1. ELECTRICAL LAWS

An important foundation for all electrical installations is a thorough knowledge of the laws that govern the operation of electricity. The general laws are few and simple, and they will be covered in some depth.

The multiple and various methods of manipulating electrical current with special circuits will not be discussed in this chapter. A number of them will be covered in Chapter 2. Coverage will be restricted to subjects that pertain to wiring for electrical construction and to basic electronics. While there are obviously many other things that can be done with electricity, only those things that pertain to the installers of common electrical systems will be covered.

The Primary Forces

The three primary forces in electricity are voltage, current flow, and resistance. These are the fundamental forces that control every electrical circuit.

Voltage is the force that pushes the current through electrical circuits. The scientific name for voltage is *electromotive force*. It is represented in formulas with the capital letter *E* and is measured in *volts*. The scientific definition of a volt is "the electromotive force necessary to force one ampere of current to flow through a resistance of one ohm."

In comparing electrical systems to water systems, voltage is comparable to water pressure. The more pressure there is, the faster the water will flow through the system. Likewise with electricity, the higher the voltage (electrical pressure), the more current will flow through any electrical system.

Current (which is measured in *amperes,* or amps for short) is the rate of flow of electrical current. The scientific description for current is *intensity of current flow.* It is represented in formulas with the capital letter *I*. The scientific definition of an ampere is a flow of 6.25×10^{23} electrons (called one *coulomb*) per second.

I compares with the rate of flow in a water system, which is typically measured in gallons per minute. In simple terms, electricity is thought to be the flow of electrons through a conductor. Therefore, a circuit that has 9 amps flowing through it will have three times as many electrons flowing through it as does a circuit that has a current of 3 amps.

Resistance is the resistance to the flow of electricity. It is measured in ohms and is represented by the capital of the Greek letter omega (Ω). The plastic covering of a typical electrical conductor has a very high resistance, whereas the copper conductor itself has a very low resistance. The scientific definition of an ohm is "the amount of resistance that will restrict one volt of potential to a current flow of one ampere."

In the example of the water system, you can compare resistance to the use of a very small pipe or a large pipe. If you have a water pressure on your system of 10 lb per square inch, for example, you can expect that a large volume of water would flow through a six-inch-diameter pipe. A much smaller amount of water would flow through a half-inch pipe, however. The half-inch pipe has a much higher resistance to the flow of water than does the six-inch pipe.

Similarly, a circuit with a resistance of 10 ohms (resistance is measured in ohms) would let twice as much current flow as a circuit that has a resistance of 20 ohms. Likewise, a circuit with 4 ohms would allow only half as much current to flow as a circuit with a resistance of 2 ohms.

The term *resistance* is frequently used in a very general sense. Correctly, it is the direct current (dc) component of total resistance. The correct term for total resistance in alternating current (ac) circuits is *impedance*. Like dc resistance, impedance is measured in ohms but is represented by the letter *Z*. Impedance includes not only dc resistance but also *inductive reactance* and *capacitive reactance*. Both inductive reactance and capacitive reactance are also measured in ohms. These will be explained in more detail later in this chapter.

Ohm's Law

From the explanations of the three primary electrical forces, you can see that the three forces have a relationship one to another. (More voltage, more current; less resistance, more current.) These relationships are calculated by using what is called Ohm's Law.

Ohm's Law states the relationships between voltage, current, and resistance. The law explains that in a dc circuit, current is directly proportional to voltage and inversely proportional to resistance. Accordingly, the amount of voltage is equal to the amount of current multiplied by the amount of resistance. Ohm's Law goes on to say that current is equal to voltage divided by resistance and that resistance is equal to voltage divided by current.

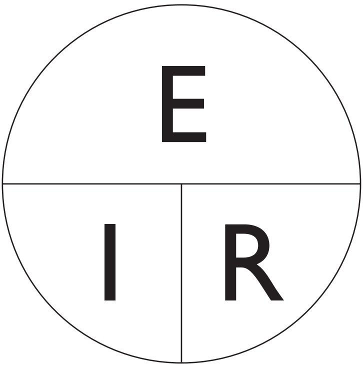
These three formulas are shown in Fig. 1-1, along with a diagram to help you remember Ohm's Law. The Ohm's Law circle can easily be used to obtain all three of these formulas.

