ELECTRICITY: Basic Theory

By **BRUCE BARKER, ACI**

ONCE AGAIN, The Word invites you to travel into the dark realm of subjects that are sometimes misunderstood by home inspectors. The Word hopes you will find this trip informative and maybe a little entertaining.

The Word's subject this month is electricity. The Word finds this subject interesting because the good inspector of electrical systems knows what is deficient, but the better inspector knows why it is deficient.

This month, we'll start by discussing some basic electrical theory. This may seem a bit dull and out of scope for what we do, but it sets the stage for understanding why some electrical deficiencies we identify every day are deficient. Inspectors who understand why something is deficient make better calls and can better explain those calls to their clients.

So much potential

The ASHI Standards of Practice (SoP) requires that we report the voltage supplied to the property we inspect, and we (should) dutifully report this. But what are we reporting? Think of voltage like water pressure in a pipe. Voltage is the pressure of electricity available at an outlet such as a receptacle, a light or an electric water heater. Voltage is measured in volts. In almost all homes in North America, this pressure is 240 volts measured between the two ungrounded (hot) wires and 120 volts measured between one hot wire and the grounded (neutral) wire.

The term potential sometimes is used to describe voltage. An easy (if not technically accurate) way to understand this term is that electricity at an outlet is just sitting there waiting to start flowing and do some work. When you stick your voltmeter probes into a 120-volt receptacle, you're measuring the potential electrical pressure between the hot wire that (we hope) is connected to the small slot and the neutral that (we hope) is connected to the large slot. Tension is another term used to describe voltage; think high-tension wires.

High electrical pressure (voltage) by itself isn't dangerous to people; think static electricity. Static electricity has high electrical pressure, but there's not much electricity flowing (current) in a static discharge. Static electricity may be annoying and it can be dangerous to electronic devices, but because there's not much electricity flowing, it rarely does serious damage to people.

Conversely, low electrical pressure isn't always safe; think a 12-volt car battery. Because car batteries can produce a lot of current, a shock from a car battery certainly can cook flesh and cause a lot of pain.

We should not conclude, however, that electrical pressure is irrelevant to safety; think arc flash and arc blast. An arc flash and arc blast occur when electricity jumps between materials, much like lightning. An arc flash and blast can occur in 120-volt residential systems, but is more likely as the voltage and available current increase.

Like lightning, injuries caused by the extreme heat and the high-pressure wave produced by an arc flash and arc blast can be as injurious as any electrical shock. When dealing with residential and especially commercial power circuits, higher voltages demand higher respect and greater safety measures.

Let it flow

ASHI SoP also requires us to report the maximum current (service amperage) that the home's electrical system is designed to handle. Think of current like the amount or rate of flow of water in a pipe. Current is the amount of electricity that flows through a circuit or through a person. Current is measured in amperes (amps). A higher amperage means more electricity is flowing at the available pressure (voltage). The minimum service amperage rating for a new home is 100 amps, but often this is insufficient for a modern home.

When we report the service amperage rating, we are reporting the maximum amount of electricity that's safely available to run all of the electrical equipment (loads) in the home. Calculating the electrical load for a home (the service load) or for a subpanel (a feeder load) involves estimating loads such as general lights and receptacles, required receptacles such as the kitchen and laundry, fixed electrical equipment such as ranges and water heaters, and heating/cooling loads such as air conditioning condensers. A demand factor then is applied that reduces the calculated electrical load from the sum of the estimated loads. The demand factor accounts for the fact that all loads rarely are on simultaneously and even if they are on simultaneously, they won't be for long. This calculation is not particularly difficult, but it's way out of scope for a home inspection.

If you stuck ammeter probes into a receptacle, the ammeter would read zero. You shouldn't do this, however, because doing so would probably damage the ammeter. The reason the ammeter reads zero is because there's no current flowing at the receptacle until you place a load on the circuit. A light bulb is a load. To measure the current flow, you would use your clamp-on ammeter and clamp it around one of the wires; it doesn't matter which one. A clamp-on ammeter measures the magnetic field produced when current flows through the wire and displays a reading based on the strength of that magnetic field.

Does power corrupt?

