SECTION 5
Electrical Principles

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ELECTRICAL PRINCIPLES

The Electrical Principles section of this publication has been included for those who do not have a strong background in electrical principles or circuit theory. It is a very basic presentation. Those with prior knowledge may wish to skip over this and proceed to the next section.

Ohms Law

The simple use of Ohm's Law is all that is really needed to understand the theory of protective grounding. The study could be made more complex by considering the inductance associated with alternating current, but because many of the values are based on assumptions the additional complexity is not believed to be necessary for this basic presentation.

One of the first laws learned when studying electricity is Ohm's Law. It gives a fundamental relationship to three electrical quantities. These are voltage, current and resistance. If any two of them are known, the third can be calculated. Using basic algebra, the relationship can be rearranged into three forms depending upon which quantity is the unknown.

$$V = I \times R \quad \text{or} \quad I = V / R \quad \text{or} \quad R = V / I \qquad \text{(Eq. 2)}$$

Where: V = voltage, in Volts
I = Current, in Amperes
R = Resistance, in Ohms

A related quantity is power. Power is the product of multiplying the voltage times the current.

$$P = V \times I \qquad \text{(Eq. 3)}$$

Where: P = power, in watts

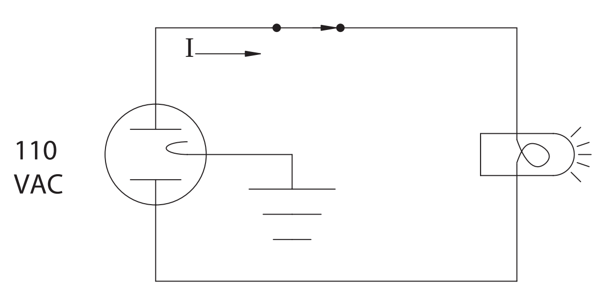
Equation 3 can be rearranged into other useful forms by substituting the appropriate form of Equation 2 for either the V or the I in Equation 3. The resulting modifications are:

$$P = I^2 \times R \quad \text{or} \quad P = E^2 / R \qquad \text{(Eq. 4)}$$

Electrical circuits are connected in series configurations, or parallel configurations or a combination of both. Ohm's Law can be applied to all three variations as follows.

Series Circuits

The simplest circuit is the series circuit consisting of a voltage source, a connected load and the interconnecting wiring. To illustrate a series circuit, consider the following example. The source is a 110 Volts AC (VAC) wall outlet. The load is a single lamp and the wiring is the cord between the lamp and the wall outlet. When the lamp is plugged in and turned on, current flows from one terminal of the outlet through one of the wires to the lamp, through the bulb and back to the outlet through the other wire. The circuit is shown in Fig. 5-1. In completed circuits, if the voltage and resistance are known, the current can be calculated using Equations 2, 3 or 4.



Simple Series Lamp Circuit
Fig. 5-1

Every current carrying part of a circuit has some resistance. Current flowing through any resistance creates a voltage drop spread over the resistive component. If all of the small and large voltage drops are added together, they equal that of the source voltage, or the wall outlet in this case. In the example, the resistance of the connecting wire is sufficiently small compared to that of the bulb, so it could be ignored (but this is not always the case).

In our example, let us assume the outlet voltage is 110 VAC and the lamp has a 100 W bulb. By substituting these values in Equations 2 and 3, the current and resistance can be determined.

P = I x V   or   100 W = I x 110 VAC

Solving for current (I) we get:

I = 100 Watts / 110 Volts or 0.91 Ampere

And resistance

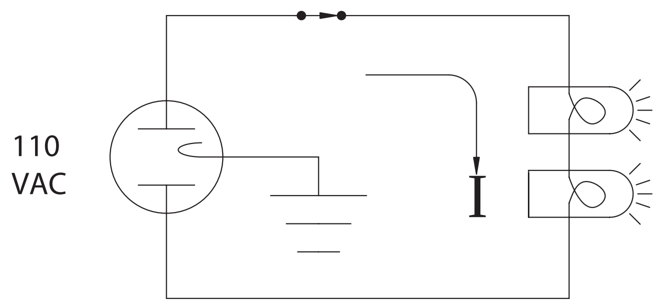
$R = (110\ VAC)^2 / 100\ Watts =$
121 Ohms

When a second lamp is connected in series with the first, the resistance of the load as seen from the wall outlet has changed. Therefore, the current changes. This is shown in Figure 5-2. The source voltage remains constant at 110 VAC. We would expect two lamps of equal size to present twice the load (or resistance) to the source. Equation 2 tells us that if we double the resistance, the current will be half the previous value for a constant voltage.