The method is this: Place your finger over the value that you want to find (E for voltage, I for current, or R for resistance), and the other two values will make up the formula. For example, if you place your finger over the E in the circle, the remainder of the circle will show $I \times R$. If you then multiply the current times the resistance, you will get the value for voltage in the circuit. If you want to find the value for current, you will put your finger over the I in the circle, and then the remainder of the circle will show $E \div R$. So, to find current, you divide voltage by resistance. Last, if you place your finger over the R in the circle, the remaining part of the circle shows $E \div I$. Divide voltage by current to find the value for resistance. These formulas set up by Ohm's Law apply to any electrical circuit, no matter how simple or how complex.

If there is one electrical formula to remember, it is certainly Ohm's Law. The Ohm's Law circle found in Fig. 1-1 makes remembering the formula simple.

Ohm's Law

Voltage = Current × Resistance
Current = Voltage ÷ Resistance
Resistance = Voltage ÷ Current



$E \div I = R$
$E \div R = I$
$I \times R = E$

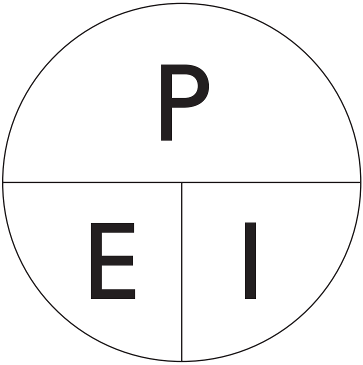
Fig. 1-1 Ohm's Law diagram and formulas.

Watts

Another important electrical term is *watts*. A watt is the unit of electrical power, a measurement of the amount of work performed. For instance, one horsepower equals 746 watts; one kilowatt (the measurement the power companies use on our bills) equals 1000 watts. The most commonly used formula for power (or watts) is voltage times current ($E \times I$).

For example, if a certain circuit has a voltage of 40 volts with 4 amps of current flowing through the circuit, the wattage of that circuit is 160 watts (40×4).

Figure 1-2 shows the Watt's Law circle for figuring power, voltage, and current, similar to the Ohm's Law circle that was used to calculate voltage, current, and resistance. For example, if you know that a certain appliance uses 200 watts and that it operates on 120 volts, you would find the formula $P \div E$ and calculate the current that flows through the appliance, which in this instance comes to 1.67 amps. In all, 12 formulas can be formed by combining Ohm's Law and Watt's Law. These are shown in Fig. 1-3.



$P \div E = I$
$P \div I = E$
$I \times E = P$

Fig. 1-2 Watt's Law circle.

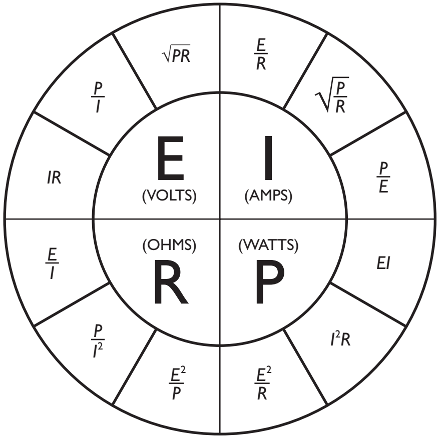


Fig. 1-3 The 12 Watt's Law formulas.

Reactance

Reactance is the part of total resistance that appears in alternating current circuits only. Like other types of resistance, it is measured in ohms. Reactance is represented by the letter X.

There are two types of reactance: inductive reactance and capacitive reactance. Inductive reactance is signified by X_L, and capacitive reactance is signified by X_C.

Inductive reactance (inductance) is the resistance to current flow in an ac circuit due to the effects of inductors in the circuit. Inductors are coils of wire, especially those that are wound on an iron core. Transformers, motors, and fluorescent light ballasts are the most common types of inductors. The effect of inductance is to oppose a change in current in the circuit. Inductance tends to make the current lag behind the voltage in the circuit. In other words, when the voltage begins to rise in the circuit, the current does not begin to rise immediately, but lags behind the voltage a bit. The amount of lag depends on the amount of inductance in the circuit.