When a load (like a light bulb) is placed on a circuit, current flows at the available pressure (voltage) to perform work (make the bulb glow). The rate of work performed is power and is expressed in watts. A 100-watt bulb draws about .83 amps at 120 volts to make the bulb glow. We'll learn why this is true in a moment.

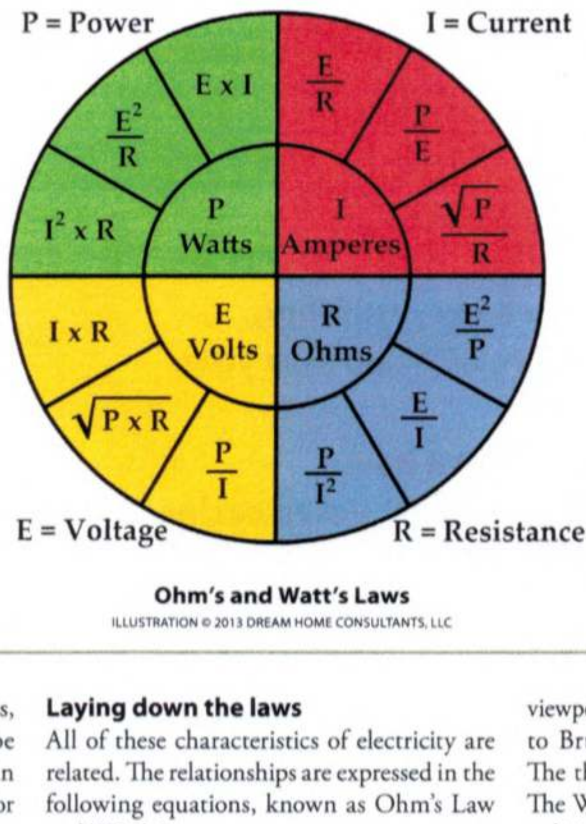
You may have seen the term volt-amps (VA), perhaps describing utility transmission wires. When you see volt-amps, think watts. One hundred kVA would be about 100,000 watts. Volt-amps is power in an alternating current circuit and accounts for factors such as the increased resistance to the flow of electricity caused by the alternating current electromagnetic field. The engineers will say that watts and volt-amps are not the same and they're right, but they're close enough for our purposes.

Is resistance futile?

All materials resist the flow of electricity. Materials with less resistance (silver, copper, aluminum) are called conductors. Materials with more resistance (rubber, cloth, most plastics, glass) are called insulators. Resistance is expressed in ohms.

Now, you may have seen the term impedance. When you see impedance, think resistance. Impedance is like resistance in an alternating current circuit. Like volt-amps, impedance makes corrections for alternating current electromagnetic fields. The engineers will say that resistance and impedance are not the same and they're right, but they're close enough for our purposes.

Illustration 1



Ohm's and Watt's Laws

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Laying down the laws

All of these characteristics of electricity are related. The relationships are expressed in the following equations, known as Ohm's Law and Watt's Law.

Power (watts) = Voltage (volts) x Current (amps)

Voltage (volts) = Current (amps) x Resistance (ohms)

If you know any two of the above values, you can calculate the others as shown in Illustration 1, above.

The most common application of these relationships, for our purposes, is found in the upper left quadrant, where we learn that when you multiply voltage by current, you get power. A 120-volt device drawing 20 amps uses 2,400 watts. If the device were designed to use 240 volts, it would draw only 10 amps to do the same work.

Why is the foregoing important? Wire size is based on current, not voltage, so one could run smaller (less expensive) wire to serve the 240-volt device and the manufacturer could possibly use less expensive parts to build the device. And, as we'll learn in a future column, heat in a circuit or device is based on current flow, so higher voltage devices should produce less heat. However, as we see in the lower right quadrant, resistance increases as you increase the voltage and increased resistance makes circuits run hotter.

Balancing these relationships is enough to drive one crazy and that's why electrical engineers make the big bucks. For our purposes, it's enough to know that these relationships exist.

The bottom line

Now that we have a foundation, we can build on it to understand issues like why over-fusing is bad, why low voltage (voltage drop) occurs and why it's bad and why loose connections are bad. Stay tuned.