I = V / R or I = V / 2R now, which is
110 VAC / 242 Ohms

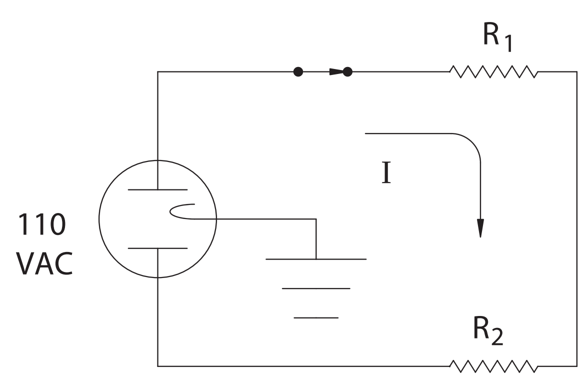
I = 0.454 Amp.

As expected, the current is now half the previous value. Remember, the source voltage remained 110 VAC but consider what happens at the load. Because the bulbs are the same size, the voltage divides equally across each. Remember that the sum of the voltage drops around a circuit must equal the source. We expect each bulb to have only 55 VAC across it and the individual brightness of each to be diminished.



Two Lamps in Series
Fig. 5-2

For simplicity, our examples use light bulbs as loads. However, the same principle applies to other loads. Substitute for the bulbs any other circuit component that has resistance. This can include a length of conductor, a transformer, motor or a combination of loads. The circuit current and voltage drops will adjust themselves based upon the resistance values of each of the components in the circuit. Figure 5-3 shows the same circuit with the lamps replaced by the electrical symbol for resistance.

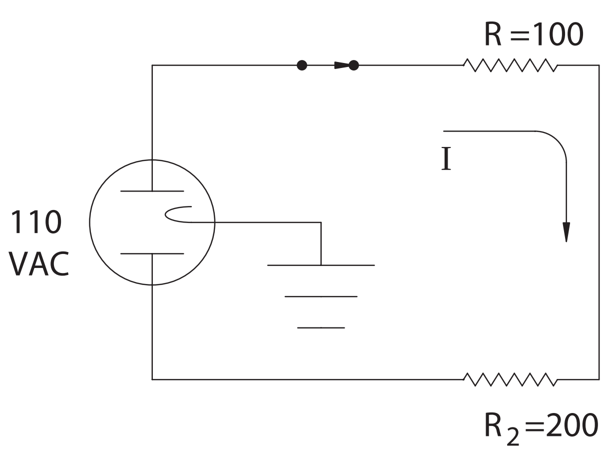


Series Circuit Using Common Symbols
Fig. 5-3

This brings us to a key point. If the resistances are not equal, the voltage drop across each component also will not be equal. The voltage on each component will be a fraction of the total applied voltage. The fraction is determined by the percentage of the component's resistance compared to the total resistance in the circuit.

Again referring to Equation 2, if the voltage applied to the series circuit and all component resistances are known, any component's voltage drop can be calculated by determining its fraction of the total resistance times the applied voltage. With the component's voltage and resistance now known, the components current can be determined which is also the circuit current in a series circuit. Or, if the available current and the resistance of a component is known, calculations can be made for the voltage drop across that component. Applications of these calculations are shown in later sections.

A circuit with unequal resistances is shown in Figure 5-4. Two resistances are in series, a 100-Ohm and a 200-Ohm, and they are connected to a 110-volt source.



Series Circuit with Unequal Resistances
Fig. 5-4

Each resistor's voltage drop is calculated using Equation 2 as follows:

R_{total} = 100 Ohm + 200 Ohm = 300 Ohm

I_{total} = 110 Volt / 300 Ohms = 0.367 amp.

