Direct Current Theory

This unit discusses basic electricity principles.

At the conclusion of this training unit the trainee should be able to:

Explain the principles of basic electricity.

Following this objective, you should be able to:

Recall the basic principles of electricity.

Relate electrical principles to work applications.

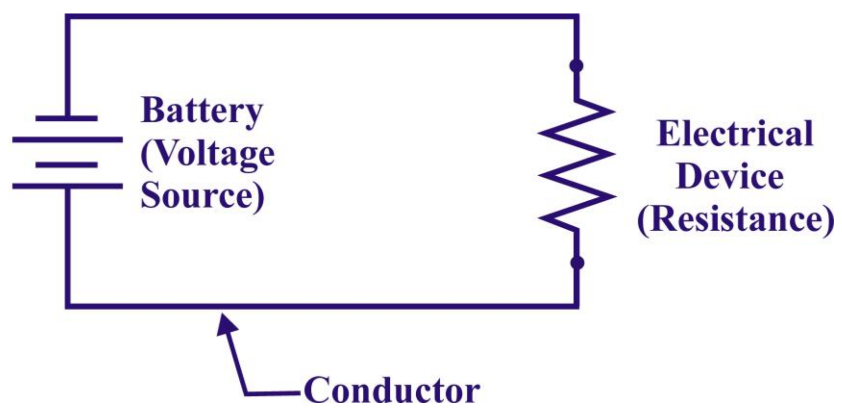
Identify how electrical principles are applied to work.

At the conclusion of this training unit the trainee should be able to apply basic electricity principles and relate these principles to their individual job. Trainees may be evaluated by completing a written exam comprised of questions from this training unit and others included in this course. A minimum of 80% accuracy is required to satisfactorily complete this training.

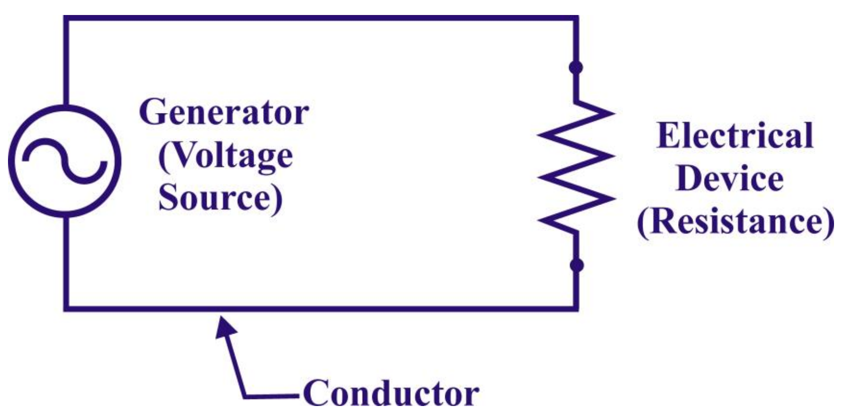
Direct Current Theory

1. The Electrical Circuit

    a. An electrical circuit is a complete path through which electrons flow between the voltage source and various electrical devices. Figures 2-1 and 2-2 are examples of simple electrical circuits.



Picture 1, Simple Circuit Using a Battery as a Voltage Source

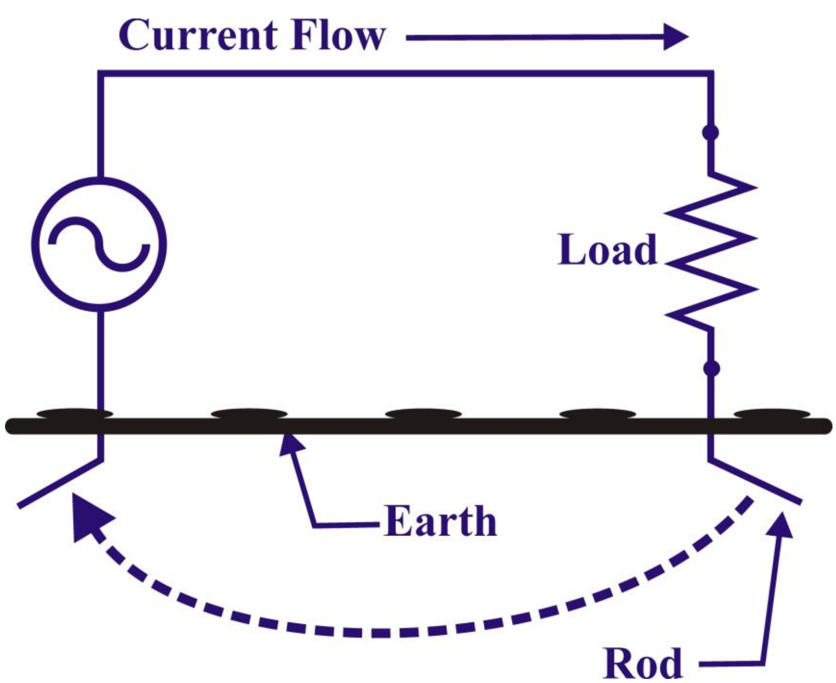


Picture 2, Simple Circuit Using a Generator as a Voltage Source

2. Closed Circuit

    a. A closed path must exist for current to flow from the voltage source, through the conductor and electrical load, and back to the voltage source.

This is a closed circuit. The voltage source, either battery or generator, forces current to flow through the conductor and electrical device then back through the conductor to the voltage source. Figures 2-1 and 2-2 are both examples of closed circuits. The earth is a conductor and can be used as one circuit conductor. Picture 3 shows current flowing through a resistance, into the ground through a rod, out of the ground through another rod, and back to the voltage source. This is also a closed circuit since there is a complete path for current flow. The schematic symbol for a connection to ground is shown in Picture 4.

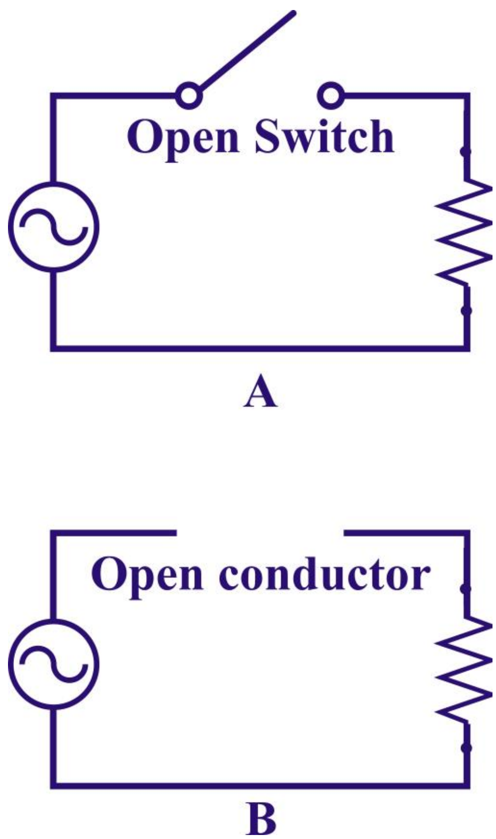


Picture 3, Earth Used As a Conductor

Picture 4, Schematic Symbol for Connection to Ground

3. Open Circuit

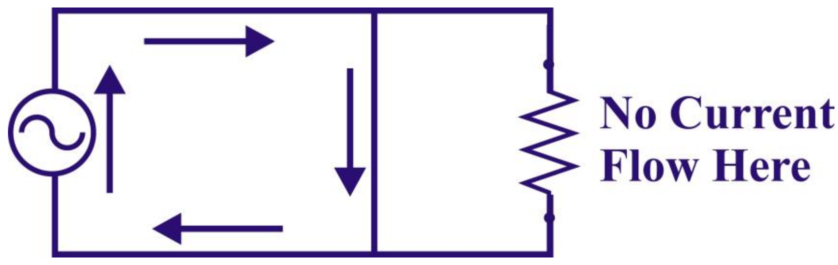
   a. If a current path does not exist in a circuit, the circuit is open. Picture s 5 A and B are examples. In Picture 5A, resistance between the open switch contacts is too great to allow current to flow. In Picture 5B, the opening in the conductor offers enough resistance to break the current path.



Picture 5, Examples of Open Circuits

4. Short Circuit

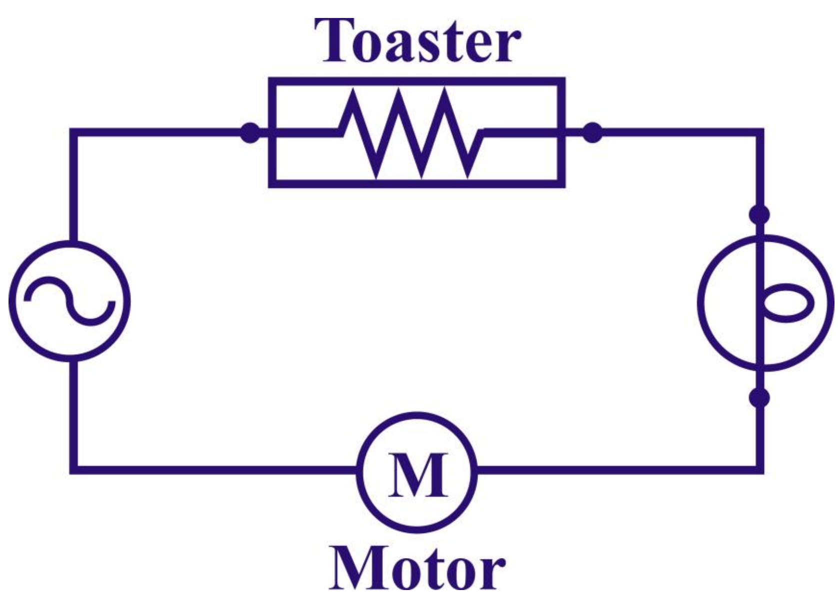
   a. Picture 6 shows a short circuit condition. Current will not flow through the electrical device because it will follow the path of least resistance through the conductor. This condition is usually undesirable. High currents are rapidly developed which can cause overheating of the voltage source and conductor, and may result in a fire. Notice that electrical current, like water, will always attempt to take the path of least resistance. If a branch splits from the main stream, the amount of electron flow (current) into that branch will depend on the branch's resistance. This concept will become clearer when parallel circuits are covered later in this chapter.



