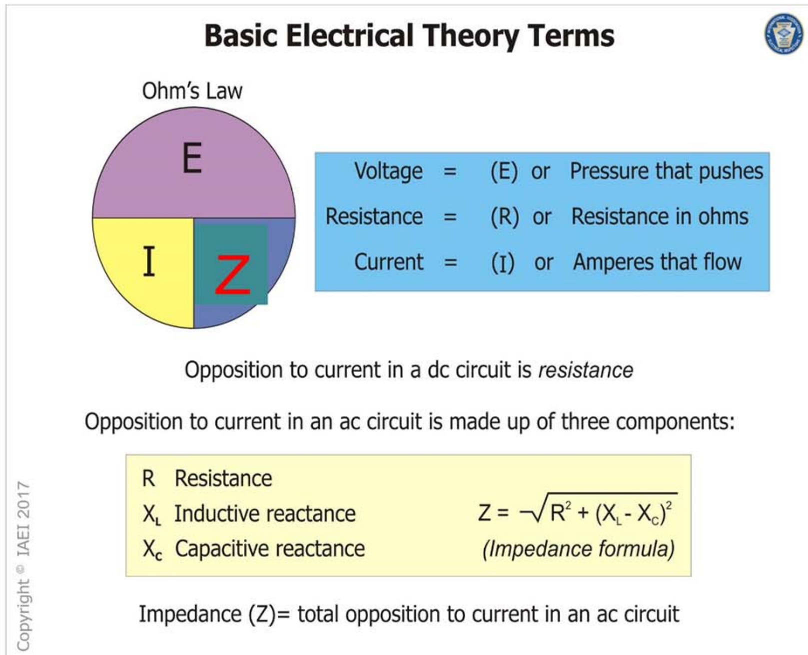
# OHM'S LAW

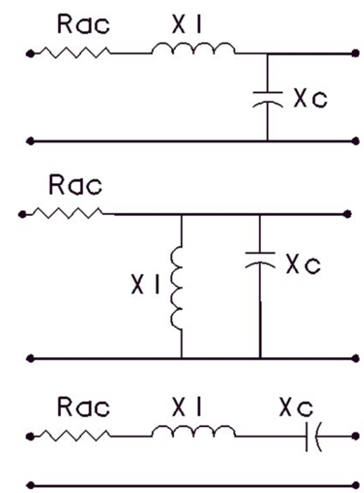
- Ohm's Law is : E= I Z and not E = I R !!
- Ohm's Law: The voltage potential difference [E or V] across a electrically conductive material is directly proportional to the resistance [R] (impedance [Z]) of the material and the current [I] flowing through the material.

  E = I x R alternately E = I x Z
- The formula that you should use for power systems is the second one because in systems where the current is not direct current [DC] such as our AC power systems or varying currents like transients or lightning currents resistance is only one component of Z.
- The impedance $Z = R + j(X_L - X_C)$ where $X_L$ and $X_C$ (series capacitance) vary with the frequency or rate of change of the current
- $X_L = 2\pi f L$ and $X_C = \frac{1}{2\pi f C}$
- The AC resistance of a conductor varies slightly with frequency due to skin effect
- Most of the analysis we will use is such that capacitive reactance is not important so : $Z = R + jX_L$










This basic slide which appears in Soares' book should be changed. The Ohm's law circle diagram should have Z in place of R.