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ELECTRICITY: Basic Theory *Part 2*

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Electricity law and order – a review

Last time, we learned about the Laws from Mr. Ohm and Mr. Watt, as shown in Illustration 1. These laws describe how the basic characteristics of electricity in a home's electrical system (voltage, current and resistance) interact to perform work (power). Voltage is like water pressure. Current is like water flow rate. Resistance inhibits electricity's flow. Power is a measure of work performed. Change one characteristic and you change all the others. Note to the engineers: These descriptions of work and power aren't completely technically correct. They're close enough for our purposes.

Feeling low (voltage)?

A common application of these laws occurs because of the effect of current and resistance on voltage in the home's electrical system. Voltage decreases as resistance increases at a given current load. So, for example, if you add wire between the voltage source and the load, resistance increases and voltage decreases. Voltage also decreases as current increases at a given resistance. So, for example, if you turn on a high-current load device like a motor, current increases and voltage decreases.

The common label given to this phenomenon is, not surprisingly, voltage drop. An example of voltage drop is lights dimming when a compressor or other high-current load device first activates. This dimming is the result of the momentary increase in current flow that creates a voltage drop. This type of voltage drop, while annoying, is usually not considered a problem.

Circuits operating continuously at less than their intended voltage may experience problems. Motor loads and ballasts for fluorescent lights are particularly susceptible to problems caused by low voltage. They may function inefficiently or at less than designed output; they may overheat, and they may have reduced service life. Electronic equipment such as computers and printers may lock up or shut down, resulting in lost data, inconvenience and business interruption. Resistance loads such as incandescent lights and heating and cooking appliances will operate at less than designed output. Consistently low voltage also costs money. The wires themselves consume more power that is wasted as heat.

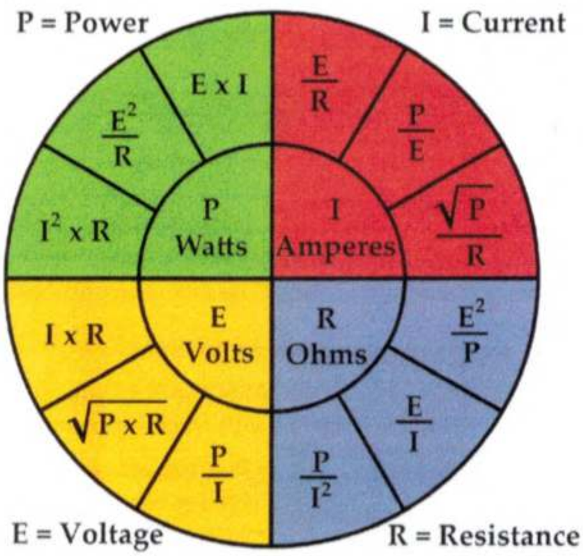
Voltage drop (at a given current load) is primarily a function of the wire diameter, material and length. Other conditions such as marginal quality splices and connections can also affect voltage drop. These factors establish the resistance between the circuit's source (the breaker or fuse) and the circuit load (the light bulb, etc.). These factors also apply to feeders between the feeder's source and a subpanel. Aluminum wire has a higher resistance than the same size copper wire. A longer wire has more resistance than a shorter wire. Increasing the wire length (or increasing the current load) creates a voltage drop that could adversely affect devices. Conversely, increasing the wire diameter decreases the voltage drop. Increasing wire diameter is a common cure for voltage drop issues.

Acceptable voltage drop?

Confusion surrounds the question of acceptable voltage drop. What's acceptable depends on who you ask and on the situation. The National Electric Code (NEC) and ANSI Standard C84.1 are sometimes cited when discussing voltage drop.

The NEC does not limit voltage drop in branch circuits. Fine print note [210-19(A) I.N.No. 4] recommends sizing branch circuit

Illustration 1



Ohm's and Watt's Laws

conductors to prevent a total voltage drop exceeding 5%, including feeder losses. Informational Notes (formerly Fine Print Notes) are for information only and are not enforceable. NEC Section 110-3(B), however, says that equipment must be installed in accordance with its listing or labeling. Most electrical equipment is designed to operate at no less than 10% below its labeled voltage rating.