Picture 6, Short Circuit

5. Series Circuits

   a. Picture 7 shows a circuit with a motor, lamp, and toaster. It has three loads. There is only one path for current to follow. Any circuit in which the current has only one path to follow is called a series circuit.

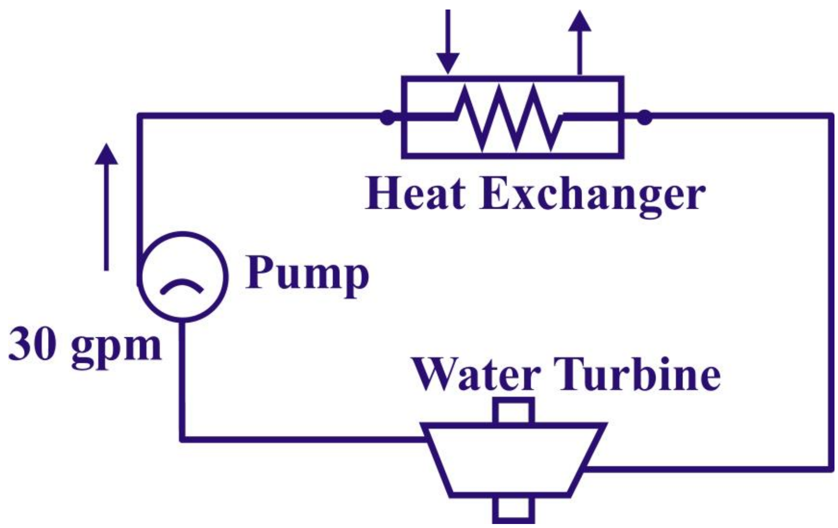


Picture 7, Basic Series Circuit

6. Series Current

   a. Current flow at any given point in a series circuit is equal to the current flow at any other point. In other words, current is the same throughout a series circuit. This can be seen using the mechanical analogy in Picture

8. If the pump is supplying 30 gallons per minute to the system, then the flow rate in the heat exchanger and the water turbine must also be 30 gpm. In other words, the flow rate at any point in the system is 30 gpm.



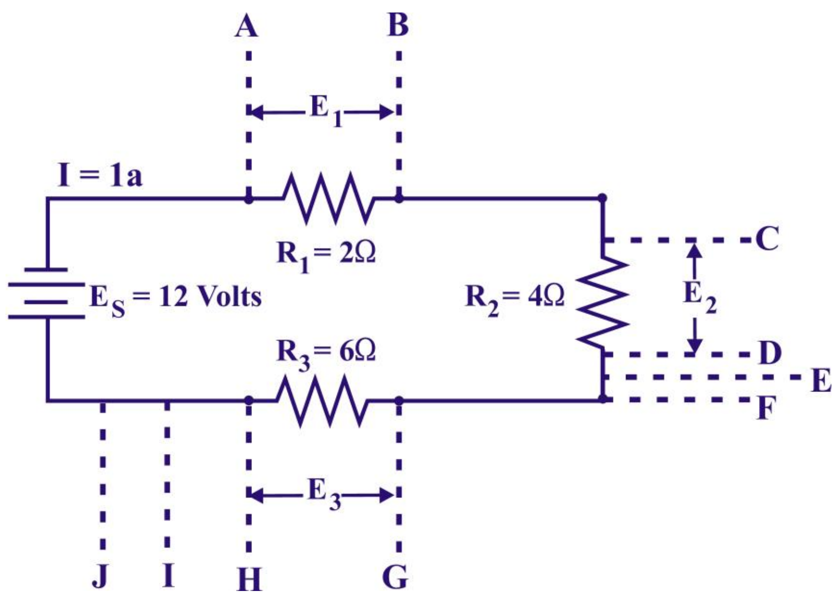
Picture 8, Mechanical Analogy of Current in a Series Circuit

b. The current in a series circuit can be expressed mathematically as follows:

$$I = I = I = \ldots$$

7. Series Voltage

a. Voltage causes current to flow through a load. In Picture 9, 12 volts are causing 1 amp to flow through 2 ohm, 4 ohm, and 6 ohm loads. Voltage can only exist between two points in a circuit (not at just one point), and then only if the two points are separated by a load (resistance). Therefore, there will be voltage between points A & B, C & D, and G & H. There will not be voltage between points E & F or I & J due to the negligible resistance of the conductor. All materials have some value of resistance. E is used to represent the voltage drop between various points. An example of this, the voltage drop across R, is shown as E. Source voltage is represented by E.



Picture 9, Voltage Drops Across Series Loads

b. How much voltage (Ex) will exist between points A & B, C & D, AND G & H? The source voltage is 12 volts, but some will be used to force the 1 amp of current through the 2 ohm resistance. Ohm's Law states that voltage equals current multiplied by resistance, or E = I x R. voltage across points A & B is equal to current (1 amp) multiplied by resistance (2 ohms), or E = IR= 1 x 2 = 2 volts. Therefore, the source voltage of 12 volts will "drop" 2 volts across resistance R1. This is equivalent to the pressure drop that is experienced across a component in a piping system, such as an orifice. The next resistance the current encounters is R2. Using Ohm's Law, E2 = 1 x 4 = 4 volts. The final resistance encountered is R3. Therefore, E3=1 x 6 = 6 volts. Current is the same, 1 amp, through all resistances in a series circuit.

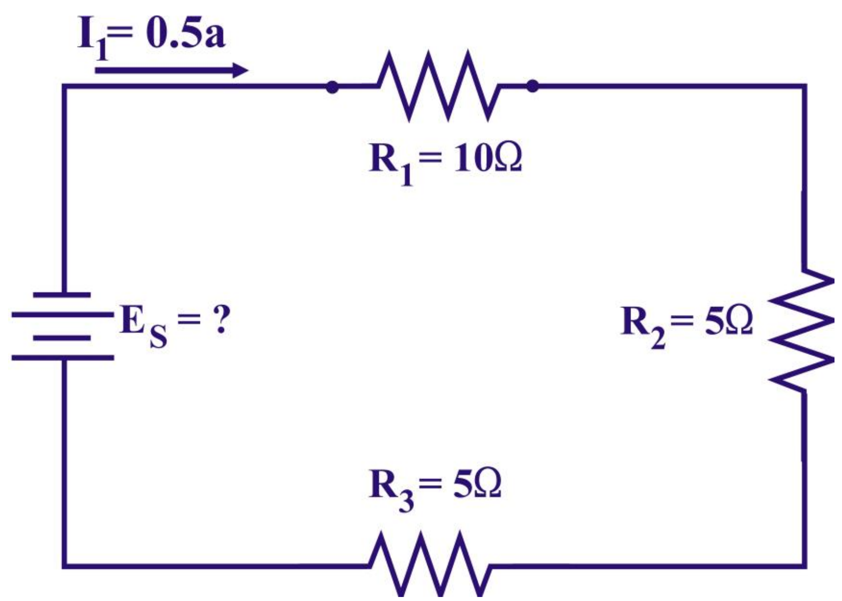
c. The sum of voltage drops is 12 volts. In a series circuit, the sum of voltage drops is equal to the source voltage.

E + E + E + E

d. Loads use all voltage supplied by the source.

Example:

For the figure below, find the source voltage.



Picture 10, Example Circuit

e. Answer: There are two ways to solve this problem.

1) Solution One

a) Since E = I x R and IT = 0.5a, we can solve for RT.

b) Recall that resistances in series are cumulative.

c) Thus, RT = R^1 + R^2 + R^3 = 10Ω + 5Ω + 5Ω = 20Ω

d) Applying Ohm's Law, E = IR = 0.5a x 20Ω

e) Therefore, ES = 10 volts.

2) Solution Two

a) Solve for the individual voltage drops and then add.

b) Current is the same throughout the series circuit.

c) Thus, $E^1 = 1^1 \text{ x } R^1 = 0.5\text{a x } 10\Omega = 5$ volts

d) $E^2 = I^2 \text{ x } R^2 = 0.5\text{a x } 5\Omega = 2.5$ volts

e) $E^3 = I^3 \text{ x } R^3 = 0.5\text{a x } 5\Omega = 2.5$ volts

f) Since series voltages are additive then,

g) $Es + E^1 + E^2 + E^3 = 5v + 2.5v + 2.5\ v$

h) Therefore, Es = 10 volts

8. Series Resistance

a. Since the sum of voltage drops is equal to the source voltage and the current is equal at all points in a series circuit, using Ohm's Law, an equation for total circuit resistance (RT) can be developed.

b. Since:

$$ES = E1 + E2 + EA$$

c. Replacing the voltages with the Ohm's Law equivalent

$$ITRT = I1R1 + I2R2 + InRn$$

d. Dividing by current, since I = I = I = I , an equation for total circuit resistance is obtained:

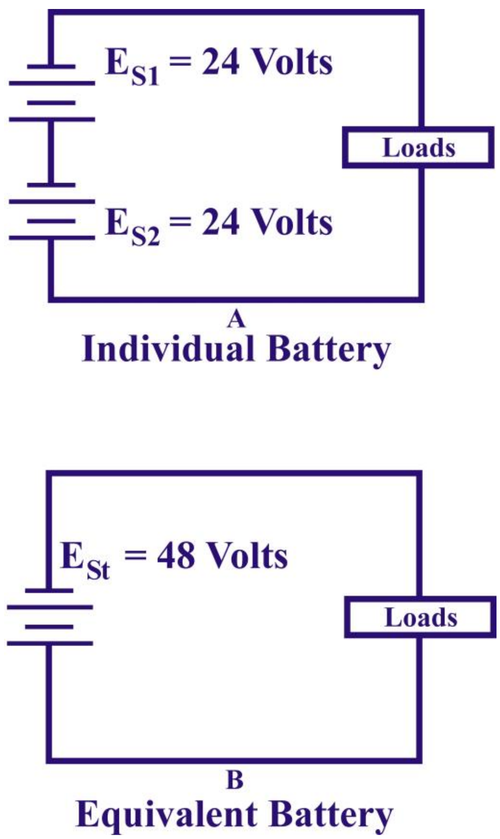
$$R = R + R + R$$

e. The total resistance (R) in a series circuit is equal to the sum of all the individual resistances. This is equivalent to total flow resistance in Picture 8 being the sum of the flow restriction of the heat exchanger, water turbine, and piping.

