ \Omega)(120\ \text{V})}{12.31\ \Omega + 10\ \Omega} = \mathbf{66.21\ V}$$

versus 100 V under no-load conditions.

Voltage V_c is

$$V_c = \frac{(12\ \Omega)(66.21\ \text{V})}{12\ \Omega + 20\ \Omega} = \mathbf{24.83\ V}$$

versus 60 V under no-load conditions.

The effect of load resistors close in value to the resistor employed in the voltage divider network is, therefore, to decrease significantly some of the terminal voltages.

If the load resistors are changed to the 1 kΩ level, the terminal voltages will all be relatively close to the no-load values. The analysis is similar to the above, with the following results:

$$V_a = \mathbf{120\ V} \quad V_b = \mathbf{98.88\ V} \quad V_c = \mathbf{58.63\ V}$$

If we compare current drains established by the applied loads, we find for the network in Fig. 7.40 that

$$I_{L_2} = \frac{V_{L_2}}{R_{L_2}} = \frac{66.21\ \text{V}}{20\ \Omega} = 3.31\ \text{A}$$

and for the 1 kΩ level,

$$I_{L_2} = \frac{98.88\text{ V}}{1\text{ k}\Omega} = 98.88\text{ mA} < 0.1\text{ A}$$

As demonstrated above, the greater the current drain, the greater the change in terminal voltage with the application of the load. This is certainly verified by the fact that I_{L_2} is about 33.5 times larger with the 20 Ω loads.

The next example is a design exercise. The voltage and current ratings of each load are provided, along with the terminal ratings of the supply. The required voltage divider resistors must be found.

EXAMPLE 7.12 Determine R_1, R_2, and R_3 for the voltage divider supply in Fig. 7.41. Can 2 W resistors be used in the design?

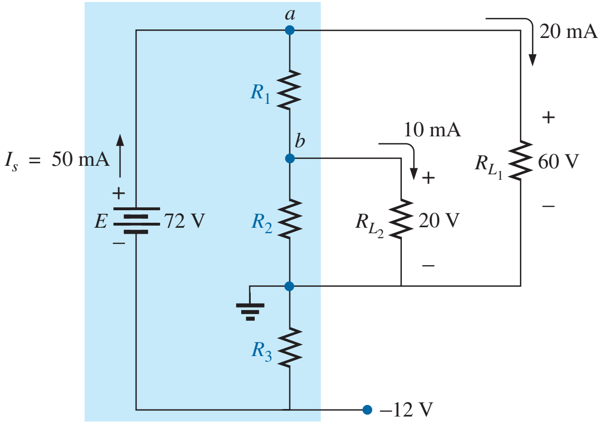


FIG. 7.41
Voltage divider supply for Example 7.12.

Solution: R_3:

$$R_3 = \frac{V_{R_3}}{I_{R_3}} = \frac{V_{R_3}}{I_s} = \frac{12\text{ V}}{50\text{ mA}} = \mathbf{240\ \Omega}$$

$$P_{R_3} = (I_{R_3})^2 R_3 = (50\text{ mA})^2\, 240\ \Omega = 0.6\text{ W} < 2\text{ W}$$

R_1: Applying Kirchhoff's current law to node *a*:

$$I_s - I_{R_1} - I_{L_1} = 0$$

and $I_{R_1} = I_s - I_{L_1} = 50\text{ mA} - 20\text{ mA} = 30\text{ mA}$

$$R_1 = \frac{V_{R_1}}{I_{R_1}} = \frac{V_{L_1} - V_{L_2}}{I_{R_1}} = \frac{60\text{ V} - 20\text{ V}}{30\text{ mA}} = \frac{40\text{ V}}{30\text{ mA}} = \mathbf{1.33\ k\Omega}$$

$$P_{R_1} = (I_{R_1})^2 R_1 = (30\text{ mA})^2\, 1.33\text{ k}\Omega = 1.197\text{ W} < 2\text{ W}$$

R_2: Applying Kirchhoff's current law at node *b:*

$$I_{R_1} - I_{R_2} - I_{L_2} = 0$$

and $I_{R_2} = I_{R_1} - I_{L_2} = 30\text{ mA} - 10\text{ mA} = 20\text{ mA}$

$$R_2 = \frac{V_{R_2}}{I_{R_2}} = \frac{20\text{ V}}{20\text{ mA}} = \mathbf{1\ k\Omega}$$

$$P_{R_2} = (I_{R_2})^2 R_2 = (20\text{ mA})^2\, 1\text{ k}\Omega = 0.4\text{ W} < 2\text{ W}$$

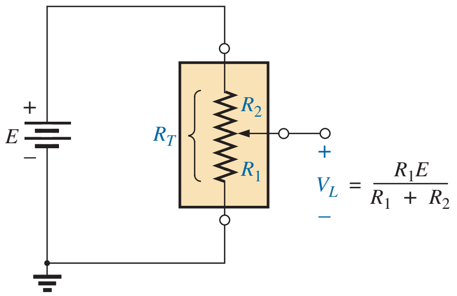


FIG. 7.42
Unloaded potentiometer.

Since P_{R_1}, P_{R_2}, and P_{R_3} are less than 2 W, 2 W resistors can be used for the design.

7.8 POTENTIOMETER LOADING

For the unloaded potentiometer in Fig. 7.42, the output voltage is determined by the voltage divider rule, with R_T in the figure representing the total resistance of the potentiometer. Too often it is assumed that the voltage across a load connected to the wiper arm is determined solely by the potentiometer and the effect of the load can be ignored. This is definitely not the case, as is demonstrated here.

When a load is applied as shown in Fig. 7.43, the output voltage V_L is now a function of the magnitude of the load applied since R_1 is not as shown in Fig. 7.42 but is instead the parallel combination of R_1 and R_L.

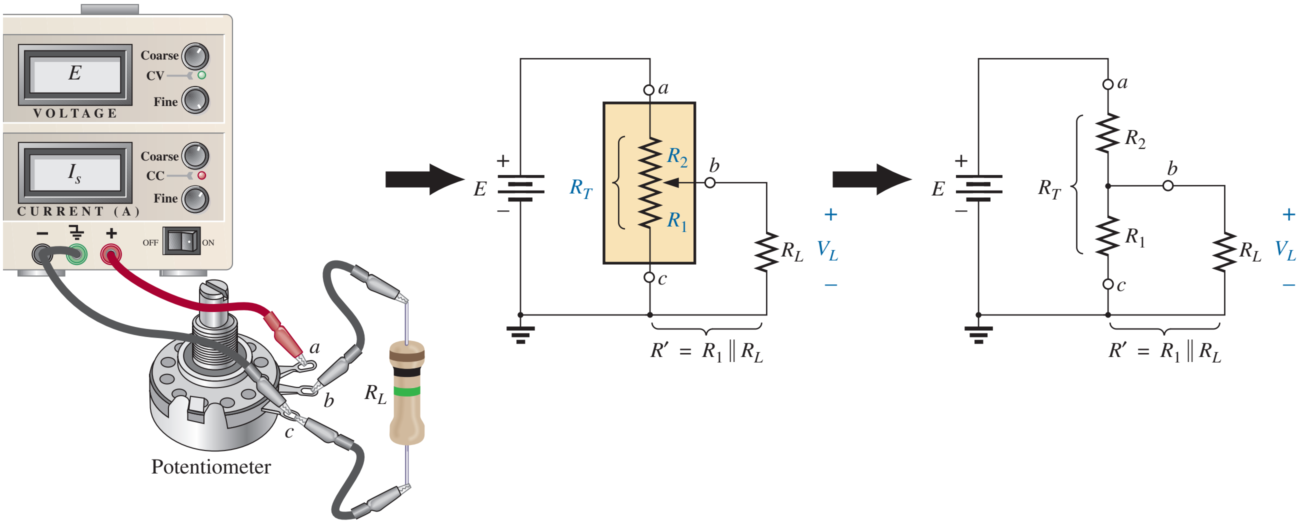


FIG. 7.43
Loaded potentiometer.

The output voltage is now

$$\boxed{V_L = \frac{R'E}{R' + R_2} \quad \text{with } R' = R_1 \| R_L} \tag{7.1}$$

If you want to have good control of the output voltage V_L through the controlling dial, knob, screw, or whatever, you must choose a load or potentiometer that satisfies the following relationship:

$$\boxed{R_L \gg R_T} \tag{7.2}$$

In general,

when hooking up a load to a potentiometer, be sure that the load resistance far exceeds the maximum terminal resistance of the potentiometer if good control of the output voltage is desired.

For example, let's disregard Eq. (7.2) and choose a 1 MΩ potentiometer with a 100 Ω load and set the wiper arm to 1/10 the total resistance, as shown in Fig. 7.44. Then

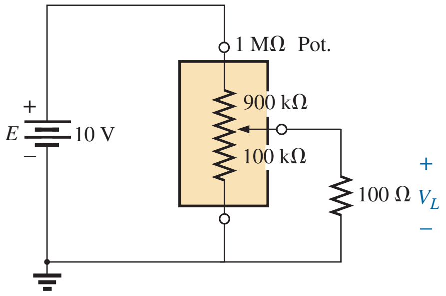


FIG. 7.44
Loaded potentiometer with $R_L \ll R_T$.

$$R' = 100\text{ k}\Omega \parallel 100\ \Omega = 99.9\ \Omega$$

and $$V_L = \frac{99.9\ \Omega(10\text{ V})}{99.9\ \Omega + 900\text{ k}\Omega} \cong 0.001\text{ V} = 1\text{ mV}$$

which is extremely small compared to the expected level of 1 V.