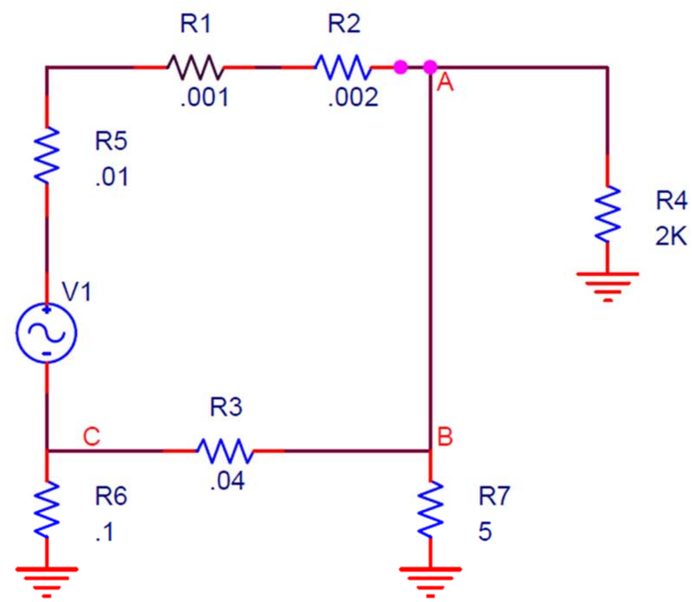
Remember: The series capacitive reactance Xc in the Z formula above and in Soares is so small at power frequencies it is practically zero for all conductors. Insulated conductors have a parallel capacitive reactance but not a series capacitance and while the capacitive reactance will subtract from the inductive reactance as shown in the formula, you should be careful in misusing this formula. The effective series impedance of a circuit, input verses output, varies depending upon the configuration of R, Xl, and Xc and frequency. In the three R,L,C circuits above, the uppermost one is the one that would model our phase, neutral, and equipment grounding conductors we will be studying.. Transformer and motor windings would look different.

# ELECTRICAL CIRCUIT THEORY KNOWLEDGE BASE

- In order to get the maximum benefit from this course and to understand WHY behind the principles of grounding we wil cover, you should be comfortable with the following concepts and formulas
  - Compute voltage drops for AC and DC circuits using Ohm's Law:

    $$E = I \times R = I \times Z$$

  - Combine series and parallel resistances and inductances into a single equivalent
  - Solve a circuit such as the one shown to determine voltage potentials between any of the nodes ( A, B, C, and ground) shown in the circuit diagram to the right
  - You should also be familiar with the voltage divider rule which greatly simplifies the analysis
  - Another concept that helps is knowing how to build a Thevenin equivalent circuit to break this system down into more manageable pieces







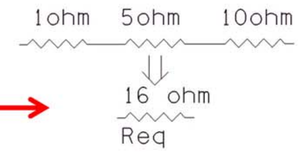
The basic circuit above is representative of a basic system comparable to the grounding systems we will be discussing. You can think of the source V1 representing the voltage from a typical transformer. The resistances R1, R2, and R5 the resistances or impedances of the transformer and phase conductor. R3 the impedance of the equipment grounding conductor and R6 and R7 the resistance of the grounding electrodes imbedded in the earth. The resistance R4 might represent some other higher resistance path such as the human body.

# EQUIVALENT RESISTANCE FORMULAS

- Two or more resistors in series you merely add the resistances to form a single equivalent resistor Req

  Req = R1 + R2 + R3 +…..

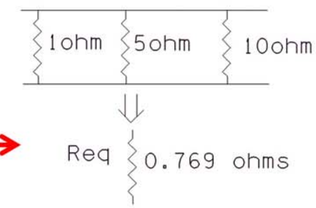
  Note: Req will always be greater than the largest resistor's value




- For two or more resistances in parallel you can reduce them to form an equivalent resistor Req by adding the reciprocals of the resistances

  1/Req = 1/R1 + 1/R2 + 1/R3 +…..)

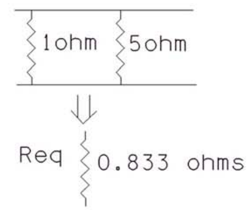
  Note: Req for will always be smaller than the value of the smallest resistor




- If you have two resistors in parallel

  Req = R1 x R2 / (R1 + R2)

  Can use this formula in place of the other by breaking the system down into pairs of resistors in parallel








These are the basic resistance reduction formulas we will use within this course. While we could use the formulas for impedances by just replacing R with Z, it would not be as easy because we would need to worry about angles between R and X of the impedance. Nevertheless, many times we would not be loosing that much accuracy in our power circuits by just treating R and Z the same.