9. Series Voltage Sources

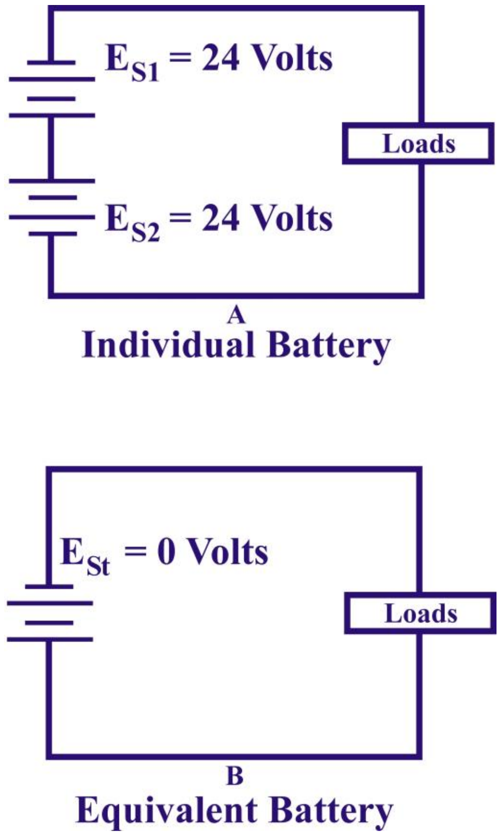
a. Voltages are cumulative in a series circuit. This knowledge is used to determine the effect of voltage sources added in series.

b. If two 24 volt batteries are placed in series to aid each other, (Picture 10A), source voltage as seen by the load is 48 volts (Picture 10B).



Picture 11, Connected in Series Aiding

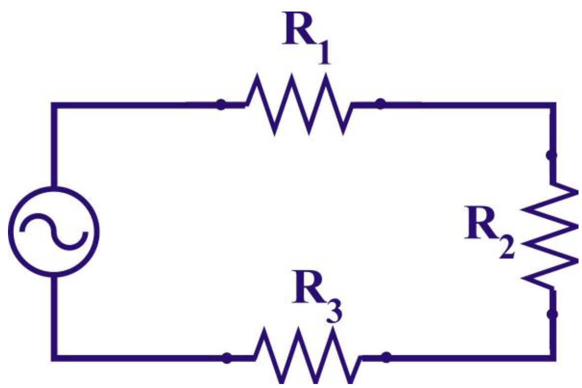
c. If the same two batteries are placed in series and oppose each other (Picture 11A), source voltage as seen by the load is 0 volts (Picture 11B).



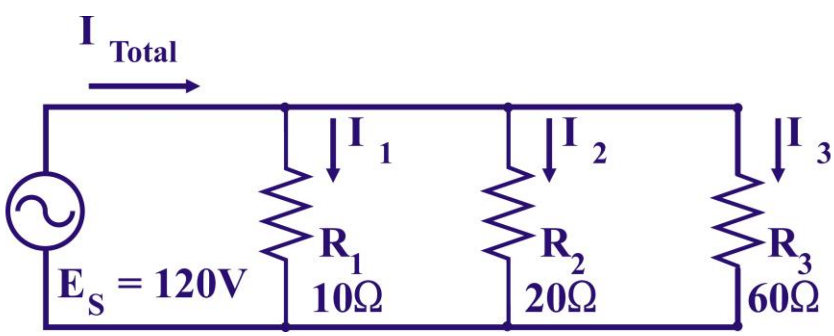
Picture 12, Batteries Connected in Series Opposing

10. Parallel Circuits

11. In a series circuit, loads were connected end-to-end, and current had only one path to follow. In a parallel circuit, loads are connected for current to divide at each load. Picture 12 shows a series circuit; Picture 13 shows a parallel circuit.



Picture 13, Series Circuit



Picture 14, Parallel Circuit

12. Parallel Voltage

    a. In Picture 12, current has only one path. The amount of current is the same through R1, R2, R3.. In Picture 13, current has three branches. Part of total current (IT) will flow through R1, part through R2, and the rest through R3. Voltage across R1, R2, and R3 will be the same as the voltage source (Es) applied to that branch.

E = E = E = E

b. In Picture 13, the voltage drop across each resistance is 120 volts. Each load has a direct connection to the source voltage; there is no resistance between the source voltage and the branches to "drop" voltage. Therefore, the voltage drop across each parallel branch must be equal. If there were any significant resistance between the voltage source and either side of the parallel circuit this would not be true.

13. Parallel Current

a. Current (I^1) through R^1 is equal to the voltage across R^1, E^1, divided by resistance of R^1.

b. $I = \frac{E_1}{R_1}$

c. Therefore, $I = \frac{120}{10} = 12$ amps

d. $I = \frac{E_2}{R_2} = \frac{120}{20} = 6$ amps

e. $I = \frac{E_3}{R_3} = \frac{120}{60} = 2$ amps

f. Total current IT = I1 + I2 + I = 12 + 6 + 2 = 20 amps. In a parallel circuit, total current is equal to the sum of individual currents.

I = I + I + I + I

14. Parallel Resistance

a. As loads (resistances) are added in parallel, they simply become additional paths for current. Therefore, total current supplied by the source must increase as loads are added. If total current is increased, total resistance must decrease. As branches are added in parallel, the total resistance (as seen from the voltage source) decreases. Total resistance in parallel is developed mathematically as:

b. Given: $I_T = I_1 + I_2 + I_3 + I_n$

c. Replacing the currents with the Ohm's Law equivalent:

$$\frac{E_s}{R_T} = \frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3} + \frac{E_n}{R_n}$$

d. Dividing by voltage, since to obtain an equation in terms of resistance

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_n}$$

e. Rearranging: $R_T = \dfrac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_n}}$

f. Example: Find the total resistance of a circuit which has two 5 ohm and one 10 ohm loads connected in parallel.

g. Answer:

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{1}{5} + \frac{1}{5} + \frac{1}{10}} = \frac{1}{\frac{5}{10}} = \frac{10}{5} = 2$$

$$R_T = 2 \text{ ohms}$$

h. In Example 2-2, total resistance is less than the smallest resistance in the parallel circuit. When resistances are added in parallel, total resistance will always be less than the smallest resistance in the circuit.

i. If all resistances in parallel are the same value, then Equation 2-6 can be reduced to the following:

$$R_T = \frac{R}{N}$$

j. Example: If five loads of 20 ohms each are connected in parallel, then what is the total resistance?

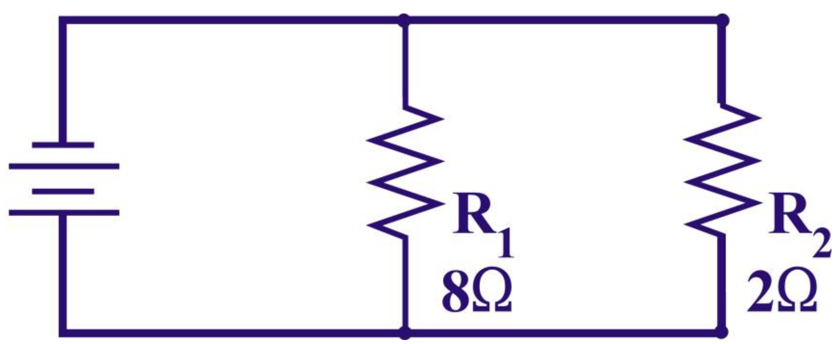
k. Answer:

Since $R_T = \frac{R}{N} = \frac{20\Omega}{5}$

Therefore, $R_T = 4\Omega$

l. If two resistances of different value are connected in parallel, then equation 2-6 can be reduced to: $R_T = \frac{R_1 x R_2}{R_1 + R_2}$

m. Example: For the figure below, calculate the total resistance.



Picture 15, Example Circuit

n. Aswer:

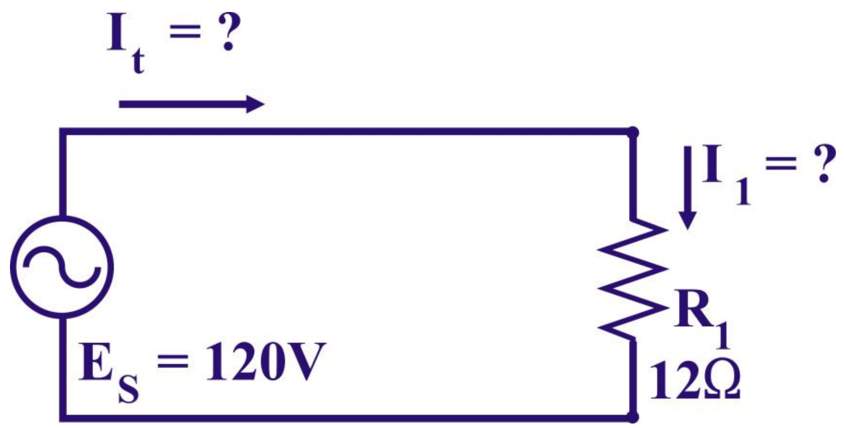
$$R_T = (R_1 x R_2) \div (R_1 + R_2) = (8x2) \div (8+2) = \frac{16}{10}$$

o. $R_T = 1.6 \text{ ohms}$

p. To understand how parallel loads (resistance) affect current, start with the simple series circuit (Picture 14a).

q. Source voltage is 120 volts, R^1 = 12Ω and in a series circuit, RT = 12Ω.

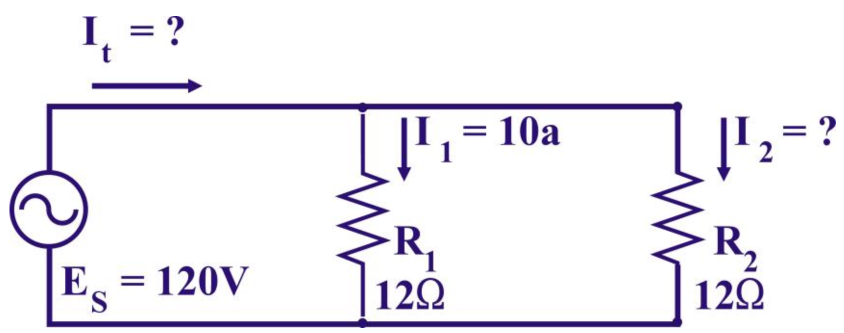
r. To solve for I_1, apply Ohm's Law.