In fact, if we move the wiper arm to the midpoint,

$$R' = 500\text{ k}\Omega \parallel 100\ \Omega = 99.98\ \Omega$$

and $$V_L = \frac{(99.98\ \Omega)(10\text{ V})}{99.98\ \Omega + 500\text{ k}\Omega} \cong 0.002\text{ V} = 2\text{ mV}$$

which is negligible compared to the expected level of 5 V. Even at $R_1 = 900\text{ k}\Omega$, V_L is only 0.01 V, or 1/1000 of the available voltage.

Using the reverse situation of $R_T = 100\ \Omega$ and $R_L = 1\text{ M}\Omega$ and the wiper arm at the 1/10 position, as in Fig. 7.45, we find

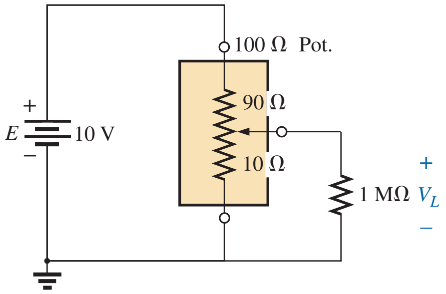


FIG. 7.45
Loaded potentiometer with $R_L \gg R_T$.

$$R' = 10\ \Omega \parallel 1\text{ M}\Omega \cong 10\ \Omega$$

and $$V_L = \frac{10\ \Omega(10\text{ V})}{10\ \Omega + 90\ \Omega} = 1\text{ V}$$

as desired.

For the lower limit (worst-case design) of $R_L = R_T = 100\ \Omega$, as defined by Eq. (7.2) and the halfway position of Fig. 7.43,

$$R' = 50\ \Omega \parallel 100\ \Omega = 33.33\ \Omega$$

and $$V_L = \frac{33.33\ \Omega(10\text{ V})}{33.33\ \Omega + 50\ \Omega} \cong 4\text{ V}$$

It may not be the ideal level of 5 V, but at least 40% of the voltage E has been achieved at the halfway position rather than the 0.02% obtained with $R_L = 100\ \Omega$ and $R_T = 1\text{ M}\Omega$.

In general, therefore, try to establish a situation for potentiometer control in which Eq. (7.2) is satisfied to the highest degree possible.

Someone might suggest that we make R_T as small as possible to bring the percent result as close to the ideal as possible. Keep in mind, however, that the potentiometer has a power rating, and for networks such as Fig. 7.45, $P_{max} \cong E^2/R_T = (10\text{ V})^2/100\ \Omega = 1\text{ W}$. If R_T is reduced to 10 Ω, $P_{max} = (10\text{ V})^2/10\ \Omega = 10\text{ W}$, which would require a *much larger* unit.

EXAMPLE 7.13 Find voltages V_1 and V_2 for the loaded potentiometer of Fig. 7.46.

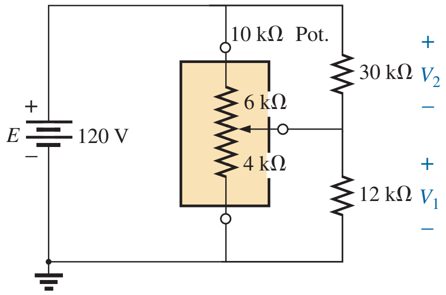


FIG. 7.46
Example 7.13.

Solution: Ideal (no load):

$$V_1 = \frac{4\text{ k}\Omega(120\text{ V})}{10\text{ k}\Omega} = \mathbf{48\text{ V}}$$

$$V_2 = \frac{6\text{ k}\Omega(120\text{ V})}{10\text{ k}\Omega} = \mathbf{72\text{ V}}$$

Loaded:

$$R' = 4\text{ k}\Omega \parallel 12\text{ k}\Omega = 3\text{ k}\Omega$$
$$R'' = 6\text{ k}\Omega \parallel 30\text{ k}\Omega = 5\text{ k}\Omega$$
$$V_1 = \frac{3\text{ k}\Omega(120\text{ V})}{8\text{ k}\Omega} = \mathbf{45\text{ V}}$$
$$V_2 = \frac{5\text{ k}\Omega(120\text{ V})}{8\text{ k}\Omega} = \mathbf{75\text{ V}}$$

The ideal and loaded voltage levels are so close that the design can be considered a good one for the applied loads. A slight variation in the position of the wiper arm will establish the ideal voltage levels across the two loads.

7.9 AMMETER, VOLTMETER, AND OHMMETER DESIGN

Now that the fundamentals of series, parallel, and series-parallel networks have been introduced, we are prepared to investigate the fundamental design of an ammeter, voltmeter, and ohmmeter. Our design of each uses the **d'Arsonval analog movement** of Fig. 7.47. The movement consists basically of an iron-core coil mounted on jewel bearings between a permanent magnet. The helical springs limit the turning motion of the coil and provide a path for the current to reach the coil. When a current is passed through the movable coil, the fluxes of the coil and permanent magnet interact to develop a torque on the coil that cause it to rotate on its bearings. The movement is adjusted to indicate zero deflection on a meter scale when the current through the coil is zero. The direction of current through the coil then determines whether the pointer displays an up-scale or below-zero indication. For this reason, ammeters and voltmeters have an assigned polarity on their terminals to ensure an up-scale reading.

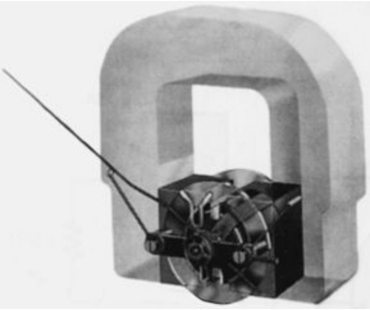


FIG. 7.47
d'Arsonval analog movement.
(Courtesy of Weston Instruments, Inc.)

D'Arsonval movements are usually rated by current and resistance. The specifications of a typical movement may be 1 mA, 50 Ω. The 1 mA is the *current sensitivity (CS)* of the movement, which is the current required for a full-scale deflection. It is denoted by the symbol I_{CS}. The 50 Ω represents the internal resistance (R_m) of the movement. A common notation for the movement and its specifications is provided in Fig. 7.48.

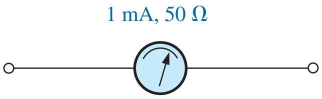


FIG. 7.48
Movement notation.

The Ammeter

The maximum current that the d'Arsonval movement can read independently is equal to the current sensitivity of the movement. However, higher currents can be measured if additional circuitry is introduced. This additional circuitry, as shown in Fig. 7.49, results in the basic construction of an ammeter.

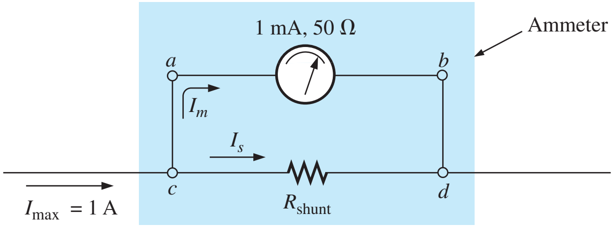


FIG. 7.49
Basic ammeter.

The resistance R_{shunt} is chosen for the ammeter in Fig. 7.49 to allow 1 mA to flow through the movement when a maximum current of 1 A enters the ammeter. If less than 1 A flows through the ammeter, the movement will have less than 1 mA flowing through it and will indicate less than full-scale deflection.

Since the voltage across parallel elements must be the same, the potential drop across *a-b* in Fig. 7.49 must equal that across *c-d*; that is,

$$(1\text{ mA})(50\ \Omega) = R_{\text{shunt}}I_s$$

Also, I_s must equal 1 A − 1 mA = 999 mA if the current is to be limited to 1 mA through the movement (Kirchhoff's current law). Therefore,

$$\begin{aligned}(1\text{ mA})(50\ \Omega) &= R_{\text{shunt}}(999\text{ mA})\\ R_{\text{shunt}} &= \frac{(1\text{ mA})(50\ \Omega)}{999\text{ mA}}\\ &\cong 0.05\ \Omega\end{aligned}$$

In general,

$$\boxed{R_{\text{shunt}} = \frac{R_m I_{CS}}{I_{\max} - I_{CS}}} \qquad \textbf{(7.4)}$$

One method of constructing a multirange ammeter is shown in Fig. 7.50, where the rotary switch determines the R_{shunt} to be used for the maximum current indicated on the face of the meter. Most meters use the same scale for various values of maximum current. If you read 375 on the 0–5 mA scale with the switch on the 5 setting, the current is 3.75 mA; on the 50 setting, the current is 37.5 mA; and so on.

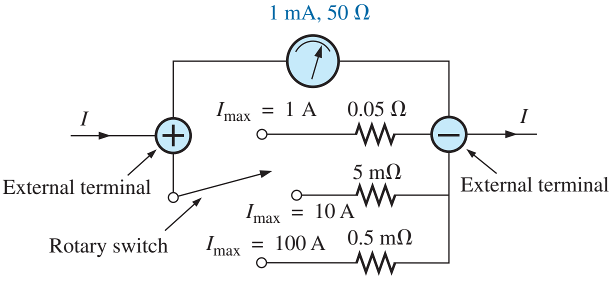


FIG. 7.50
Multirange ammeter.