When using these reduction formulas keep in mind the notes highlighted above in green. If during your computations you get an answer that does not comply with those notes. you have made a mistake. If your cannot remember the basic formula for parallel resistors in the second bullet, memorize the last one. You will get the same answer. For example if we took the second circuit with a 1, 5, and 10 ohm resistors in parallel, we could reduce it in two steps by first combining two resistors, such as the 1 and 5 ohm and then combine that equivalent resistor with the 10 ohm. Doing so we would get for the 1 and 5 ohm combination: Req = 1 x 5/(1+5) = 5/6 = .833 ohms. Then combining that equivalent with the 10 ohm resistor we get: Req = .833 x 10 / (.833+10) = 8.33 / 10.833 = 0.769 ohms.

It is very important you get used to using the first and last formulas above as they will allow you to visualize equivalent circuits more readily. You will also find that when some R values are very large or very small compared to other R values they can have a minimal effect on the Req for the series or parallel circuit. For instance in the upper series circuit the impact of the 1 ohm resistor is very negligible compared to that of the 10 ohm resistor. Conversely in the second diagram the 10 ohm resistor has very small impact on the Req reduction.

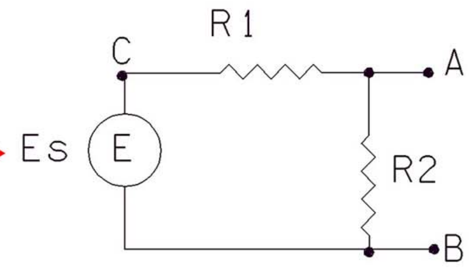
# VOLTAGE DIVIDER FORMULA

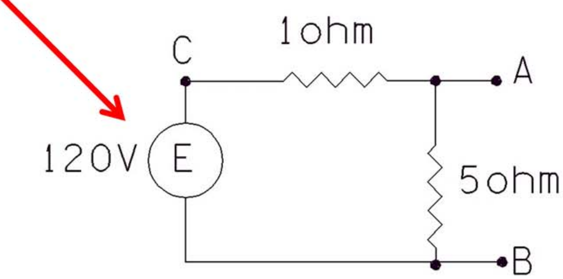
- In any circuit we can compute the voltage across a combination of resistors or impedances using the voltage divider formula
- Basic formula for two impedances or resistors in series (diagram to right)
- Voltage between A and B (Eab)

  Eab = Source voltage (Es) x R2 / (R1 + R2)
- Example: Source = 120V and resistors shown in diagram.
- Eab = 120 x [5 / (1 + 5)] = 120 x 5/6 = 120 x 0.833 = 100V
- If we wanted the voltage between A and C (Eac) we would flip the R1 and R2 in the formula and get:

  Eac = 120 x [1/(1+5)] = 120 x 1/6 = 120 x 0.167 = 20V

  Notice: That Eab + Eac = Es. We have satisfied the basic circuit law that all of the voltage drops around a loop have to add up to the source voltages in that loop.







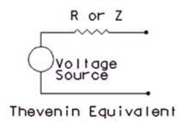

We will be using Thevenin’s Theorem next in circuit reduction and to do so we will need to compute open circuit voltages at different points of the system. The voltage divider rule comes in very handy for reducing a circuit according to Thevenin’s Theorem.

Notice that the voltage divider rule is simply applied by picking the resistor or impedance you would like to know the voltage across. That would become the resistance in the numerator. Then divide that resistance by the sum of all of the series resistors in the loop back to the source. If the resistor you want the voltage across consists of resistors in series or parallel, first reduce the series or parallel set to one equivalent resistor using the formulas in the previous slide, then apply the voltage divider rule. Just break the circuit up into smaller manageable portions.