The formula for inductive reactance is as follows:

$$X_L = 2\pi FL$$

In this formula, *F* represents the *frequency* (measured in *hertz*) and *L* represents inductance, measured in *henries*. You will notice that according to this formula, the higher the frequency, the greater the inductive reactance. Accordingly, inductive reactance is much more of a problem at high frequencies than at the 60 Hz level.

In many ways, capacitive reactance (capacitance) is the opposite of inductive reactance. It is the resistance to current flow in an ac circuit due to the effects of capacitors in the circuit. The unit for measuring capacitance is the *farad (F)*. Technically, one farad is the amount of capacitance that would allow you to store one *coulomb* (6.25×10^{23}) of electrons under a pressure of one volt. Because the storage of one coulomb under a pressure of one volt is a tremendous amount of capacitance, the capacitors you commonly use are rated in *microfarads* (millionths of a farad).

Capacitance tends to make current lead voltage in a circuit. Note that this is the opposite of inductance, which tends to make current lag. Capacitors are made of two conducting surfaces (generally some type of metal plate or metal foil) that are just slightly separated from each other (see Fig. 1-4). They are not electrically connected. Thus, capacitors can store electrons but cannot allow them to flow from one plate to the other.

In a dc circuit, a capacitor gives almost the same effect as an open circuit. For the first fraction of a second, the capacitor will store electrons, allowing a small current to flow. But after the capacitor is full, no further current can flow because the circuit is incomplete. If the same capacitor is used in an ac circuit, though, it will store electrons for part of the first alternation and then release its electrons and store others when the current reverses direction. Because of this, a capacitor, even though it physically interrupts a circuit, can store enough electrons to keep current moving in the circuit. It acts as a sort of storage buffer in the circuit.

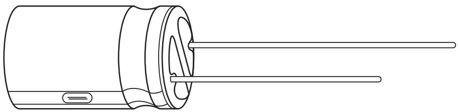


Fig. 1-4 Capacitor.

In the following formula for capacitive reactance, F is frequency and C is capacitance, measured in farads.

$$X_C = \frac{1}{2\pi FC}$$

Impedance

As explained earlier, impedance is very similar to resistance at lower frequencies and is measured in ohms. Impedance is the total resistance in an alternating current circuit. An alternating current circuit contains normal resistance but may also contain certain other types of resistance called *reactance,* which are found only in ac (alternating current) circuits. This reactance comes mainly from the use of magnetic coils (*inductive reactance*) and from the use of capacitors (*capacitive reactance*). The general formula for impedance is as follows:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

This formula applies to all circuits, but specifically to those in which dc resistance, capacitance, and inductance are present.

The general formula for impedance when only dc resistance and inductance are present is this:

$$Z = \sqrt{R^2 + X_L^2}$$

The general formula for impedance when only dc resistance and capacitance are present is this:

$$Z = \sqrt{R^2 + X_C^2}$$

Resonance

Resonance is the condition that occurs when the inductive reactance and capacitive reactance in a circuit are equal. When this happens, the two reactances cancel each other, leaving the circuit with no impedance except for whatever dc resistance exists in the circuit. Thus, very large currents are possible in resonant circuits.

Resonance is commonly used for filter circuits or for tuned circuits. By designing a circuit that will be resonant at a certain frequency, only the current of that frequency will flow freely in the circuit. Currents of all other frequencies will be subjected to much higher impedances and will thus be greatly reduced or essentially eliminated. This is how a radio receiver can tune in one station at a time. The capacitance or inductance is adjusted until the circuit is resonant at the desired frequency. Thus, the desired frequency flows through the circuit and all others are shunned. Parallel resonances occur at the same frequencies and values as do series resonances.

In the following formula for resonances, F_R is the frequency of resonance, L is inductance measured in henries, and C is capacitance measured in farads.

$$F_R = \frac{1}{2\pi \sqrt{LC}}$$

The simplest circuits are series circuits—circuits that have only one path in which current can flow, as shown in Fig. 1-5. Notice that all of the components in this circuit are connected end-to-end in a series.