The Voltmeter

A variation in the additional circuitry permits the use of the d'Arsonval movement in the design of a voltmeter. The 1 mA, 50 Ω movement can also be rated as a 50 mV (1 mA × 50 Ω), 50 Ω movement, indicating that the maximum voltage that the movement can measure independently is 50 mV. The millivolt rating is sometimes referred to as the *voltage sensitivity (VS).* The basic construction of the voltmeter is shown in Fig. 7.51.

The R_{series} is adjusted to limit the current through the movement to 1 mA when the maximum voltage is applied across the voltmeter. A lesser voltage simply reduces the current in the circuit and thereby the deflection of the movement.

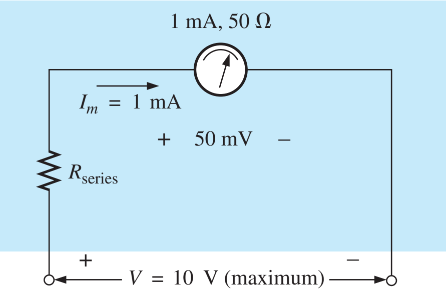


FIG. 7.51
Basic voltmeter.

Applying Kirchhoff's voltage law around the closed loop of Fig. 7.51, we obtain

$$[10\text{ V} - (1\text{ mA})(R_{\text{series}})] - 50\text{ mV} = 0$$

or
$$R_{\text{series}} = \frac{10\text{ V} - (50\text{ mV})}{1\text{ mA}} = 9950\ \Omega$$

In general,

$$\boxed{R_{\text{series}} = \frac{V_{\max} - V_{VS}}{I_{CS}}} \qquad \textbf{(7.5)}$$

One method of constructing a multirange voltmeter is shown in Fig. 7.52. If the rotary switch is at 10 V, $R_{\text{series}} = 9.95\text{ k}\Omega$; at 50 V, $R_{\text{series}} = 40\text{ k}\Omega + 9.95\text{ k}\Omega = 49.95\text{ k}\Omega$; and at 100 V, $R_{\text{series}} = 50\text{ k}\Omega + 40\text{ k}\Omega + 9.95\text{ k}\Omega = 99.95\text{ k}\Omega$.

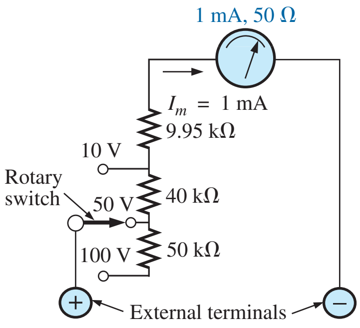


FIG. 7.52
Multirange voltmeter.

The Ohmmeter

In general, ohmmeters are designed to measure resistance in the low, mid-, or high range. The most common is the **series ohmmeter**, designed to read resistance levels in the midrange. It uses the series configuration in Fig. 7.53. The design is quite different from that of the ammeter or voltmeter because it shows a full-scale deflection for zero ohms and no deflection for infinite resistance.

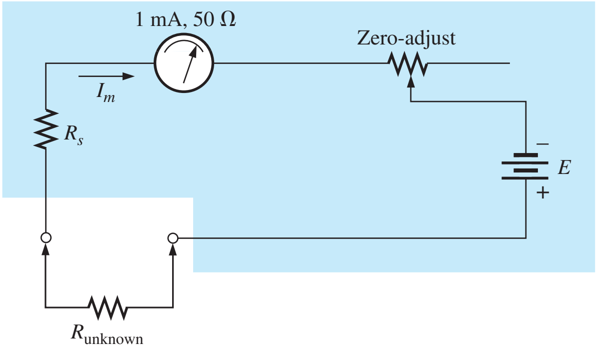


FIG. 7.53
Series ohmmeter.

To determine the series resistance R_s, the external terminals are shorted (a direct connection of zero ohms between the two) to simulate zero ohms, and the zero-adjust is set to half its maximum value. The resistance R_s is then adjusted to allow a current equal to the current sensitivity of the movement (1 mA) to flow in the circuit. The zero-adjust is set to half its value so that any variation in the components of the meter that may produce a current more or less than the current sensitivity can be compensated for. The current I_m is

$$\boxed{I_m(\text{full scale}) = I_{CS} = \frac{E}{R_s + R_m + \dfrac{\text{zero} - \text{adjust}}{2}}} \qquad \textbf{(7.6)}$$

and
$$\boxed{R_s = \frac{E}{I_{CS}} - R_m - \frac{\text{zero-adjust}}{2}} \qquad \textbf{(7.7)}$$

If an unknown resistance is then placed between the external terminals, the current is reduced, causing a deflection less than full scale. If the terminals are left open, simulating infinite resistance, the pointer does not deflect since the current through the circuit is zero.

An instrument designed to read very low values of resistance appears in Fig. 7.54. Because of its low-range capability, the network design must be a great deal more sophisticated than described above. It uses electronic components that eliminate the inaccuracies introduced by lead and contact resistances. It is similar to the above system in the sense that it is completely portable and does require a dc battery to establish measurement conditions. Special leads are used to limit any introduced resistance levels. The maximum scale setting can be set as low as 0.00352 (3.52 mΩ).

The **megohmmeter** (often called a *megger*) is an instrument for measuring very high resistance values. Its primary function is to test the insulation found in power transmission systems, electrical machinery, transformers, and so on. To measure the high-resistance values, a high dc voltage is established by a hand-driven generator. If the shaft is rotated above some set value, the output of the generator is fixed at one selectable voltage, typically 250 V, 500 V, or 1000 V. A photograph of a commercially available tester is shown in Fig. 7.55. For this instrument, the range is zero to 5000 MΩ.

FIG. 7.54
Milliohmmeter.
(Courtesy of Keithley Instruments, Inc.)

FIG. 7.55
Megohmmeter.
(Courtesy of AEMC® Instruments, Foxborough, MA.)

7.10 APPLICATIONS

Boosting a Car Battery

Although boosting a car battery may initially appear to be a simple application of parallel networks, it is really a series-parallel operation that is worthy of some investigation. As indicated in Chapter 2, every dc supply has some internal resistance. For the typical 12 V lead-acid car battery, the resistance is quite small—in the milliohm range. In most cases, the low internal resistance ensures that most of the voltage (or power) is delivered to the load and not lost on the internal resistance. In Fig. 7.56, battery #2 has discharged because the lights were left on for three hours during a movie. Fortunately, a friend who made sure his own lights were off has a fully charged battery #1 and a good set of 16-ft cables with #6 gage stranded wire and well-designed clips. The investment in a good set of cables with sufficient length and heavy wire is a wise one, particularly if you live in a cold climate. Flexibility, as provided by stranded wire, is also a very desirable characteristic under some conditions. Be sure to check the gage of the

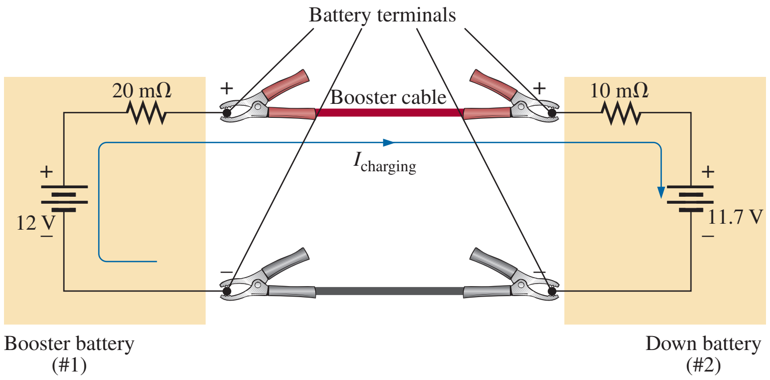


FIG. 7.56
Boosting a car battery.

wire and not just the thickness of the insulating jacket. You get what you pay for, and the copper is the most expensive part of the cables. Too often the label says "heavy-duty," but the gage number of the wire is too high.

The proper sequence of events in boosting a car is often a function of to whom you speak or what information you read. For safety sake, some people recommend that the car with the good battery be turned off when making the connections. This, however, can create an immediate problem if the "dead" battery is in such a bad state that when it is hooked up to the good battery, it immediately drains the good battery to the point that neither car will start. With this in mind, it does make some sense to leave the car running to ensure that the charging process continues until the starting of the disabled car is initiated. *Because accidents do happen, it is strongly recommended that the person making the connections wear the proper type of protective eye equipment. Take sufficient time to be sure that you know which are the positive and negative terminals for both cars.* If it's not immediately obvious, keep in mind that the negative or ground side is usually connected to the chassis of the car with a relatively short, heavy wire.