Picture 16, Series Circuit

$$I_1 = \frac{E}{R} = \frac{120}{12} = 10\,\text{amps}$$

s. Since this is a series circuit, I also equals 10 amps. Now add an additional 12 ohm load in parallel with the first (Picture 14b).



Picture 17, Two Branch Parallel Circuit

t. To solve for I^2, apply Ohm's Law to that branch.

$$I_2 = \frac{E_s}{R_2} = \frac{120\,\text{v}}{12\,\Omega}$$

$$I_2 = 10\,\text{amps}$$

u. To solve for RT, use Equation 2-7 since resistances are of the same value.

$$R_T = \frac{12}{2}$$

$$R_T = 6 \text{ ohms}$$

v. To solve for IT, one of two methods can be employed.

1) Apply Ohm's Law using valued for total voltage and resistance.

$$I_T = \frac{E_S}{R_T} = \frac{120}{6\Omega}$$

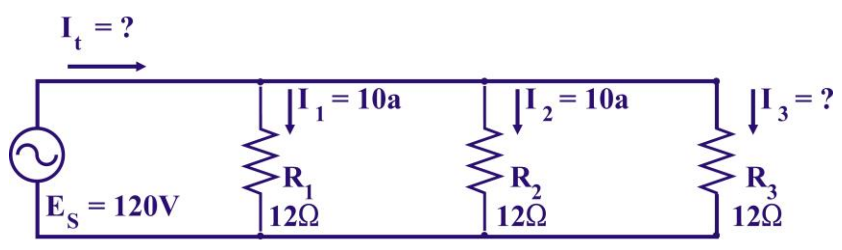
$$I_T = 20 \text{ amps}$$

2) 2. Sum up individual branch currents.

$$I_T = I_1 + I_2 = 10a + 10a$$
$$I_T = 20 \text{amps}$$

w. Current in the original branch has not changed. This is because neither voltage applied to that branch, nor resistance in the branch, has been changed. As loads are added in parallel, current in the original branches does not change, but total current supplied by the voltage source must increase by a value equal to the branch's resistance divided into the applied voltage across that branch (I = E/R).

x. Finally, add additional 24 ohm load in parallel (Picture 14c).



Picture 18, A Three Branch Parallel Circuit

y. To solve for current in branch 3 (I³), again apply Ohm's Law.

$$I_3 = \frac{E_S}{R_3} = \frac{120\,v}{24\,\Omega}$$

$$I_3 = 5\,\text{amps}$$

z. A branch that has double resistance, draws only half the original current.

aa. To solve for total resistance use

$$R_T = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \frac{1}{\frac{1}{12} + \frac{1}{12} + \frac{1}{24}} = \frac{1}{\frac{2}{24} + \frac{2}{24} + \frac{1}{24}} = \frac{1}{\frac{5}{24}} = \frac{24}{5}$$

R = 4.8 Ω

bb. To solve for total current (I , again, one of two methods can be used.

1) 1. Apply Ohm's Law

$$I_T = \frac{E_S}{R_T} = \frac{120\,v}{4.8\Omega}$$

$$I_T = 25\,\text{amps}$$

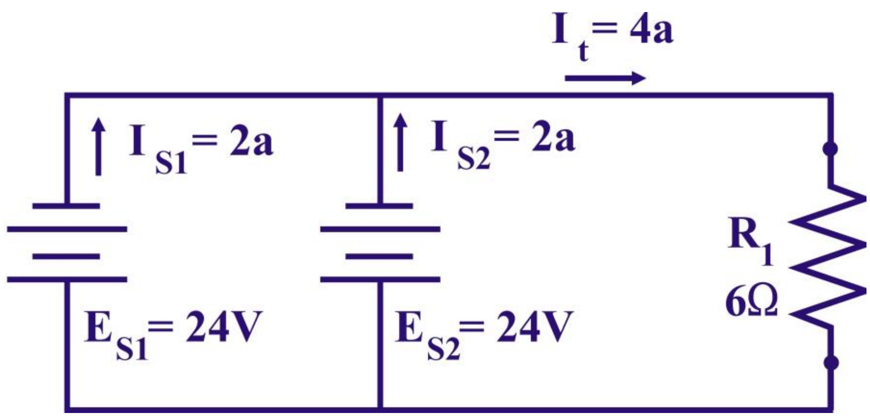
cc. 2. Add individual branch currents

I = I¹ + I² + I³ = 10a + 10a + 5a

I = 25 amps

15. Parallel Voltage Sources

a. Examples of parallel circuits have shown loads connected in parallel. Source voltages can also be connected in parallel (Picture 15).

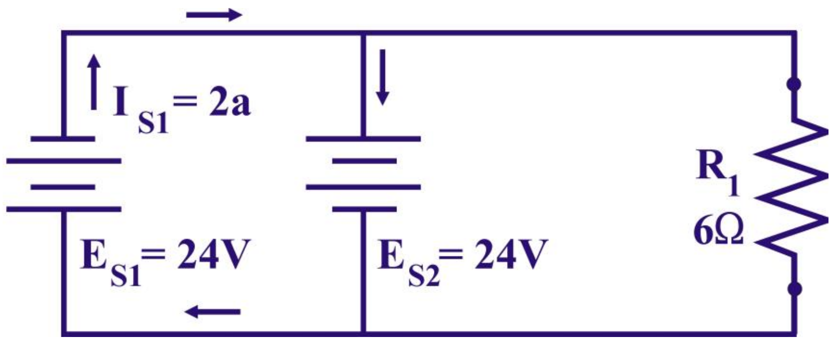


Picture 19, Equal Parallel Sources

b. Total required current by resistive load is 4 amps. The source voltage has not changed, but each of the voltage sources need only supply half the required current. If each voltage source is rated at 4 amps max, then each source is operating at only 50% of capacity (compared to a single 24 volt source operating at 100% capacity). Therefore, by placing voltage sources in parallel, current capability (current available) is increased while terminal voltage remains constant.

c. Each source voltage must be the same, otherwise the larger voltage source will send current to the lower voltage source, treating it as a load.

d. It is important to connect parallel power sources correctly. Picture 16 shows the incorrect way. Here, two batteries form a circuit where current will flow through the batteries but not through the load.



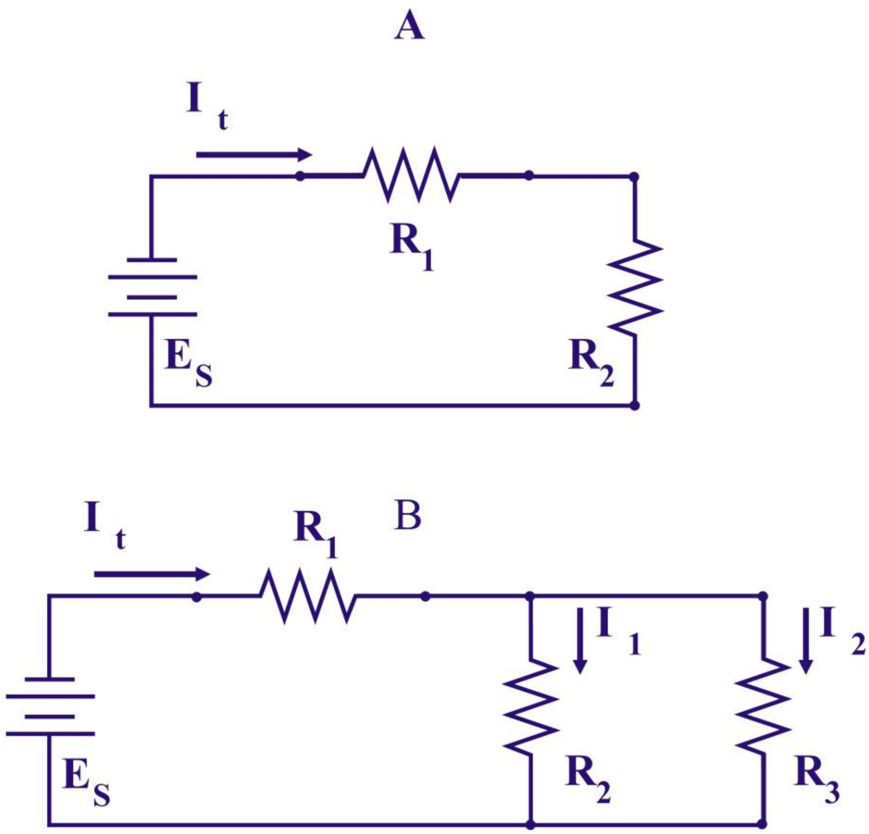
Picture 20, Incorrect Parallel Source Connection

e. This is very undesirable because internal resistance of the voltage source is very small compared to . Very high current can be experienced in this condition and could lead to high temperatures and possible fires or explosions. An example of this occurs when an attempt is made to jump a car with improperly connected cables. The results can be explosive.

16. Series – Parallel Circuits

a. In a series circuit, loads are connected end-to-end and the same current flows through all loads. In a parallel circuit, current has two or more paths to follow. Current through each branch is directly dependent upon its resistance, and total current is equal to the sum of the individual currents. However, a series-parallel circuit is one in which part of the circuit is a series circuit and part is a parallel circuit. Series-parallel circuits are sometime referred to as complex circuits.

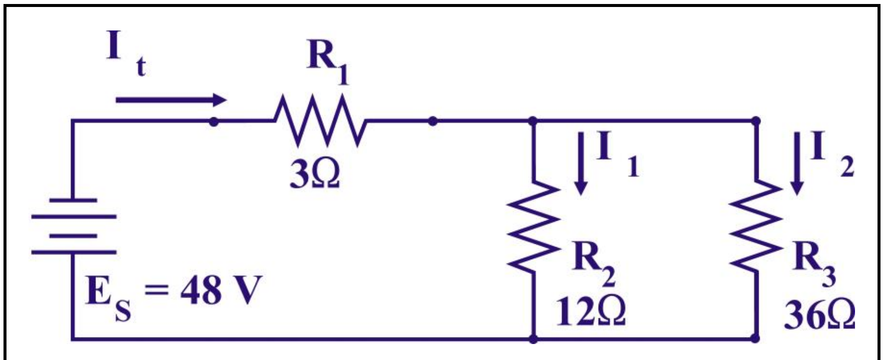
b. Picture 17a is a series circuit. Voltage current, and resistance follow series laws previously discussed. If an additional branch is added (Picture 17b), the circuit becomes series-parallel. Total circuit resistance decreases. The source voltage (Es) will drop some voltage across R1. The difference between Es and the voltage drop across R1 is the remaining voltage. It is applied across the parallel branch R2 and R3. However, when total current reaches point A, it divides into branch R2 and branch R3. Recall, the amount of current that enters is dependent upon branch resistance. The voltage drop across R2 will be the same as voltage drop across R3.