# THEVENIN CIRCUIT REDUCTION

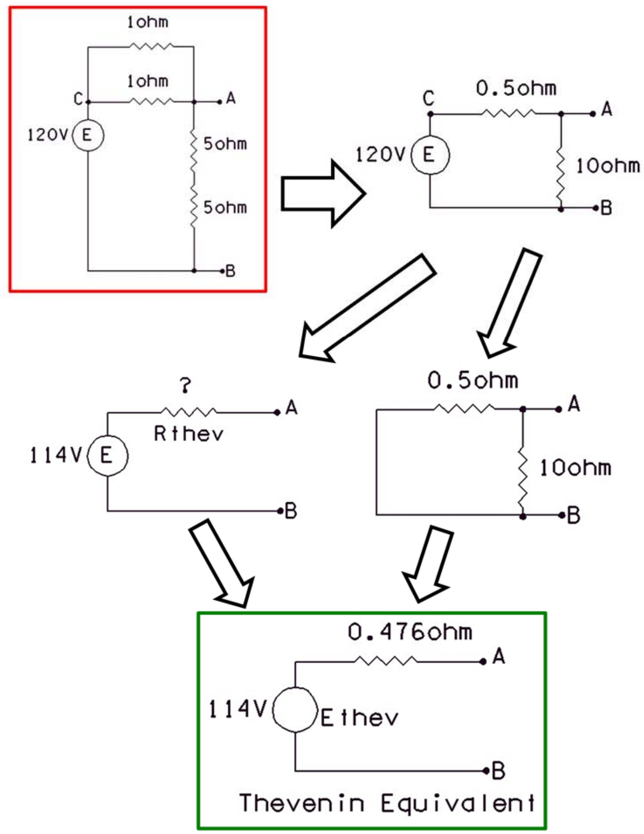
Using Thevenin circuit reduction methods we can simplify circuits such that the voltages important to us in grounding system design are more apparent

- Goal: Reduce a system of voltage sources and impedances to the equivalent of a single voltage source in series with a single impedance




Reduction steps:

1. Pick a branch or points in a circuit where you are interested in the voltage or current flow
2. Compute the voltage across the points looking back to the power source as if the rest of the circuits did not exist. That becomes the Thevenin equivalent voltage source.
3. Compute the Thevenin equivalent impedance of the circuit looking back towards the source with the voltage source replaced by a short circuit using standard resistance and impedance formulas.
4. Repeat the reduction as necessary until you have a single voltage and impedance representing the system you are interested in

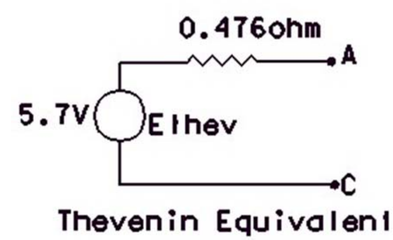







If we were interested in the circuit performance between terminals A and C, we could reduce that to a Thevenin equivalent the same way. The Ethev for terminals A and C could be found using the voltage divider rule. This would give us a new Ethev of: 120V x 0.5/10.5 = 5.7 ≈ 6 V.

We would use the same resistance formulas to find Rthev and it would not change in this case because it would just be the same 0.5 and 10 ohm resistors in parallel. Thus, our equivalent circuit from terminals A to C would be that shown below.




If we had the basic circuit above outlined in red and we wanted to know what voltage we would read across terminals A and B we could write some loop equations and solve them. That would require solving two simultaneous equations because there are two loops! If we shorted the terminals A and B, we could compute the current that would flow between A and B. However, how we have three loops so to speak. Instead of using simultaneous equations, we can also simplify the circuit using Thevenin's Theorem and our resistance and voltage divider rules and reduce the circuit down to the one shown in green.

We now know that if we place a high-impedance voltmeter across terminals A and B we would measure 114V. If we shorted terminals A and B, we would see 114V/0.476 ohms = 239.5 amps flowing by just using Ohm's Law.