When you are sure of which are the positive and negative terminals, first connect one of the red wire clamps of the booster cables to the positive terminal of the discharged battery—all the while being sure that the other red clamp *is not touching the battery or car.* Then connect the other end of the red wire to the positive terminal of the fully charged battery. Next, connect one end of the black cable of the booster cables to the negative terminal of the booster battery, and finally connect the other end of the black cable to the engine block of the stalled vehicle (not the negative post of the dead battery) away from the carburetor, fuel lines, or moving parts of the car. Lastly, have someone maintain a constant idle speed in the car with the good battery as you start the car with the bad battery. After the vehicle starts, remove the cables in the *reverse order* starting with the cable connected to the engine block. Always be careful to ensure that clamps don't touch the battery or chassis of the car or get near any moving parts.

Some people feel that the car with the good battery should charge the bad battery for 5 to 10 minutes before starting the disabled car so the disabled car will be essentially using its own battery in the starting process. Keep in mind that the instant the booster cables are connected, the booster car is making a concerted effort to charge both its own battery and the drained battery. At starting, the good battery is asked to supply a heavy current to start the other car. It's a pretty heavy load to put on a single battery. For the situation in Fig. 7.56, the voltage of battery #2 is less than that of battery #1, and the charging current will flow as shown. The resistance in series with the boosting battery is more because of the long length of the booster cable to the other car. The current is limited only by the series milliohm resistors of the batteries, but the voltage difference is so small that the starting current will be in safe range for the cables involved. The initial charging current will be $I = (12\text{ V} - 11.7\text{ V})/(20\text{ m}\Omega + 10\text{ m}\Omega) = 0.3\text{ V}/30\text{ m}\Omega = 10\text{ A}$. At starting, the current levels will be as shown in Fig. 7.57 for the resistance levels and battery voltages assumed. At starting, an internal resistance for the starting circuit of $0.1\ \Omega = 100\text{ m}\Omega$ is assumed. Note that the battery of the disabled car has now charged up to 11.8 V with an associated increase in its power level. The presence of two batteries requires that the analysis wait for the methods to be introduced in the next chapter.

Note also that the current drawn from the starting circuit for the disabled car is over 100 A and that the majority of the starting current is provided by the battery being charged. In essence, therefore, the majority of the starting current is coming from the disabled car. The good battery has provided an initial charge to the bad battery and has provided the addi-

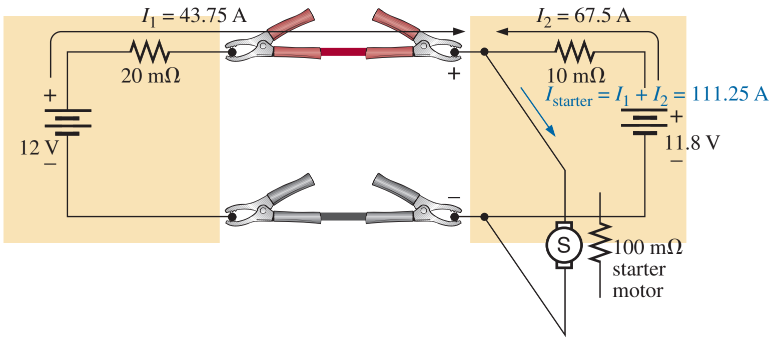


FIG. 7.57
Current levels at starting.

tional current necessary to start the car. But, in total, it is the battery of the disabled car that is the primary source of the starting current. For this very reason, the charging action should continue for 5 or 10 minutes before starting the car. If the disabled car is in really bad shape with a voltage level of only 11 V, the resulting levels of current will reverse, with the good battery providing 68.75 A and the bad battery only 37.5 A. Quite obviously, therefore, the worse the condition of the dead battery, the heavier the drain on the good battery. A point can also be reached where the bad battery is in such bad shape that it cannot accept a good charge or provide its share of the starting current. The result can be continuous cranking of the disabled car without starting and possible damage to the battery of the running car due to the enormous current drain. Once the car is started and the booster cables are removed, the car with the discharged battery will continue to run because the alternator will carry the load (charging the battery and providing the necessary dc voltage) after ignition.

The above discussion was all rather straightforward, but let's investigate what may happen if it is a dark and rainy night, you are rushed, and you hook up the cables incorrectly as shown in Fig. 7.58. The result is two series-aiding batteries and a very low resistance path. The resulting current can then theoretically be extremely high [$I = (12\text{ V} + 11.7\text{ V})/30\text{ m}\Omega = 23.7\text{ V}/30\text{ m}\Omega = 790\text{ A}$], perhaps permanently damaging the electrical system of both cars and, worst of all, causing an explosion that may seriously injure someone. It is therefore very important that you treat the process of boosting a car with great care. Find that flashlight, double-check the connections, and be sure that everyone is clear when you start that car.

Before leaving the subject, we should point out that getting a boost from a tow truck results in a somewhat different situation: The connections to the

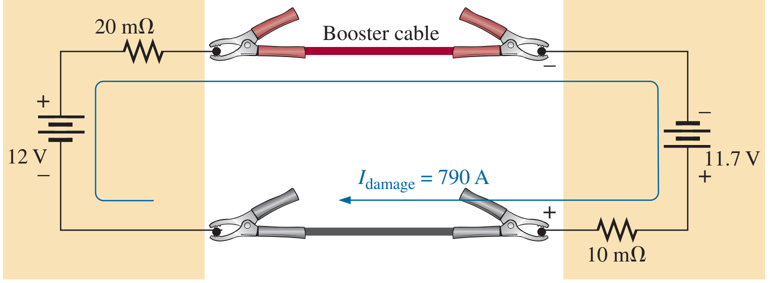


FIG. 7.58
Current levels if the booster battery is improperly connected.

battery in the truck are very secure; the cable from the truck is a heavy wire with thick insulation; the clamps are also quite large and make an excellent connection with your battery; and the battery is heavy-duty for this type of expected load. The result is less internal resistance on the supply side and a heavier current from the truck battery. In this case, the truck is really starting the disabled car, which simply reacts to the provided surge of power.

Electronic Circuits

The operation of most electronic systems requires a distribution of dc voltages throughout the design. Although a full explanation of why the dc level is required (since it is an ac signal to be amplified) will have to wait for the introductory courses in electronic circuits, the dc analysis will proceed in much the same manner as described in this chapter. In other words, this chapter and the preceding chapters are sufficient background to perform the dc analysis of the majority of electronic networks you will encounter if given the dc terminal characteristics of the electronic elements. For example, the network in Fig. 7.59 using a transistor will be covered in detail in any introductory electronics course. The dc voltage between the base (*B*) of the transistor and the emitter (*E*) is about 0.7 V under normal operating conditions, and the collector (*C*) is related to the base current by $I_C = \beta I_B = 50 I_B$ (β varies from transistor to transistor). Using these facts will enable us to determine all the dc currents and voltages of the network using the laws introduced in this chapter. In general, therefore, be encouraged that you will use the content of this chapter in numerous applications in the courses to follow.

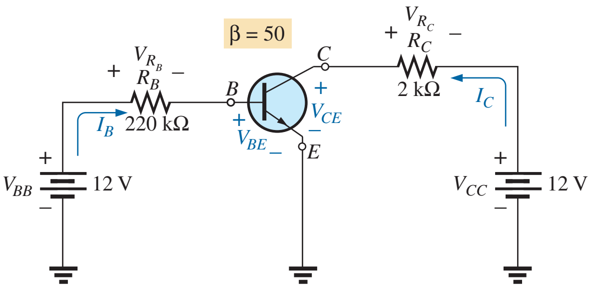


FIG. 7.59

dc bias levels of a transistor amplifier.

For the network in Fig. 7.59 we begin our analysis by applying Kirchhoff's voltage law to the base circuit:

$$+V_{BB} - V_{R_B} - V_{BE} = 0 \quad \text{or} \quad V_{BB} = V_{R_B} + V_{BE}$$

and $$V_{R_B} = V_{BB} - V_{BE} = 12\text{ V} - 0.7\text{ V} = 11.3\text{ V}$$

so that $$V_{R_B} = I_B R_B = 11.3\text{ V}$$

and $$I_B = \frac{V_{R_B}}{R_B} = \frac{11.3\text{ V}}{220\text{ k}\Omega} = \mathbf{51.4\ \mu A}$$

Then $$I_C = \beta I_B = 50 I_B = 50(51.4\ \mu\text{A}) = \mathbf{2.57\ mA}$$

and $$+V_{CE} + V_{R_C} - V_{CC} = 0 \quad \text{or} \quad V_{CC} = V_{R_C} + V_{CE}$$

with $$V_{CE} = V_{CC} - V_{R_C} = V_{CC} - I_C R_C = 12\text{ V} - (2.57\text{ mA})(2\text{ k}\Omega)$$
$$= 12\text{ V} - 5.14\text{ V} = \mathbf{6.86\ V}$$

For a typical dc analysis of a transistor, all the currents and voltages of interest are now known: I_B, V_{BE}, I_C, and V_{CE}. All the remaining voltage, current, and power levels for the other elements of the network can now be found using the basic laws applied in this chapter.

The above example is typical of the type of exercise you will be asked to perform in your first electronics course. For now you only need to be exposed to the device and to understand the reason for the relationships between the various currents and voltages of the device.

7.11 COMPUTER ANALYSIS

PSpice

Voltage Divider Supply We will now use PSpice to verify the results of Example 7.12. The calculated resistor values will be substituted and the voltage and current levels checked to see if they match the handwritten solution.