Calculated individually:

Voltage drop across the 100 Ohm:

= I x R = 0.367 amp. x 100 Ohm
= 36.7 Volts

And

Voltage drop across the 200 Ohm:

= 0.367 amp x 200 Ohm = 73.3 Volts

Or voltage calculated as a percentage of the total:

Voltage across the 100 Ohm:

= (100 Ohm / 300 Ohm) x 110 Volts
= 36.7 Volts

And

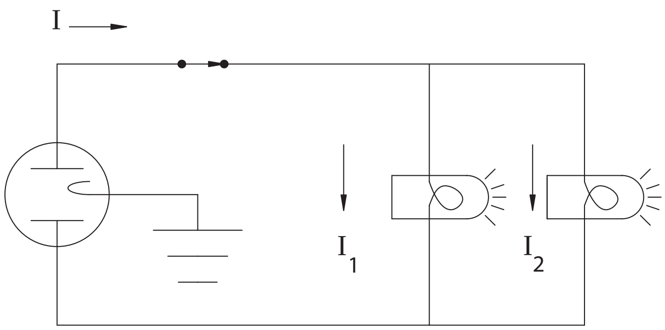
Voltage across the 200 Ohm:

= (200 Ohm / 300 Ohm) x 110 Volts
= 73.3 Volts

In either calculation, the voltages add up to equal the 110-Volt source voltage.

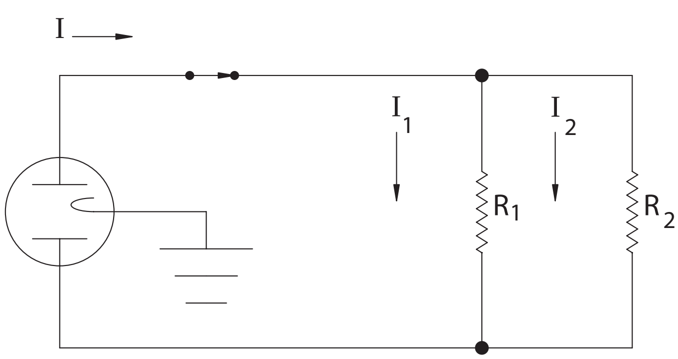
Parallel Circuits

Not all circuits are connected in series as described in the previous section. Another basic configuration is the parallel circuit. Consider our two 100 W lamps from before, but now connected in parallel as shown in Fig. 5-5. The wall outlet remains 110 VAC. In this case each lamp passes the full 0.91 amp of current as before, because the voltage across it is the full 110 VAC. The wall outlet is now supplying a total of 1.82 amp, because each lamp draws the full current. **The sum of the branch currents must equal that supplied.**



Parallel Circuit
Fig. 5-5

In this case, again the lamps have equal resistance and the current divides equally between the two paths. If there are unequal resistances, the current divides in inverse proportion to their resistances. That is, the lower the resistance of the path, the more current goes through that path. **This is the foundation principle of personal protective grounding, placing a very low resistance jumper in parallel with a much higher resistance worker.** Figure 5-6 shows the parallel circuit with the lamps replaced by the electrical symbol for resistance. Equation 5 shows the calculations for this circuit.



Parallel Circuit
Fig. 5-6

For example:

$$I_1 = \frac{R_2}{(R_1 + R_2)} \times I_{TOTAL} \qquad \text{Eq. 5}$$

(Remember, current divides in inverse proportion to the total resistance)

If R_1 represents a line worker and R_2 the personal protective jumper, the equation becomes:

$$I_{MAN} = \frac{(R_{JUMPER}) \times I_{AVAILABLE}}{(R_{MAN} + R_{JUMPER})} \qquad \text{Eq. 5a}$$

Resistances in parallel circuits can be reduced to a single, equivalent value for use in calculations. This is done by:

$$\frac{1}{R_{TOTAL}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots\ldots \frac{1}{R_{LAST}} \qquad \text{Eq. 6a}$$

A simplified form of Equation 6a when dealing with only two resistances is found by algebraically rearranging the equation. Remember R_1 and/or R_2 could be the sum of a series of resistances.

$$R_{TOTAL} = (R_1 \times R_2) / (R_1 + R_2) \qquad \text{Eq. 6b}$$

A key point in parallel circuits is that some current will flow through every possible path. The current magnitude in each path will depend upon the resistance of each path. The only means of completely eliminating current flow is to eliminate the path.