Picture 21, Series and Series – Parallel Circuits

17. Reducing

a. Picture 18 is a series-parallel circuit. The source voltage (Es) and resistances of the load are known. Not known are RT, IT, I2, I3, and the voltage drops across R1, R2, and R3. To solve for these unknowns, reduce a series-parallel circuit to a simple series circuit.

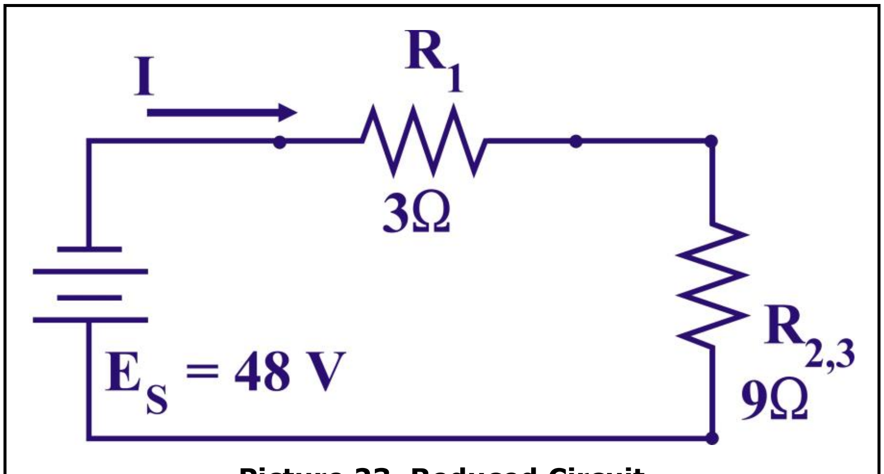


Picture 22, Series-Parallel Circuit

b. The source voltage (Es) is known. Total current (IT) is found by applying Ohm's Law, when total resistance (RT) is known. Since all three resistances are known, it is possible to compute RT by first finding combined resistance of the parallel circuit R2-3 using Equation 2-8. Equation 2-6 could also be used, but Equation 2-8 is simpler.

$$R_{2-3} = (R_2 x R_3) \div (R_2 + R_3) = (12x36) \div (12+36) = 432 \div 48 = 9\text{ohms}$$

c. Nine ohms may be substituted for the parallel branches, R2 and R3. Using Picture 18 and substituting R2-3 for R2 and R3, gives the circuit in Picture 19. The series-parallel circuit has been reduced to a simple series circuit with R2-3 equivalent to parallel resistances of R2 and R3.



Picture 23, Reduced Circuit

d. To solve for RT (this is a series circuit, so resistances are additive), use Equation 2-2 to find total circuit resistance.

$$R_T = R_1 + R_{2-3} = 3+9$$

$$R_T = 12 \text{ ohms}$$

e. With total resistance and supply voltage known, total current (IT) is found by applying Ohm's Law.

$$I_T = \frac{E_S}{R_T} = \frac{48\text{v}}{12\Omega}$$

$$I_T = 4 \text{amps}$$

f. Now that total current is known, the circuit is returned to its original format (Picture 20).

g. Voltage drop across R1 is determined by applying Ohm's Law.

$$E_1 = I_T x R_1 = 4a x 3\Omega$$

$$E_1 = 12 \text{ volts}$$

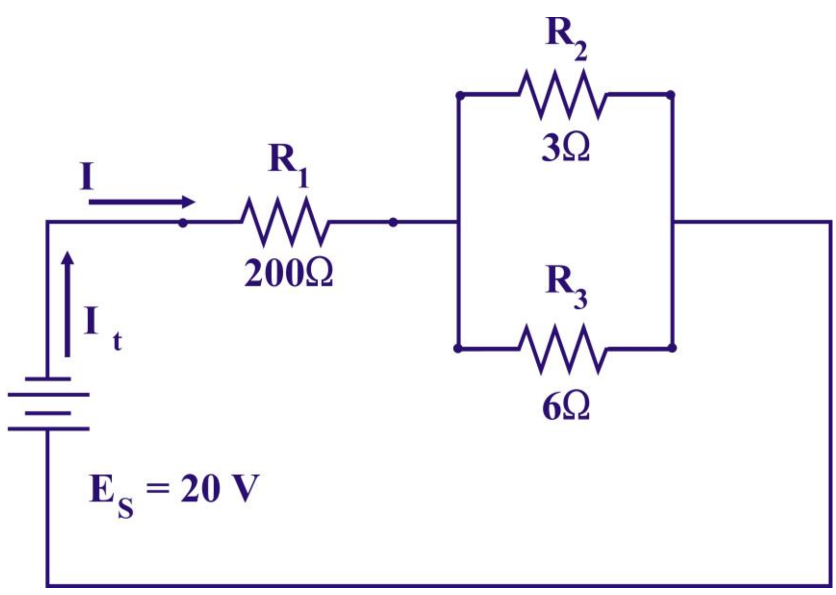
h. If the 48 volt source drops 12 volts on R1, then 36 volts (48-12=36) remain to be applied across the remaining resistances in the circuit. Voltages in a parallel circuit are equal (Equation 2-4). Therefore, 36 volts are dropped across R2 and 36 volts are dropped across R3. With this information I2 and I3 are computed by applying Ohm's Law.

$$I_2 = \frac{E}{R_2} = \frac{36}{12} = 3\text{amps}$$

$$I_3 = \frac{E}{R_3} = \frac{36}{36} = 1\text{amp}$$

i. To verify these values, recall that 4 amps were available (IT) to the circuit, and the sum of individual branch currents is 4 amps (3 + 1 = 4)

j. Examle: Solve for RT, IT, E1, I2, E2, I3 and E3.



Picture 24, Example Circuit

k. Answer:

1) Solve for the equivalent branch resistance in order to reduce the circuit.

$$R_{2-3} = (R_2 x R_3) \div (R_2 + R_3) = (3x6) \div (3+6) = 18 \div 9 = 2 \text{ohms}$$

2) Compute RT

RT=R1 + R2-3=2 + 2 =4 ohms

3) Determine IT

$$I_T = \frac{E_s}{R_T} = \frac{20}{4} = 5 \text{amps}$$

4) Determine E1

$$E_1 = I_T x R_1 = 5a\,x\,2\Omega = 10\,\text{volts}$$

5) Determine the branch voltage

$$E_{2-3} = E_S - E_1 = 20 - 10 = 10\,\text{volts}$$

6) Since R2 and R3 make up a parallel circuit, then:

E2 = 10 volts

E3 = 10 volts

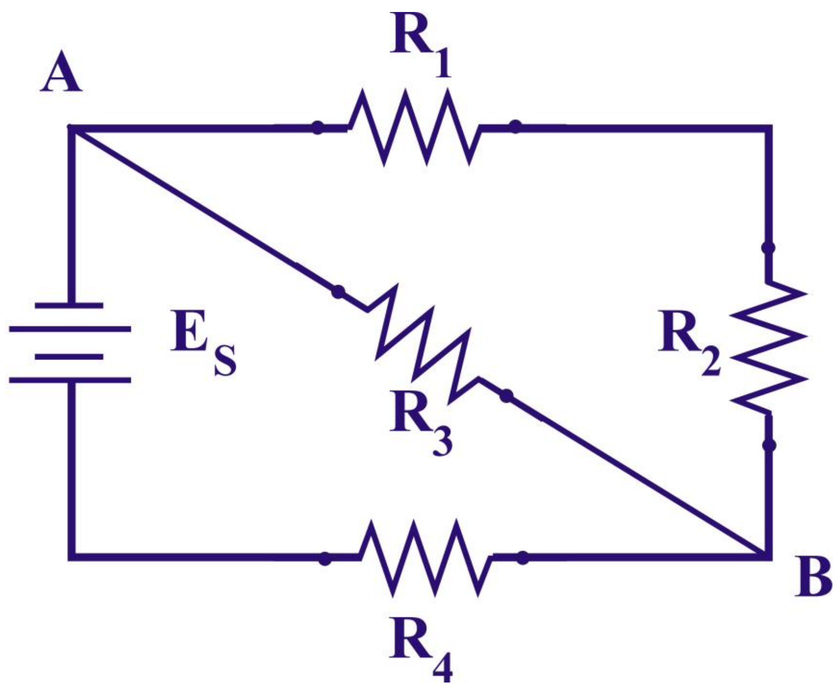
7) Solve for the individual branch currents by applying Ohm’s Law.