As shown in Fig. 7.60, the network is drawn as in earlier chapters using only the tools described thus far—in one way, a practice exercise for everything learned about the **Capture CIS Edition.** Note in this case that rotating the first resistor sets everything up for the remaining resistors. Further, it is a nice advantage that you can place one resistor after another without going to the **End Mode** option. Be especially careful with the placement of the ground, and be sure that **0/SOURCE** is used. Note also that resistor R_1 in Fig. 7.60 was entered as 1.333 kΩ rather than 1.33 kΩ as in Example 7.12. When running the program, we found that the computer solutions were not a perfect match to the longhand solution to the level of accuracy desired unless this change was made.

Since all the voltages are to ground, the voltage across R_{L_1} is 60 V; across R_{L_2}, 20 V; and across R_3, −12 V. The currents are also an excellent

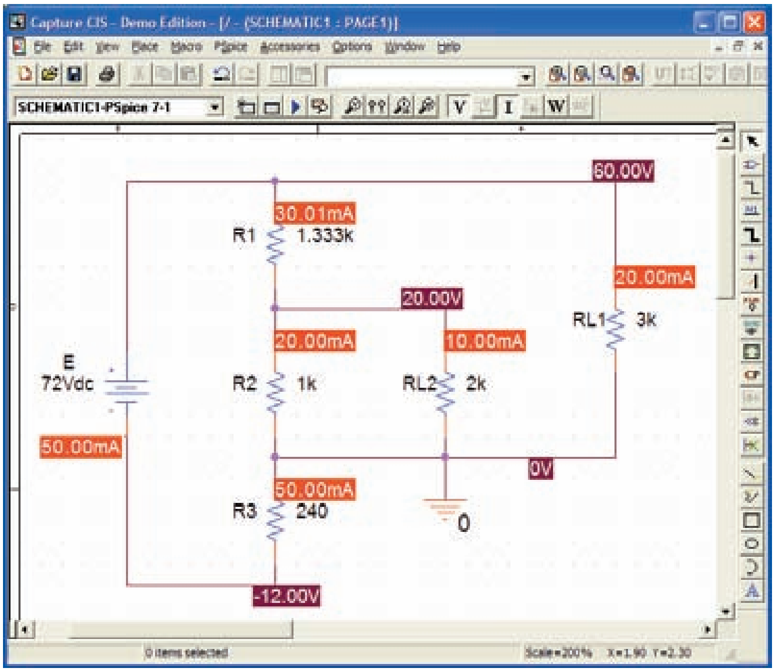


FIG. 7.60

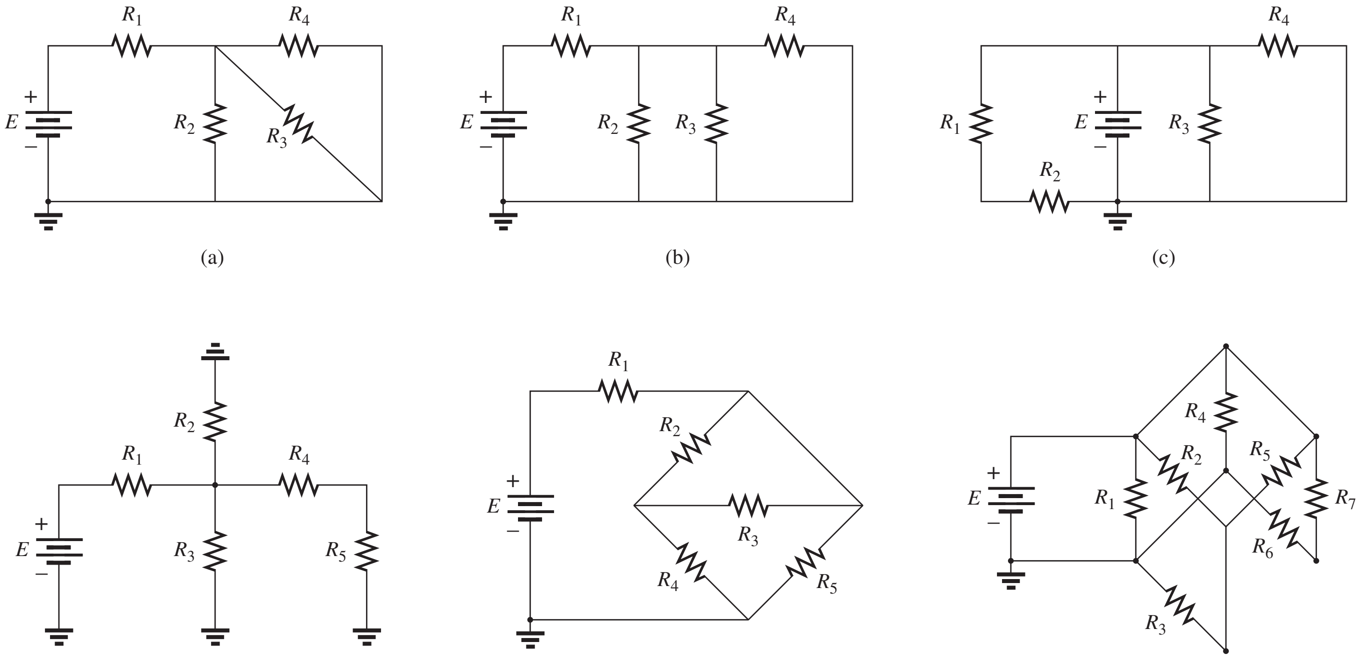
Using PSpice to verify the results of Example 7.12.

match with the handwritten solution, with $I_E = 50$ mA, $I_{R_1} = 30$ mA, $I_{R_2} = 20$ mA, $I_{R_3} = 50$ mA, $I_{R_{L2}} = 10$ mA, and $I_{R_{L1}} = 20$ mA. For the display in Fig. 7.60, the **W** option was disabled to permit concentrating on the voltage and current levels. This time, there is an exact match with the longhand solution.

PROBLEMS

SECTIONS 7.2–7.5 Series-Parallel Networks

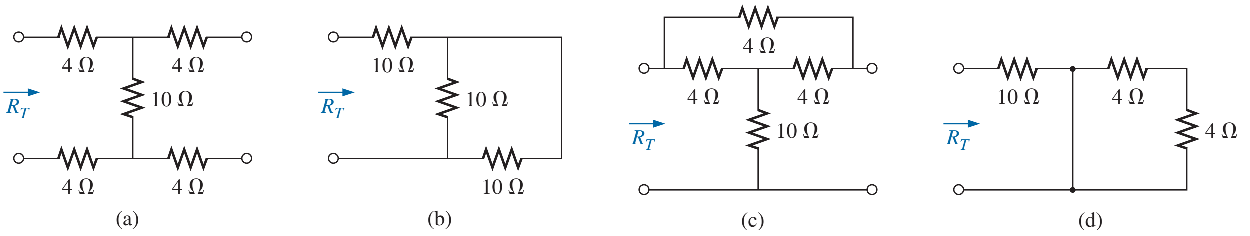
1. Which elements (individual elements, not combinations of elements) of the networks in Fig. 7.61 are in series? Which are in parallel? As a check on your assumptions, be sure that the elements in series have the same current and that the elements in parallel have the same voltage. Restrict your decisions to single elements, not combinations of elements.



(a) (b) (c) (d) (e) (f)

FIG. 7.61
Problem 1.

2. Determine R_T for the networks in Fig. 7.62.



(a) (b) (c) (d)

FIG. 7.62
Problem 2.

3. For the network in Fig. 7.63:

- **a.** Does $I_s = I_5 = I_6$? Explain.
- **b.** If $I_s = 10$ A and $I_1 = 4$ A, find I_2.
- **c.** Does $I_1 + I_2 = I_3 + I_4$? Explain.
- **d.** If $V_2 = 8$ V and $E = 14$ V, find V_3.
- **e.** If $R_1 = 4\ \Omega$, $R_2 = 2\ \Omega$, $R_3 = 4\ \Omega$, and $R_4 = 6\ \Omega$, what is R_T?
- **f.** If all the resistors of the configuration are 20 Ω, what is the source current if the applied voltage is 20 V?
- **g.** Using the values of part (f), find the power delivered by the battery and the power absorbed by the total resistance R_T.

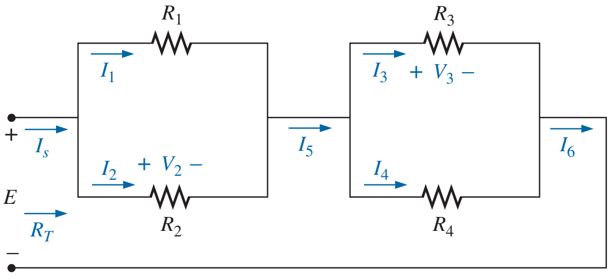


FIG. 7.63
Problem 3.

4. For the network in Fig. 7.64:

- **a.** Find the total resistance R_T.
- **b.** Find the source current I_s and currents I_2 and I_3.
- **c.** Find current I_5.
- **d.** Find voltages V_2 and V_4.