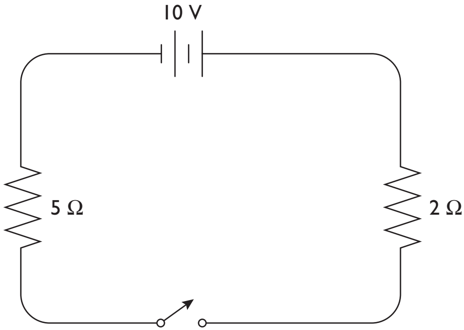


Fig. 1-5 Series circuit.

Series Circuits

Voltage

The most important and basic law of series circuits is *Kirchhoff's Law.* It states that the sum of all voltages in a series circuit equals zero. This means that the voltage of a source will be equal to the total of voltage drops (which are of opposite polarity) in the circuit. In simple and practical terms, the sum of voltage drops in the circuit will always equal the voltage of the source.

Current

The second law for series circuits is really just common sense—that the current is the same in all parts of the circuit. If the circuit has only one path, what flows through one part will flow through all parts.

Resistance

In series circuits, dc resistances are additive, as shown in Fig. 1-6. The formula is this:

$$R_T = R_1 + R_2 + R_3 + R_4 + R_5$$

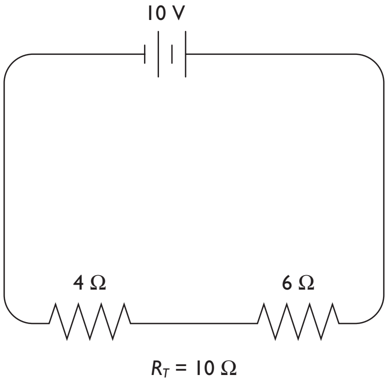


Fig. 1-6 dc resistances in a series circuit.

Capacitive Reactance

To calculate the value of capacitive reactance for capacitors connected in series, use the product-over-sum method (for two capacitances only) or the reciprocal-of-the-reciprocals method (for any number of capacitances). The formula for the product-over-sum method is as follows:

$$X_T = \frac{X_1 \times X_2}{X_1 + X_2}$$

The formula for the reciprocal-of-the-reciprocals method is this:

$$X_T = \frac{1}{\frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \frac{1}{X_4} + \frac{1}{X_5}}$$

Inductive Reactance

In series circuits, inductive reactance is additive. Thus, in a series circuit:

$$X_T = X_1 + X_2 + X_3 + X_4 + X_5$$

Parallel Circuits

A parallel circuit is one that has more than one path through which current will flow. A typical parallel circuit is shown in Fig. 1-7.

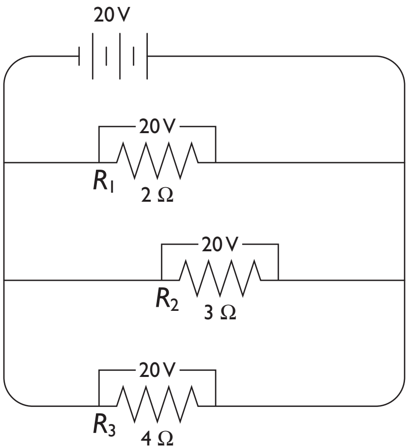


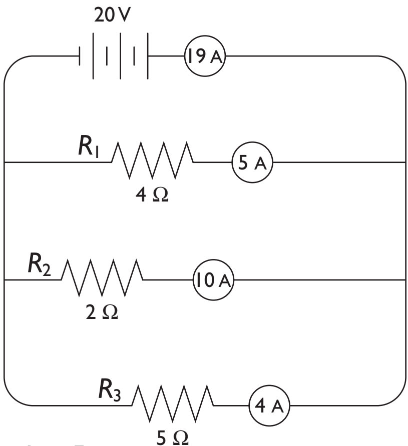
Fig. 1-7 Parallel circuit.

Voltage

In parallel circuits with only one power source (as shown in Fig. 1-7), the voltage is the same in every branch of the circuit.

Current

In parallel circuits, the amperage (level of current flow) in the branches adds to equal the total current level seen by the power source. Fig. 1-8 shows this in diagrammatic form.



$I_1 = 5$ A
$I_2 = 10$ A
$I_3 = 4$ A
$I_T = 19$ A

Fig. 1-8 Parallel circuit, showing current values.