I2 = E2-3 ÷R2 = 10 ÷3 = 3.33 amps

I3 = E2-3 ÷R3 = 10 ÷6 = 1.66 amps

18. Redrawing

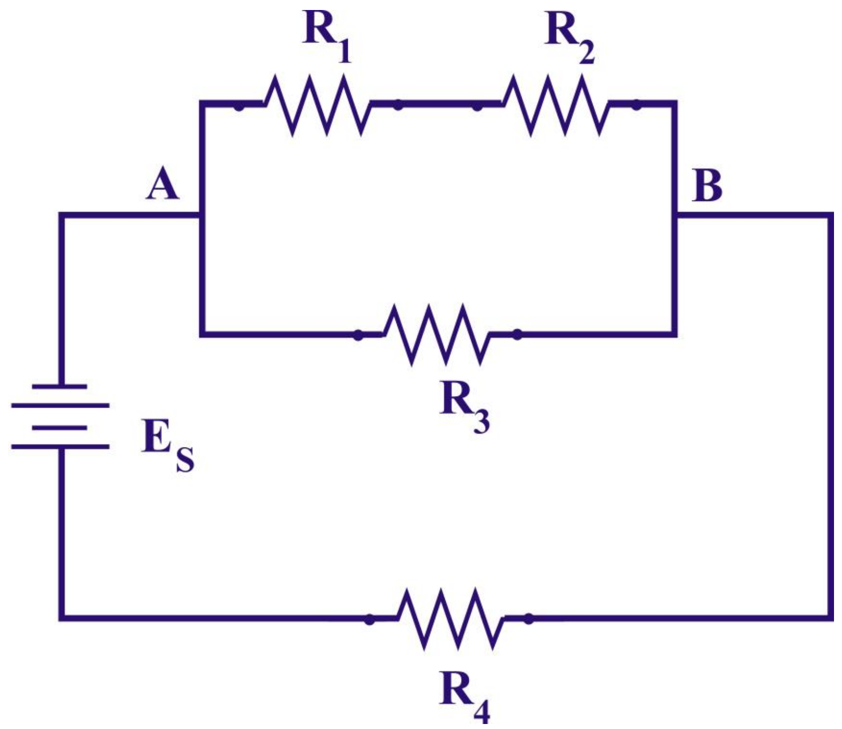
a. Analysis of series-parallel circuits is complex for another reason. Frequently, the circuit appears confusing because the series portions and the parallel portions are difficult to distinguish. This is why the term "complex" originated. An example of this is Picture 21. Loads are not easily identifiable as series loads or parallel loads. Branches are not as easily identifiable. Before utilizing the method of reducing a circuit it must be redrawn.



Picture 25, Series – Parallel Circuit

b. The purpose of redrawing is to make loads and branches more identifiable. When redrawing a circuit, a parallel branch starts whenever current must divide. In Picture 21, current must divide at point A. Some current flows through R3 and the rest flows through the R1-R2 branch. At point B current combines once again. At this point the parallel circuit ends. Current then flows through R4 and back to the voltage source.

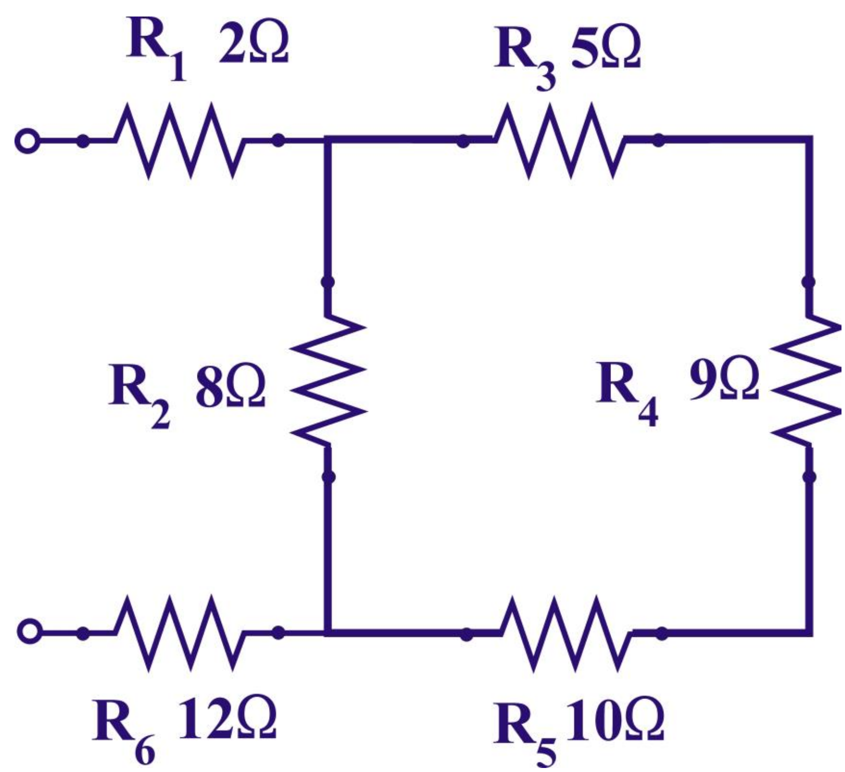
c. Redrawing Picture 21 results in Picture 22.



Picture 26, Series – Parallel Circuit

d. The various series and parallel paths are now easily recognizable. Redrawing is an important technique available in the analysis of series-parallel circuits.

19. Example: Find total resistance.

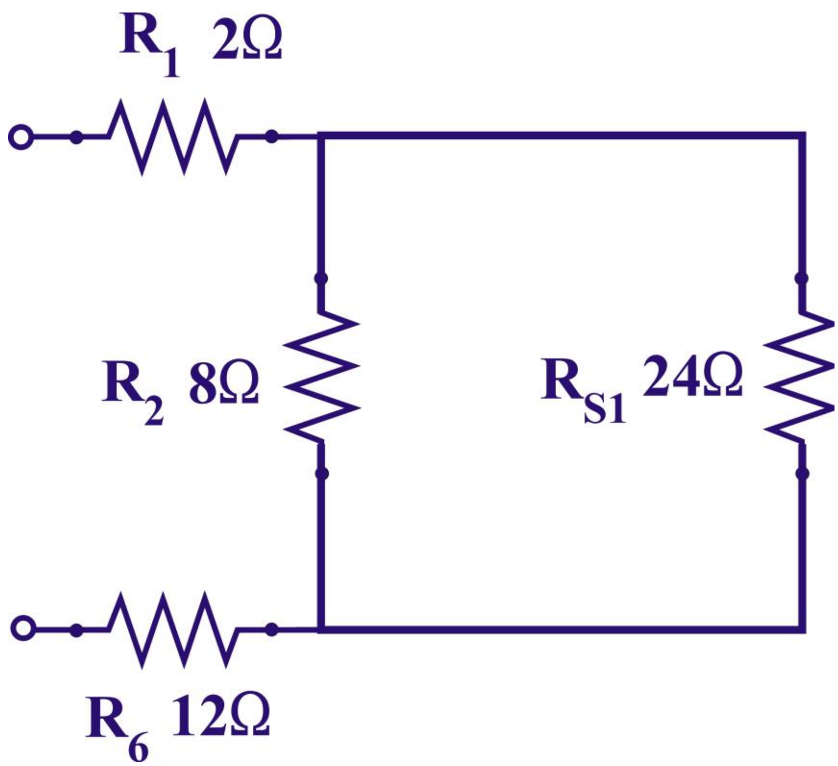


Picture 27, Example Original Circuit

20. Answer:

a. Determine the equivalent resistance of the series portion of the branch R_3, R_4, and R_5 and redraw the circuit.

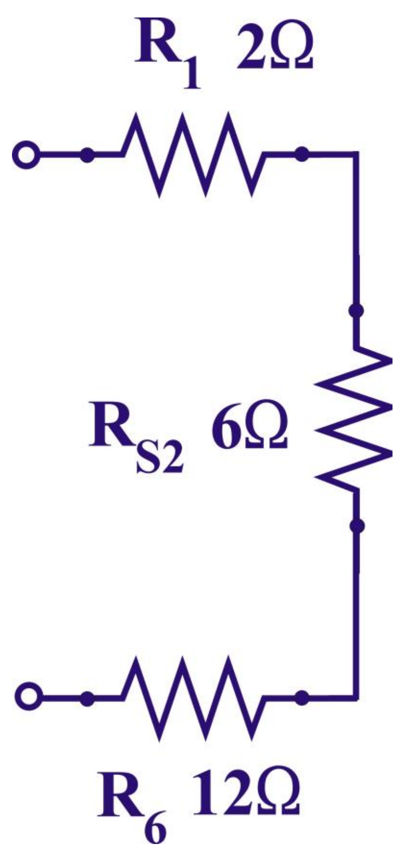
$$R_{S^1} = R_3 + R_4 + R_5 = 5 + 9 + 10 = 24 ohms$$



Picture 28, First Simplification

21. Calculate the equivalent resistance of the parallel circuit of R_2, and RS_1 and redraw the circuit.

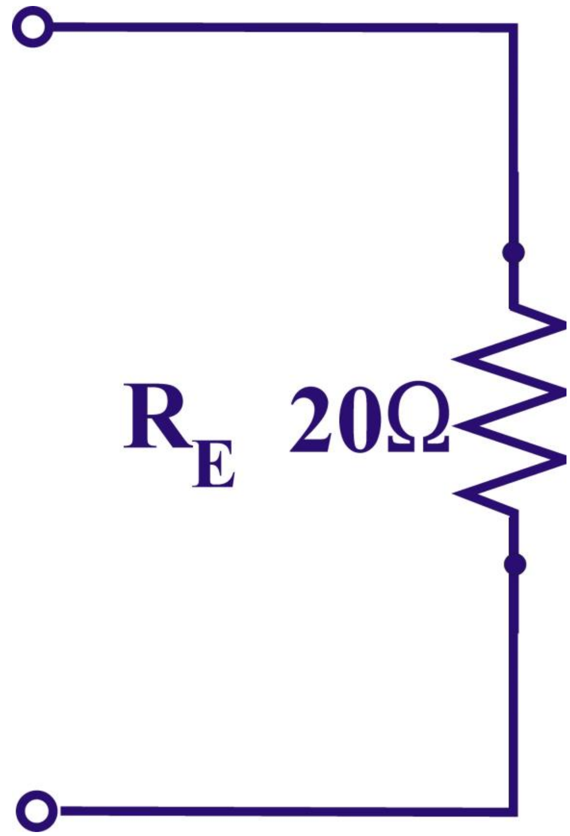
$$R_{S^2} = (R_2 \, x \, R_{S^1}) \div (R_2 \, x R_{S^1}) = (8x24) \div (8+24) = 192 \div 32 = 6 \, ohms$$