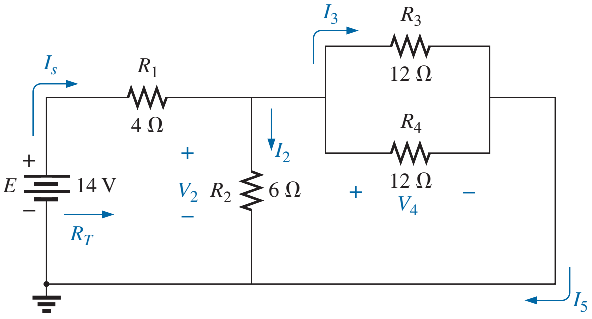


FIG. 7.64
Problem 4.

5. For the network in Fig. 7.65:

- **a.** Determine R_T.
- **b.** Find I_s, I_1, and I_2.
- **c.** Find voltage V_4.

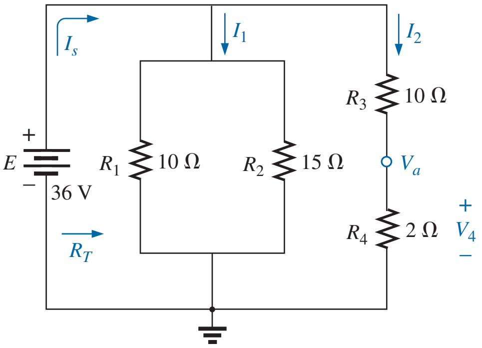


FIG. 7.65
Problem 5.

6. For the circuit board in Fig. 7.66:

- **a.** Find the total resistance R_T of the configuration.
- **b.** Find the current drawn from the supply if the applied voltage is 48 V.
- **c.** Find the reading of the applied voltmeter.

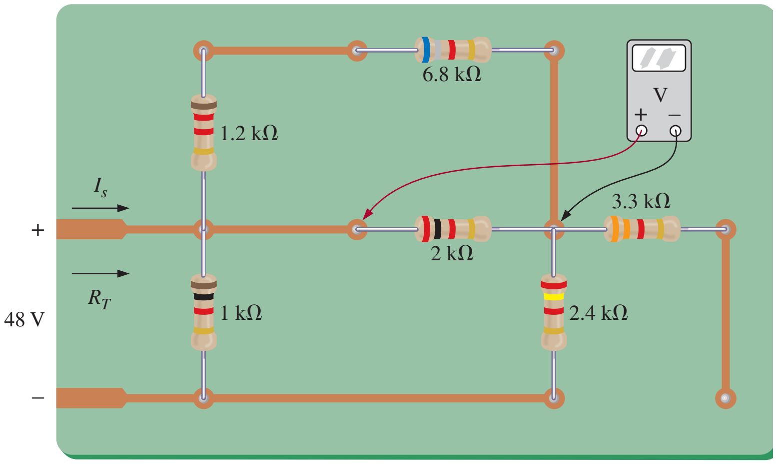


FIG. 7.66
Problem 6.

***7.** For the network in Fig. 7.67:
- **a.** Find currents I_s, I_2, and I_6.
- **b.** Find voltages V_1 and V_5.
- **c.** Find the power delivered to the 3 kΩ resistor.

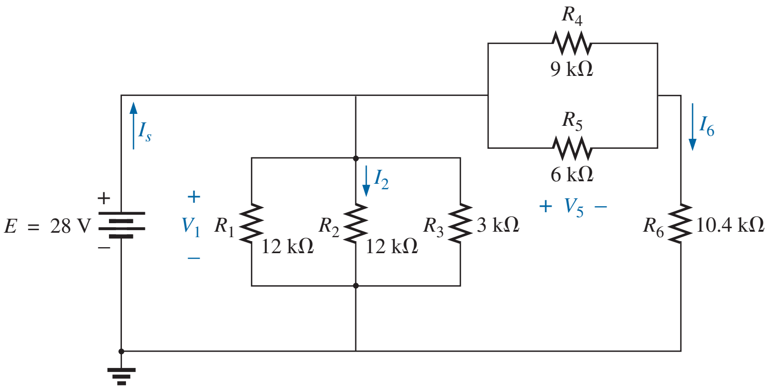


FIG. 7.67
Problem 7.

***8.** For the series-parallel configuration in Fig. 7.68:
- **a.** Find the source current I_s.
- **b.** Find currents I_3 and I_9.
- **c.** Find current I_8.
- **d.** Find voltage V_x.

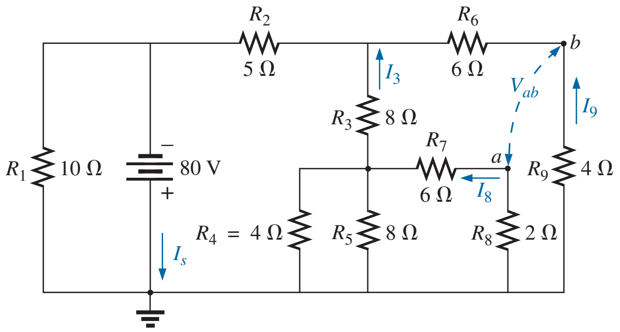


FIG. 7.68
Problem 8.

9. Determine the currents I_1 and I_2 for the network in Fig. 7.69.

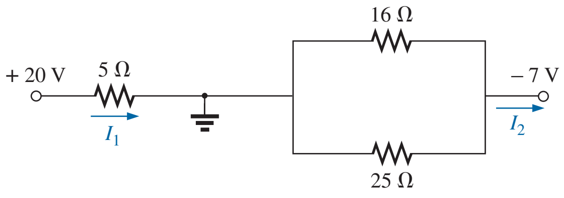


FIG. 7.69
Problem 9.

10. **a.** Find the magnitude and direction of the currents I, I_1, I_2, and I_3 for the network in Fig. 7.70.
b. Indicate their direction on Fig. 7.70.

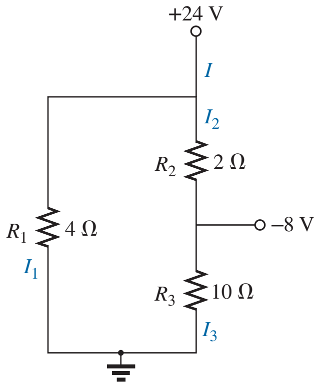


FIG. 7.70
Problem 10.

***11.** For the network in Fig. 7.71:
- **a.** Determine the currents I_s, I_1, I_3, and I_4.
- **b.** Calculate V_a and V_{bc}.

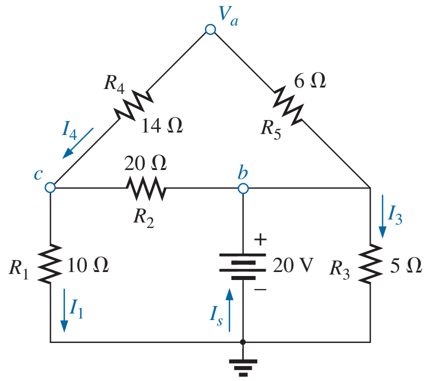


FIG. 7.71
Problem 11.

12. For the network in Fig. 7.72:

a. Determine the current I_1.

b. Calculate the currents I_2 and I_3.

c. Determine the voltage levels V_a and V_b.

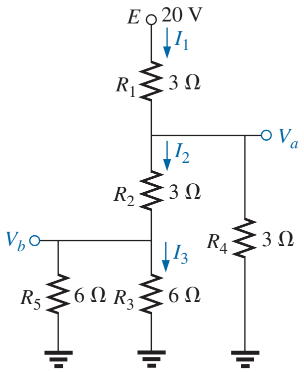


FIG. 7.72
Problem 12.

***13.** Determine the dc levels for the transistor network in Fig. 7.73 using the fact that $V_{BE} = 0.7$ V, $V_E = 2$ V, and $I_C = I_E$. That is:

a. Determine I_E and I_C.

b. Calculate I_B.

c. Determine V_B and V_C.

d. Find V_{CE} and V_{BC}.

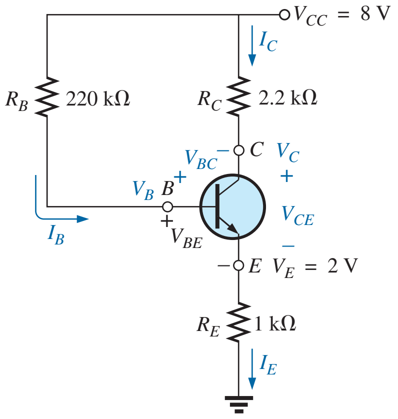


FIG. 7.73
Problem 13.

***14.** The network in Fig. 7.74 is the basic biasing arrangement for the *field-effect transistor* (FET), a device of increasing importance in electronic design. (*Biasing* simply means the application of dc levels to establish a particular set of operating conditions.) Even though you may be unfamiliar with the FET, you can perform the following analysis using only the basic laws introduced in this chapter and the information provided on the diagram.

a. Determine the voltages V_G and V_S.

b. Find the currents I_1, I_2, I_D, and I_S.

c. Determine V_{DS}.

d. Calculate V_{DG}.

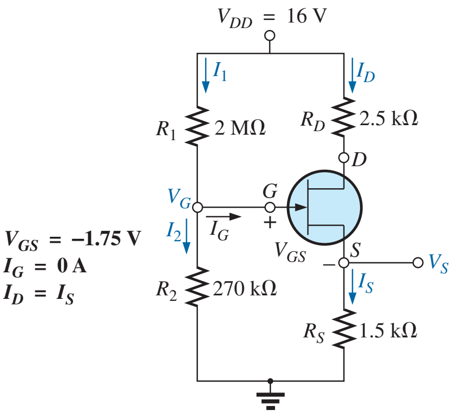


FIG. 7.74
Problem 14.