In any circuit a voltage drop is developed only if current flows through the resistive element. And, the larger the resistance, the larger the voltage drop, as shown in Fig. 5-7.

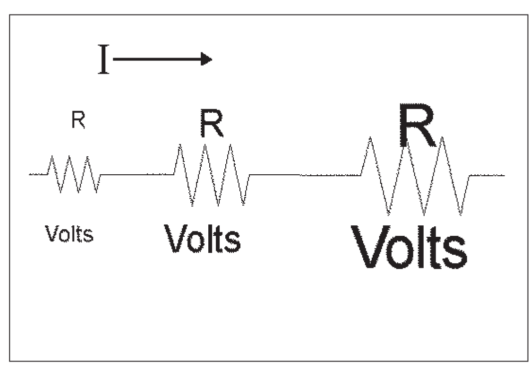


Fig. 5-7

Combination Series/Parallel Circuits

The real world is filled with circuits. Few are as simple as the pure series or parallel ones described above. Most are combinations of series and parallel connections. The typical worksite is an example of this. Consider a de-energized single-phase source connected to the conductor feeding the worksite (series). A worker is standing on a wood pole above a cluster bar in contact with the conductor with a jumper bypassing him (parallel). The cluster bar is connected both to the Earth and to the return neutral (parallel). Perhaps, also, it is connected to an overhead static line (additional parallel). The cluster bar is also bonded to the pole, and per the OSHA acceptable methods of grounding for employers that do not perform an engineering determination found in 1910.269 Appendix C, should also be in conductive contact with a metal spike or nail that penetrates the wood at least as far as the climber's gaffs.

As complicated as this appears, it can be reduced to a simple equivalent circuit for ease of analysis. To do so requires the determination of the resistances of the conductor, neutral, safety jumpers and the possible static wire. A realistic estimation can be used, because the normal loads on the line will not be disconnected and they will affect the final value. An exact determination is beyond the scope of this presentation. Assumptions about the worker (typically 1,000 Ohms) and earth resistances and source and return paths can be made. Each parallel portion can be reduced to an equivalent resistance using Equations 5 or 6. Total circuit resistance can be found by adding all the series resistances plus the parallel equivalents. If the source voltage is known, it allows calculation of the fault current available at a worksite. While this is a valid technique, it is included primarily to illustrate the process used. The engineering department of the utility should be consulted for a more accurate value.

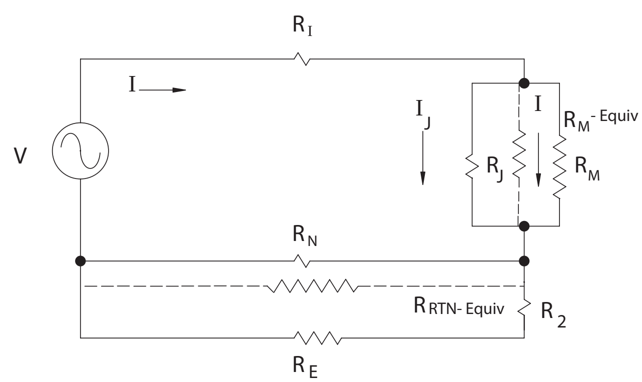
It then becomes necessary to analyze only the connections at the worksite. As an aid to analysis, Table 5-1 presents the DC resistance of several common conductors in Ohms per 1,000 ft. If it becomes necessary to include a return path through the Earth, a value of resistance must be assigned to that path.

The ratings used for cable are specified in ASTM B8 and are presented in Table 5-1.

AWG Size	Resistance (Ohms/1,000 ft.)
#2	0.1563
1/0	0.0983
2/0	0.0779
3/0	0.0620
4/0	0.0490

Copper Wire Resistances
Table 5-1

Note: There may be minor resistance changes depending upon the winding and bundling of the small strands that make up the cable, i.e. concentric stranded, bundled, rope lay, etc. They should not affect the use of these values.



Series/Parallel Circuit
Fig. 5-8

Figure 5-8 illustrates this scenario. As an example of the calculations involved, all the mentioned components have been included. Assume the source may achieve 12 kV, even momentarily.