Picture 29, Second Simplification

22. Solve for the final total resistance for the simple series circuit R_1, R_{S2}, and R_6.

23. RT = R1 + RS2 + RE = 2 + 6 + 12 = 20 ohms



Picture 30, Equivalent Circuit Resistance

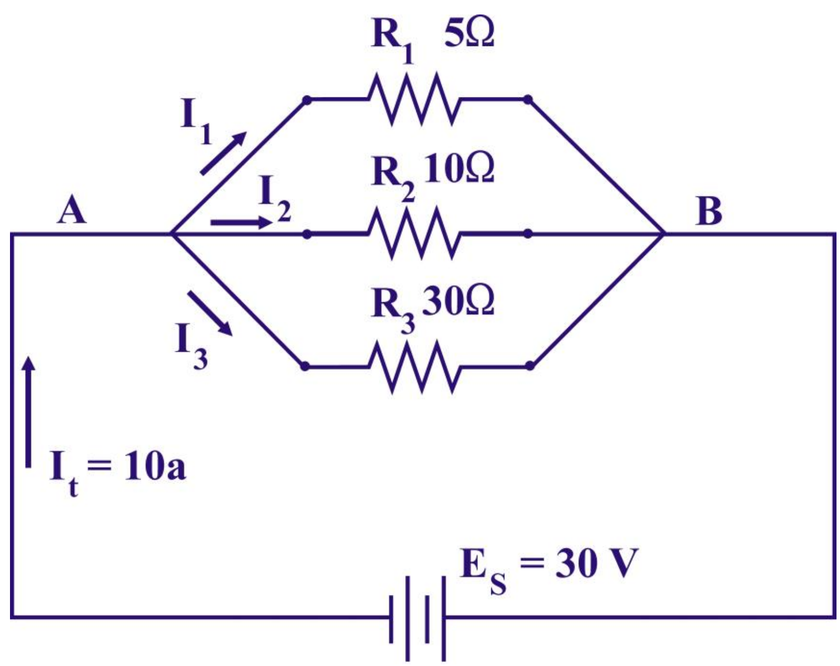
24. Kirchhoff's Laws

    a. Two laws can aid in the analysis of electrical circuits. They are Kirchhoff's current law and Kirchhoff's voltage law. These laws are very useful in the analysis of complex circuits.

25. Kirchhoff's Current Law

a. This law states that the current flowing into a given point in a circuit is equal to the current flowing away from that point. This is another way of saying that as many electrons leave a junction as enter it.

b. Electron current flow is from negative to positive. Keeping that in mind, note how current flow will be established in Picture 23.



Picture 31, Application of Kirchhoff's Current Law

c. To solve for I1, I2, and I3 use the known voltage applied to each branch of the parallel circuit. There are 30 volts across each branch of the circuit. By applying Ohm's Law, each of the branch currents can be found.

$$I_1 = \frac{E}{R_1} = \frac{30}{5} = 6\text{amps}$$

$$I_2 = \frac{E}{R_2} = \frac{30}{10} = 3\text{amps}$$

$$I_3 = \frac{E}{R_3} = \frac{30}{30} = 1\text{amp}$$

d. To verify these values, Kirchhoff's current law is applied. All current flowing into a point is assigned a positive value and all current flowing out of a point is assigned a negative value. Under these conditions, Kirchhoff's current law states:

IT=I1 + I2 + I3 or IT − I1 − I2 − I3 = 0

26. To apply this to Picture 23, compare current entering point A (IT) and the current leaving point A (I_1, I_2, I_3).

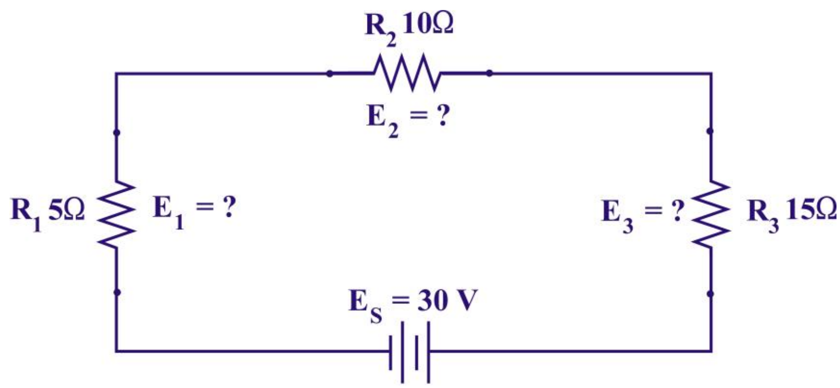
10 - 6 - 3 - 1 = 0

27. Since the above statement is correct, this verifies the values are correct.

28. Kirchhoff's Voltage Law

a. This law states that the algebraic sum of voltages in a closed loop is equal to zero. In other words, voltage drops must be equal to the total source voltage(s).

b. To find the voltage drops across R1, R2 and R3 in Picture 24 apply previously learned methods to compute the individual voltage drops and verify results using Kirchhoff’s voltage law.



Picture 32, Voltage Exercise

c. First, determine current flowing through the resistors. To do this, first determine the total resistance for series resistances and then apply Ohm’s Law to determine total current.

RT = R1 + R2 + R3 = 5 + 10 + 15 = 30 ohms

29. Thus,

$$I_T = \frac{E_S}{R_T} = \frac{30}{30} = 1\,\text{amp}$$

a. Next, determine the individual voltage drops across each resistance using Ohm’s Law.

E1=IT R1= 1 x 5 = 5 volts

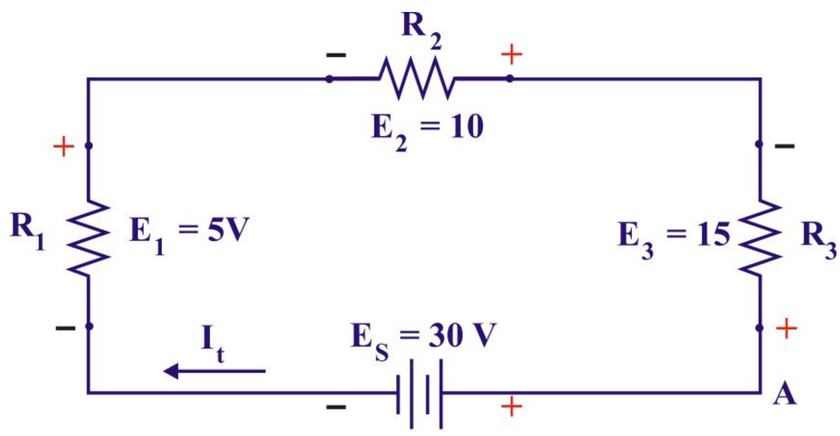
E2=IT R2= 1 x 10 = 10 volts

E3=IT R3= 1 x 15 = 15 volts

b. To verify these values, apply Kirchhoff's voltage law.

30. Since current flows from the negative to the positive terminal, voltage drop across a load must be negative where current enters the load and positive where current exits as shown in Picture 25. Kirchhoff's voltage law can then be expressed as:

$E_S - E_1 - E_2 - E_3 = 0$



Picture 33, Application of Kirchhoff's Voltage Law

a. To verify values for voltage drops, total all voltage in the circuit (starting at any convenient point). For this case, start with the voltage source (A).

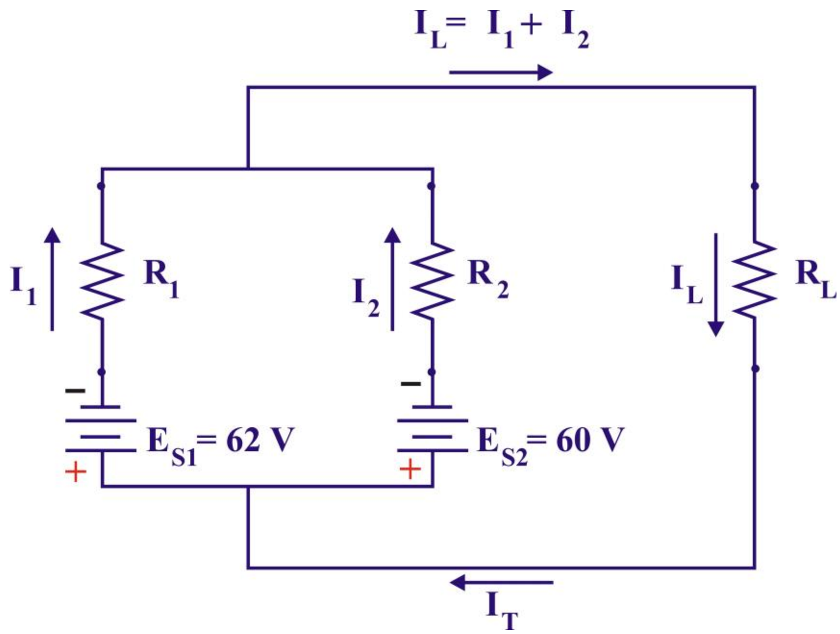
30 - 5 - 10 - 15 = 0

b. Since it is true, our computed values do not violate the law and are probably correct.

c. Kirchhoff's laws support rules used when working with series, parallel, and series-parallel circuits.

d. Kirchhoff's Voltage and Current Law Combined

e. Many complex circuits can be solved through simultaneous equations developed by application of Kirchhoff's laws. Picture 26 is an example of parallel power sources supplying a load.



Picture 34, Parallel Sources Supplying a Common Load

1) To solve this problem, write equations, applying Kirchhoff's voltage law, which includes E_{S1}, R_L and E_{S2}, R_L (start at common point below the power sources):

$E_{S1}-R_1I_1-R_LI_L=0$ (loop 1)

$E_{S2}-R_2I_2-R_LI_L=0$ (loop 2)

2) From Kirchhoff's current law, $I_L=I_1+I_2$. Substituting into the equations:

$E_{S1}-R_1I_1-R_L(I_1+I_2)=0$ (loop 1)

$E_{S2}-R_2I_2-R_L(I_1+I_2)=0$ (loop 2)

3) Inserting known voltages and resistances:

$62 - 2I_1 - 5(I_1 + I_2) = 0$ (loop 1)

$60 - 2.5I_2 - 5(I_1 + I_2) = 0$ (loop 2)

4) Simplifying:

$62 - 7I_1 - 5I_2 = 0$ (loop 1)

$60 - 5I_1 - 7.5I_2 = 0$ (loop 2)

5) Make I_2 in loop 1 equation equal to I_2 in loop 2 equation by multiplying by 1.5, then subtract the equations.