***15.** For the network in Fig. 7.75:

a. Determine R_T.

b. Calculate V_a.

c. Find V_1.

d. Calculate V_2.

e. Determine I (with direction).

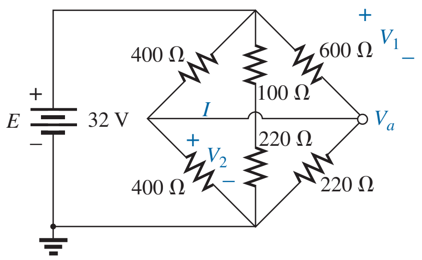


FIG. 7.75
Problem 15.

16. For the network in Fig. 7.76:

a. Determine the current I.

b. Find V_1.

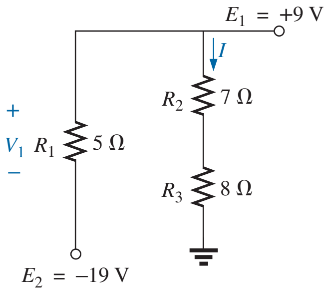


FIG. 7.76

Problem 16.

17. For the configuration in Fig. 7.77:

a. Find the currents I_2, I_6, and I_8.

b. Find the voltages V_4 and V_8.

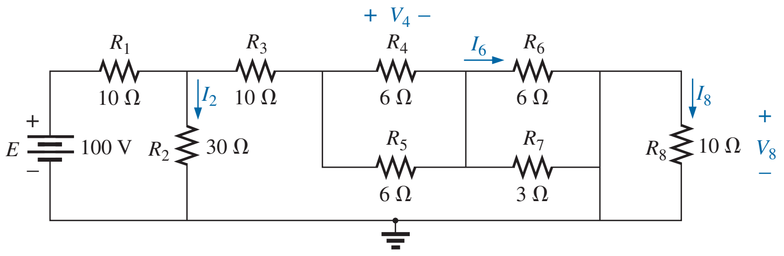


FIG. 7.77

Problem 17.

18. Determine the voltage V and the current I for the network in Fig. 7.78.

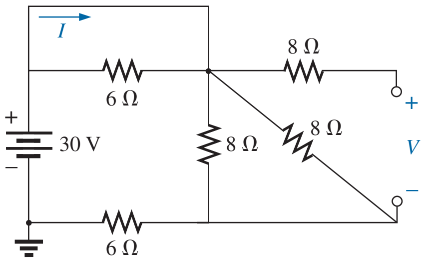


FIG. 7.78

Problem 18.

***19.** For the network in Fig. 7.79:

a. Determine R_T by combining resistive elements.

b. Find V_1 and V_4.

c. Calculate I_3 (with direction).

d. Determine I_s by finding the current through each element and then applying Kirchhoff's current law. Then calculate R_T from $R_T = E/I_s$, and compare the answer with the solution of part (a).

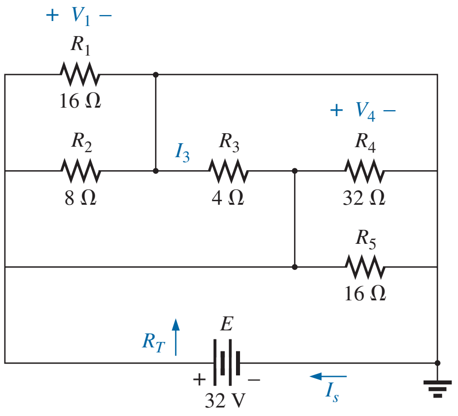


FIG. 7.79

Problem 19.

20. For the network in Fig. 7.80:

a. Determine the voltage V_{ab}. (*Hint:* Just use Kirchhoff's voltage law.)

b. Calculate the current I.

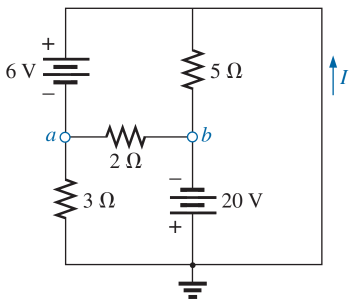


FIG. 7.80

Problem 20.

*__21.__ For the network in Fig. 7.81:

- **a.** Determine the current I.
- **b.** Calculate the open-circuit voltage V.

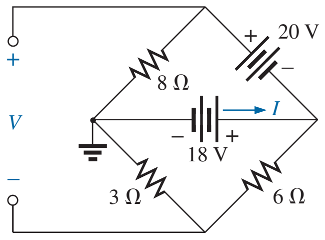


FIG. 7.81
Problem 21.

*__22.__ For the network in Fig. 7.82, find the resistance R_3 if the current through it is 2 A.

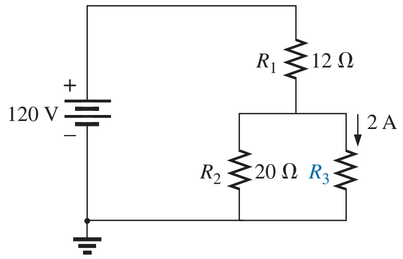


FIG. 7.82
Problem 22.

*__23.__ If all the resistors of the cube in Fig. 7.83 are 10 Ω, what is the total resistance? (*Hint:* Make some basic assumptions about current division through the cube.)

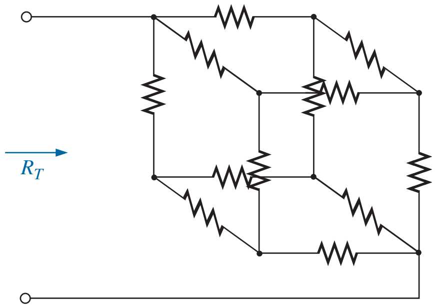


FIG. 7.83
Problem 23.

*__24.__ Given the voltmeter reading $V = 27$ V in Fig. 7.84:

- **a.** Is the network operating properly?
- **b.** If not, what could be the cause of the incorrect reading?

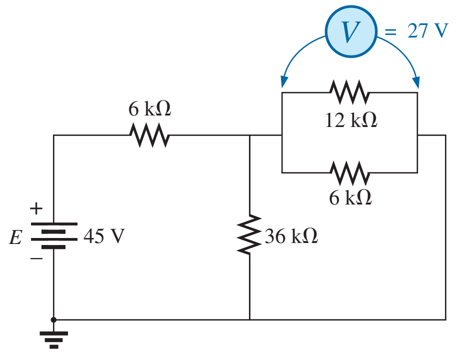


FIG. 7.84
Problem 24.

SECTION 7.6 Ladder Networks

25. For the ladder network in Fig. 7.85:

- **a.** Find the current I.
- **b.** Find the current I_7.
- **c.** Determine the voltages V_3, V_5, and V_7.
- **d.** Calculate the power delivered to R_7, and compare it to the power delivered by the 240 V supply.

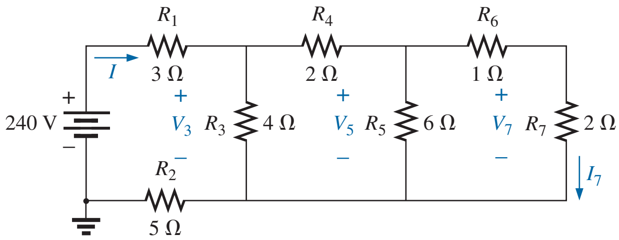


FIG. 7.85
Problem 25.

26. For the ladder network in Fig. 7.86:

- **a.** Determine R_T.
- **b.** Calculate I.
- **c.** Find I_8.

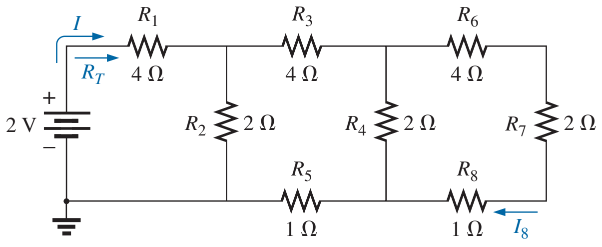


FIG. 7.86
Problem 26.

***27.** Determine the power delivered to the 10 Ω load in Fig. 7.87.

28. For the multiple ladder configuration in Fig. 7.88:
- **a.** Determine I.
- **b.** Calculate I_4.
- **c.** Find I_6.
- **d.** Find I_{10}.

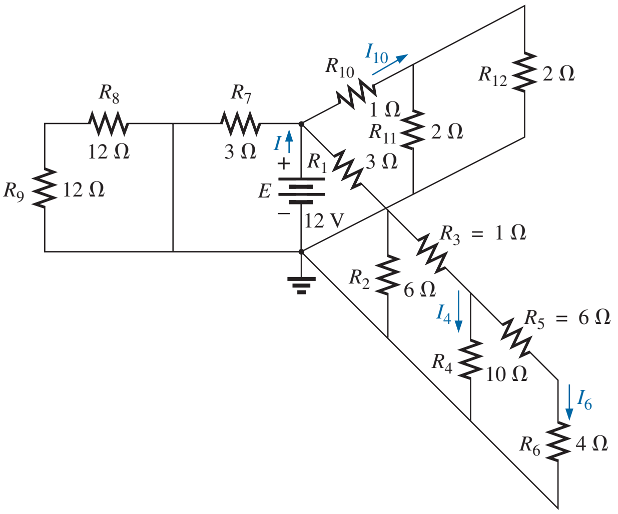


FIG. 7.88
Problem 28.