Resistance

In parallel circuits, resistance is calculated by either the product-over-sum method (for two resistances):

$$R_T = \frac{R_1 \times R_2}{R_1 + R_2}$$

Or by the reciprocal-of-the-reciprocals method (for any number of resistances):

$$R_T = \cfrac{1}{\cfrac{1}{R_1} + \cfrac{1}{R_2} + \cfrac{1}{R_3} + \cfrac{1}{R_4} + \cfrac{1}{R_5}}$$

Or, if the circuit has only branches with equal resistances:

$$R_T = R_{\text{BRANCH}} \div \text{number of equal branches}$$

The result of these calculations is that the resistance of a parallel circuit is always less than the resistance of any one branch.

Capacitive Reactance

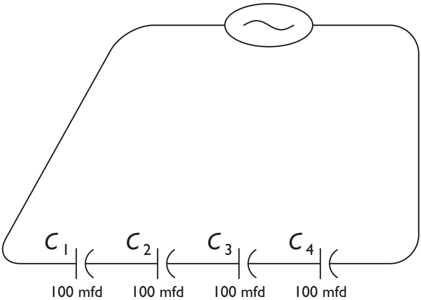
In series circuits, capacitances are additive. For an example, refer to Fig. 1-9. Notice that each branch has a capacitance of 100 microfarad ("mfd" or "µf," written with the Greek letter mu (µ), meaning *micro*). If the circuit has 4 branches, each of 100 mfd, the total capacitance is 400 mfd.

Inductive Reactance

In parallel circuits, inductances are calculated by the product-over-sum or the reciprocal-of-the-reciprocals methods.

Series-Parallel Circuits

Circuits that combine both series and parallel paths are obviously more complex than either series or parallel circuits. In general, the rules for series circuits apply to the parts of these circuits that are in series; the parallel rules apply to the parts of the circuits that are in parallel.



$C_1 = 100$ mfd
$C_2 = 100$ mfd
$C_3 = 100$ mfd
$C_4 = 100$ mfd
$C_T = 400$ mfd

Fig. 1-9 Capacitances in a series circuit.

A few clarifications follow:

Voltage

Although all branches of a parallel circuit are exposed to the same source voltage, the voltage drops in each branch will always equal the source voltage (see Fig. 1-10).

Current

Current is uniform within each series branch, whereas the total of all branches equals the total current of the source.

Resistance

Resistance is additive in the series branches, with the total resistance less than that of any one branch.

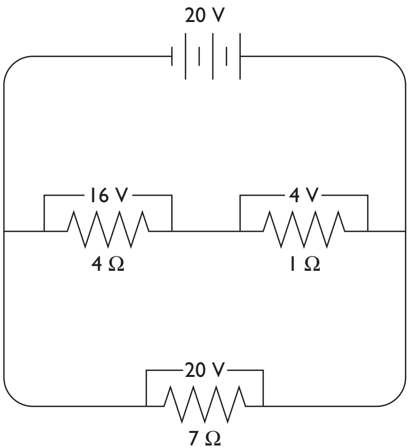


Fig. 1-10 Voltages in a series-parallel circuit.

Capacitive Reactance

X_C is calculated by the reciprocal-of-the-reciprocals method within a series branch, and the total X_C of the branches is additive.

Inductive Reactance

X_L is additive in the series branches, with the total inductive reactance less than that of any one branch.

Power Wiring

Nearly all power wiring is connected in parallel, so that all loads are exposed to the full line voltage. Loads connected in series would experience only part of the line voltage.

One of the most widely used calculations for power installations is simply to calculate amperage when only voltage and power are known. (See Fig. 1-2 and the associated discussion.)

For power wiring, capacitance is rarely a problem. One exception is that long runs of cables can develop a significant level of capacitance either between the conductors or between one or more of the conductors and a metal conduit encasing them. A proper grounding system will normally drain such a charge. If, however, there is a flaw in the grounding system, such as a bonding jumper not properly connected, strange voltages can show up in the system. These voltages are called *phantom voltages*.

Inductance, unlike capacitance, is a serious problem in power wiring. Inductive reactance causes a difficulty with a wiring system's *power factor*. This will be covered in some depth in Chapter 7.