$I_1 = 6a$

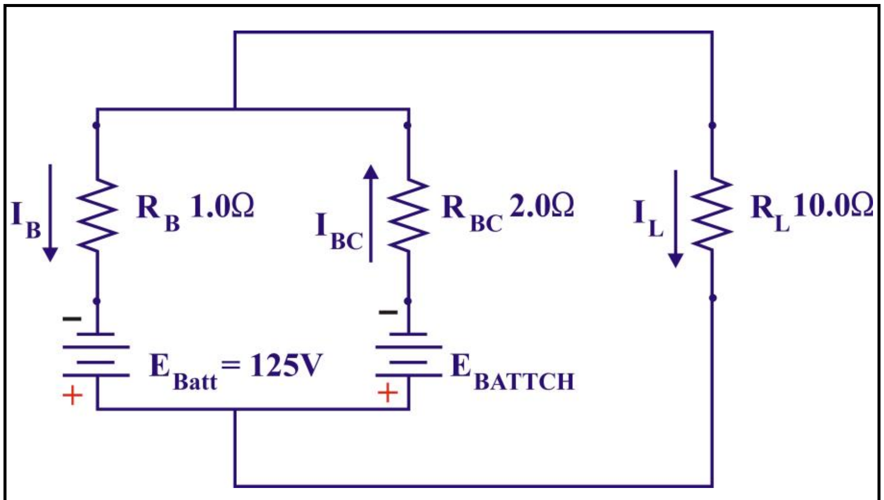
6) Substitute I_1 in a simplified equation and solve for I_2

$$62 - 7I_1 - 5I_2 = 0$$
$$62 - 7(6) - 5I_2 = 0$$
$$20 - 5I_2 = 0 = 4a$$

7) Obtaining voltage drops across resistors:

$$E_1 = I_1R_1 = (6)(2) = 12v$$
$$E_2 = I_2R_2 = (4)(2.5) = 10v$$
$$E_3 = I_LR_L = (I_1 + I_2)(5) = (6 + 4)(5) = 50v$$

f. Example: Find the battery charger voltage (EBATTCH) in the below circuit



Picture 35, Example Circuit

31. Answer:

a. Find E_L using Kirchhoff's voltage law. Note E_b is additive to E_{BATTCH} because current is reverse (charging). Start at the junction below the voltage sources and go through R_L.

$$E_{BATT} + I_B R_B - E_L = 0$$
$$125 + (5)(1.0) - E_L = 0$$
$$E_L = 130\text{v}$$

b. Find I_L using Ohm's Law

$$I_L = \frac{E_L}{R_L} = \frac{130}{10} = 13\text{a}$$

c. Find I_{BC} using Kirchhoff's current law at junction above voltage sources

I_{BC}-I_B-I_L=0

I_{BC}-5-13=0

I_{BC}=18a

d. Find E_{BC} using Ohm's Law

$$E_{BC} = I_{BC}R_{BC} = 18x2 = 36v$$

e. Find E_{BATTCH} using Kirchhoff's voltage law. Start at the junction below the voltage sources.

E_{BATTCH}-E_{BC}-E_L=0

E_{BATTCH}-36-130=0

E_{BATTCH}=166v

32. Electrical Power

a. The Watt

1) The basic unit of electrical power is the watt (W). It is energy expended or work done per second by a current of 1 amp flowing under an electromotive force of 1 volt. In other words, one watt is equal to 1 joule per second.

b. Power Equations

1) Power can be expressed as:

P = I x E or P = IE

where: P = power (watts)

I = current (amps)

E = voltage (volts)

2) Example

a) What is the power used by an electric lamp that draws 2.5 amps from 120 volt source?

b) Answer:

P = IE = 2.5 x 120

P = 300 watts

3) That a watt is a unit of power cannot be emphasized too strongly. Current in amperes is a rate of flow of electricity and is equal to the number of coulombs per second. The power formula is written:

$$\text{Power in watts} = \frac{\text{coulombs x volts}}{\text{seconds}}$$

4) The watt measures the rate a quantity of electricity is moved through a difference in potential. Power used in a circuit (or by a device) is always additive.

PT=P1+P2+P3+Pn

5) In Ohm's Law, E = IR, the value of E is substituted to obtain another useful power formula.

P = I x E = I x IR

or

$P=I^2R$

6) Even conductors have a small amount of resistance. This implies that whenever current is flowing through a conductor, power is being used. This power is observable in the form of heat and is often referred to as "I squared R losses."

7) Example

What is the power used in a 60 ohm generator field rheostat when the field current is 2 amps?

8) Answer:

$P=I^2R$

$P=(2)^2 60=4 \times 60 = 240W$

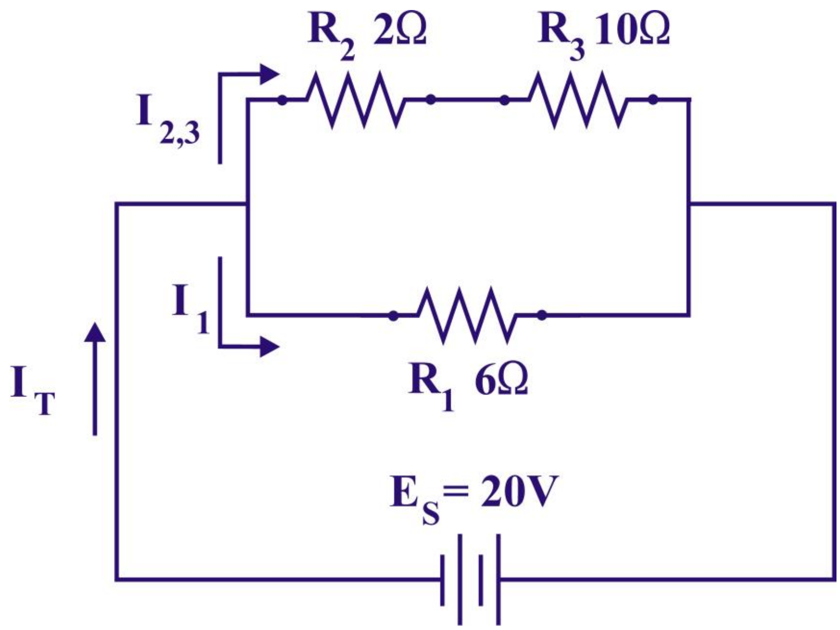
9) A third power formula is derived from I = E/R (Ohm's Law).

$$P = I \times E = \frac{E}{R} \times E$$

or

$$P = \frac{E^2}{R}$$

10) Example: Calculate total power used in the circuit shown in the diagram below.



Picture 36, Example Circuit

11) Aswer:

a) Solve for $R_{2,3}$

$R_{2,3}=R_2+R_2=2+10=12$ ohms

b) Solve for the equivalent resistance of the parallel circuit

$R_T = (R_1 x R_{2,3}) \div (R_1+R_{2,3})$

$= (6 \times 12) \div (6 + 12)$

$= 72 \div 18 = 4$ ohms

c) Solve for power

$$P = \frac{E^2}{R_T} = \frac{(20)^2}{4} = \frac{400}{4} = 100 \text{ watts}$$

12) The watt is a small unit, so a larger unit, the kilowatt (kW), is often used instead. One kilowatt is equal to 1,000 watts.

13) Example: The input to a motor is 20 kW. What is the horsepower input? Recall that 746 watts equal one horsepower.

14) Answer:

20 kW = 20 x 1,000 = 20,000W

$$\text{horsepower} = \frac{W}{746} = \frac{20{,}000W}{746} = 26.8\text{hp}$$

15) For most purposes, the relation between horsepower and kilowatt is 1 hp = 3/4 kW (approximately).

33. In Summary

1) With knowledge of behavior of voltage, current, resistance, and power, and use of their associated equations, the student should be able to interpret basic electrical circuits.

2) The control room operator constantly operates pumps, electrical switch gear and control systems. This means the operator is constantly changing a circuit arrangement and load. It is important for the operator to understand the effect of actions on electrical circuits and the plant electrical distribution systems.

3) Some key items of this chapter should be reviewed.

4) An electrical circuit is any path through which current is allowed to flow from an electrical source and back to the source. A closed circuit is the same, but usually includes some resistance or load. An open circuit is any arrangement which prevents flow of current. A short circuit is a circuit which develops a relatively low resistance between terminals of the voltage source. This source of low resistance could be anything from water between insulated contacts to a fallen power line using the earth as a conductor.

5) Electrical loads and sources can be arranged many ways. If loads are arranged end-to-end, and the current has only one path to follow, then it is a series circuit. If loads are arranged so that current must divide and take separate paths through the circuit, it is a parallel circuit. If the circuit consists of a combination, both series circuits and parallel circuits, it is a series-parallel circuit.

6) Rules to use when solving for voltage, current, or resistance in series circuits are different from those used when working with parallel circuits. In a series circuit, current is the same on all parts of the circuit. Total voltage equals the sum of individual voltage drops across the individual resistances. The total resistance equals the sum of resistances of the separate parts.

7) In a parallel circuit, the total current supplied equals the sum of individual branch currents. Total voltage across a parallel combination is the same as the voltage across each branch. Total resistance is equal to the reciprocal of the sum of the reciprocals of each resistance. When connected in parallel, total resistance will always be less than the smallest resistance involved.

8) To understand a series-parallel circuit, two basic processes are helpful. One is called reducing. This technique involves systematically simplifying various parts of the circuit until only a simple series circuit remains. The other process, called redrawing, is used when circuits get so complex that individual series circuits and parallel circuits cannot be distinguished easily. In this technique the circuit is redrawn in a familiar layout so individual circuits can be identified.

9) Kirchhoff's voltage law states that the sum of voltage drops in a circuit must be equal to the sum of voltage rises. This law is most

helpful when applied to series circuits, or other circuits which have been simplified to their equivalent series form. Kirchhoff's current law states that current flowing into a given point must be equal to current flowing out of that point. This law is most useful when dealing with current flow in and out of nodes in a parallel circuit.

10) Anytime current flows through a resistance, even a very low resistance such as wire, power is used. The basic unit of power is the watt (W) and it is defined as the power expended when 1 ampere of current flows through a resistance of 1 ohm, or the energy required to do work at the rate of 1 joule per second. Total power in a circuit is the product of total current flow in the circuit times the voltage applied.

11) Information in this chapter will be used extensively in future chapters to explain the operation of batteries, motors, and generators. Concepts and uses of voltage, current, resistance, and power are fundamental when any electrical circuit or device is discussed.

PRACTICE:

1 What is an electrical circuit?

2. What is a series circuit?