SECTION 7.7 Voltage Divider Supply (Unloaded and Loaded)

29. Given the voltage divider supply in Fig. 7.89:
- **a.** Determine the supply voltage E.
- **b.** Find the load resistors R_{L_2} and R_{L_3}.
- **c.** Determine the voltage divider resistors R_1, R_2, and R_3.

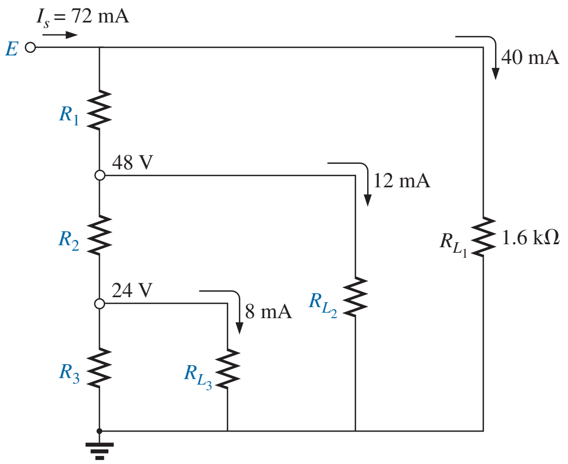


FIG. 7.89
Problem 29.

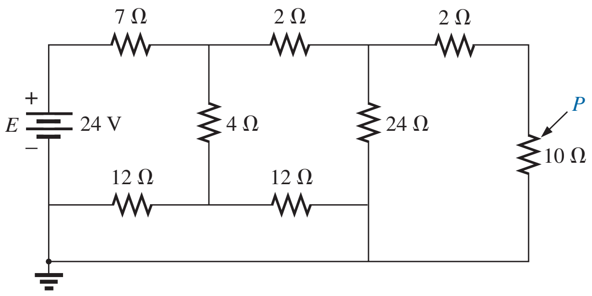


FIG. 7.87
Problem 27.

***30.** Determine the voltage divider supply resistors for the configuration in Fig. 7.90. Also determine the required wattage rating for each resistor, and compare their levels.

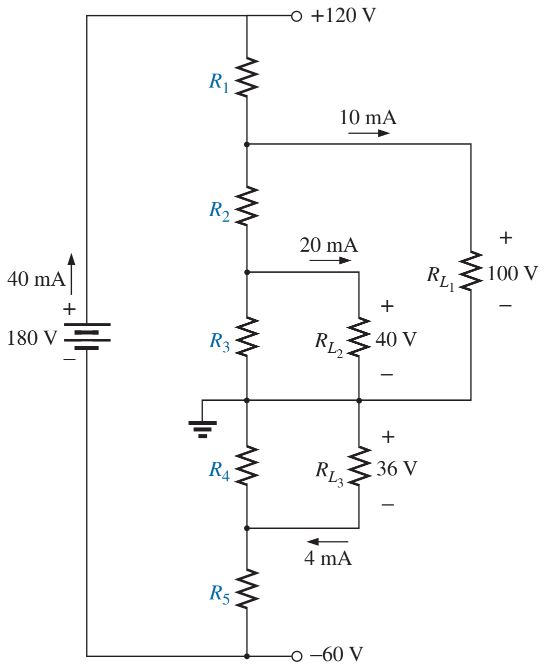


FIG. 7.90
Problem 30.

SECTION 7.8 Potentiometer Loading

*__31.__ For the system in Fig. 7.91:

- **a.** At first exposure, does the design appear to be a good one?
- **b.** In the absence of the 10 kΩ load, what are the values of R_1 and R_2 to establish 3 V across R_2?
- **c.** Determine the values of R_1 and R_2 to establish $V_{R_L} = 3$ V when the load is applied, and compare them to the results of part (b).

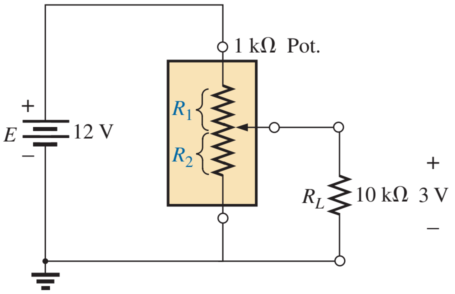


FIG. 7.91
Problem 31.

*__32.__ For the potentiometer in Fig. 7.92:

- **a.** What are the voltages V_{ab} and V_{bc} with no load applied ($R_{L_1} = R_{L_2} = \infty\ \Omega$)?
- **b.** What are the voltages V_{ab} and V_{bc} with the indicated loads applied?
- **c.** What is the power dissipated by the potentiometer under the loaded conditions in Fig. 7.92?
- **d.** What is the power dissipated by the potentiometer with no loads applied? Compare it to the results of part (c).

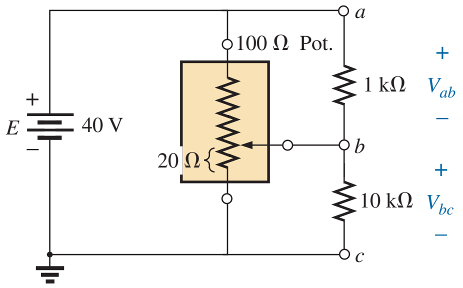


FIG. 7.92
Problem 32.

SECTION 7.9 Ammeter, Voltmeter, and Ohmmeter Design

33. A d'Arsonval movement is rated 1 mA, 100 Ω.

- **a.** What is the current sensitivity?
- **b.** Design a 20 A ammeter using the above movement. Show the circuit and component values.

34. Using a 50 μA, 1000 Ω d'Arsonval movement, design a multirange milliammeter having scales of 25 mA, 50 mA, and 100 mA. Show the circuit and component values.

35. A d'Arsonval movement is rated 50 μA, 1000 Ω.

- **a.** Design a 15 V dc voltmeter. Show the circuit and component values.
- **b.** What is the ohm/volt rating of the voltmeter?

36. Using a 1 mA, 100 Ω d'Arsonval movement, design a multirange voltmeter having scales of 5 V, 50 V, and 500 V. Show the circuit and component values.

37. A digital meter has an internal resistance of 10 MΩ on its 0.5 V range. If you had to build a voltmeter with a d'Arsonval movement, what current sensitivity would you need if the meter were to have the same internal resistance on the same voltage scale?

*__38.__ **a.** Design a series ohmmeter using a 100 μA, 1000 Ω movement; a zero-adjust with a maximum value of 2 kΩ; a battery of 3 V; and a series resistor whose value is to be determined.

- **b.** Find the resistance required for full-scale, 3/4-scale, 1/2-scale, and 1/4-scale deflection.
- **c.** Using the results of part (b), draw the scale to be used with the ohmmeter.

39. Describe the basic construction and operation of the megohmmeter.

*__40.__ Determine the reading of the ohmmeter for the configuration in Fig. 7.93.

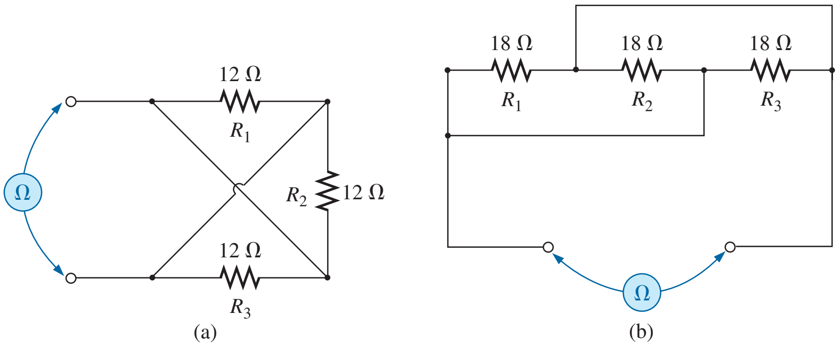


FIG. 7.93
Problem 40.

SECTION 7.11 Computer Analysis

41. Using PSpice or Multisim, verify the results of Example 7.2.

42. Using PSpice or Multisim, confirm the solutions of Example 7.5.

43. Using PSpice or Multisim, verify the results of Example 7.10.

44. Using PSpice or Multisim, find voltage V_6 of Fig. 7.32.

45. Using PSpice or Multisim, find voltages V_b and V_c of Fig. 7.40.

GLOSSARY

Complex configuration A network in which none of the elements are in series or parallel.

d'Arsonval movement An iron-core coil mounted on bearings between a permanent magnet. A pointer connected to the movable core indicates the strength of the current passing through the coil.

Ladder network A network that consists of a cascaded set of series-parallel combinations and has the appearance of a ladder.

Megohmmeter An instrument for measuring very high resistance levels, such as in the megohm range.

Series ohmmeter A resistance-measuring instrument in which the movement is placed in series with the unknown resistance.

Series-parallel network A network consisting of a combination of both series and parallel branches.

Transistor A three-terminal semiconductor electronic device that can be used for amplification and switching purposes.

Voltage divider supply A series network that can provide a range of voltage levels for an application.