V	=	Source voltage = 12,000 volts
R_1	=	5 miles of 2/0 Cu conductor = 2.10 Ohms
R_2	=	25 ft. of 2/0 Cu jumper, cluster bar to Earth = 0.002 Ohm
R_M	=	Assumed man resistance = 1,000 Ohms
R_N	=	5 miles of 2/0 Cu neutral = 2.10 Ohms
R_J	=	Personal Protective Jumper; 10 ft. of 2/0 Cu = 0.0008 Ohm
R_E	=	Earth Return resistance = 25 Ohms

First determine the total current drawn from the source. Find the equivalent resistances of each of the parallel portions. Then add all or the resistances in series together. Now knowing both the source voltage and the circuit resistances, Equation 2 can be used to determine the source current. So:

The man/jumper equivalent resistance is:

$1/R_{M\text{-}EQUIV} = 1/R_M + 1/\ R_J$
$= 1/1000 + 1/0.0008$
$= .001 + 1250$
$= 1250.001$

So

$R_{M\text{-}EQUIV} = 0.0008$ Ohm

The neutral/Earth return equivalent resistance is:

$1\ /\ R_{RTN\text{-}EQUIV} = 1\ /\ R_N + 1\ /\ (R_2 + R_E)$
$= 1\ /\ 2.10 + 1\ /\ (25 + 0.002)$

and $R_{RTN\text{-}EQUIV} = 1.937$ Ohms

The total circuit equivalent resistance is:

$R = R_1 + R_{M\text{-}EQUIV} + R_{RTN\text{-}EQUIV} = 2.10 + 0.0008 + 1.937 = 4.038$ Ohms

The current from the source:

$I_{SOURCE} = V\ /\ R = 12{,}000\ /\ 4.038$
$= 2{,}972$ Amp

The current through each of the circuit parts can now be determined.

The current through the man:

$I_{MAN} = I_{SOURCE} \times (R_J / (R_M + R_J) = 2{,}972 \times [0.0008/(1000 + 0.0008)]$

$= 0.0024$ Amp $= 2.4$ milliamp

The current through the jumper:

$I_J\ = I_{SOURCE} \times (R_M\ /\ (R_M + R_J) = 2{,}972 \times [1000\ /\ (1000 + 0.0008)]$

$= 2{,}971.998$ Amp
or $I_J = 2972 - 0.0024 = 2{,}971.998$ Amp

The current returning through the neutral:

$I_N = I_{SOURCE} \times [(R_2 + R_E)/\ (R_2 + R_E + R_N)]$

$= 2{,}972 \times [(0.002 + 25)\ /\ (0.002 + 25 + 2.10)]$
$= 2{,}742$ Amp

and that through the earth:

$I_E\ = I_{SOURCE} \times (R_N\ /\ (R_2 + R_E + R_N)$

$= 2{,}972 \times [2.10\ /\ (0.002 + 25 + 2.10)]$
$= 230$ Amp

As can be seen from this example, much less current flows through the Earth when a neutral return is included in the protective circuit because the neutral represents a much lower resistance path.

This is an example of a very basic analysis of a circuit from a source to the worksite. Included are the connecting conductors, neutral, protective jumper, Earth and the worker. However, adequate protection for the worker at the worksite can be determined without using this much detail.

It is sufficient to consider just the parallel portion of the circuit shown in Fig. 5-8 representing the worker and the protective jumper. The Engineering Department can provide the maximum fault current in the work area. This reduces the calculations required to determining the maximum resistance allowed for the jumper to maintain the voltage across, or current through the worker below the predetermined levels. Equation 5a can be rearranged to determine the maximum resistance.

$$R_{JUMPER} = \left(\frac{I_{WORKER}}{(I_{FAULT} - I_{MAN\ ALLOWED})} \right) \times R_{MAN}$$

Or Equation 2 can be used by assuming the full fault current passes through the jumper and knowing the maximum worker voltage allowed. This is sufficiently accurate because the magnitude of a fault current dwarfs the allowed body current. Any error is then on the side of safety. Equation 2 then becomes:

$R_{JUMPER} = V_{WORKER}\ /\ I_{FAULT}$

This is the approach used in Section 9, Basic Protection Methods.