Another way to address minimum acceptable branch circuit outlet voltage is by applying ANSI Standard C 84.1. This standard states that the minimum acceptable outlet (utilization) voltage over time for nominal 120-volt general lighting circuits is 110 volts and 108 volts for other circuits. Infrequent and short duration dips to 106 volts for general lighting circuits and 104 volts for other circuits are allowed under this standard.

These minimum acceptable branch circuit outlet voltages shouldn't be used without considering other factors, not the least of which is the fact that voltage from the utility (nominal voltage) isn't constant. Measuring voltage at one point in time does not provide a valid indication of voltage conditions over time. As previously discussed, manufacturers usually design devices to operate effectively at less than the nominal voltage. This is why you often see labels on devices such as motors that display an operating voltage like 115 volts for a 120-volt circuit and 230 volts for a 240-volt circuit.

Practical applications

Voltage drop usually isn't a big problem inside modern homes. Wire lengths and current loads usually are not sufficient to cause enough voltage drop to matter. Measuring voltage and measuring circuit lengths is way out of scope for a home inspection. So, how might we apply what we just learned during our inspections?

One application where we might alert our clients to a possible problem is a branch circuit serving an accessory building such as a garage. Wire ampacity limits (15 amps for #14 NM cable) are based, to a large extent, on the wire's ability to dissipate heat. Voltage drop is not considered; therefore, a circuit that may be allowed from an ampacity perspective may not work well from a voltage drop perspective.

Let's do a couple examples. Note that there are many voltage drop calculators that will produce different results depending on the inputs and on assumptions such as circuit operating temperature. Your results may vary from these results. The purpose of these examples is to give you a feel for the types of situations where voltage drop might be an issue.

The International Residential Code (IRC) allows using #14 copper wire to serve one 120-volt, 15-amp circuit in an accessory building such as a detached garage. Assume #14 copper wire, a 12-amp total load, 120 volts at the circuit's source, and a wire length of 200 feet between the service panel and the load. The voltage drop would be around 10.8% or 13 volts. Reduce the wire length to 150 feet and the voltage drop would be around 8.1% or 9.7 volts. The 200-foot circuit is a likely problem and the 150-foot circuit is a possible problem. Remember, just because the only load present in a garage is a light doesn't mean that's the way it will always be. If someone can place additional loads on a circuit, you should assume that they will.

Long branch circuit runs serving motors such as pool and well pumps are another example of where voltage drop could be a problem. Assume #12 copper wire, 7.4 amps total load, 240 volts at the circuit's source and a wire length of 200 feet from the circuit's source to the pump. The voltage drop would be around 2.1% or 5 volts. No problem here. That same pump may be connected to a 120-volt circuit where it would draw 14.8 amps. In this case, the voltage drop would be around 8.6% or 10.3 volts. This circuit could be a problem, especially if source voltage is less than 120 volts. A low-source voltage could occur for many reasons, including voltage drop between the primary panel and a subpanel such as a pool subpanel.

The bottom line

Voltage drop is a complex issue. There is no one clear standard for minimum acceptable voltage, and even if there were, determining compliance would be way out of scope. The best we can hope for is to be aware of the issue and to alert our clients when further evaluation may be prudent.

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ELECTRICITY: Basic Theory *Part 3*

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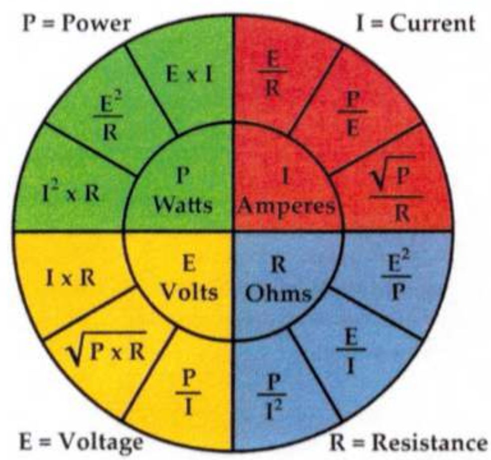

Ohm's and Watt's Laws

A Crown Joule

There's another law that's perhaps more interesting than Ohm's and Watt's Laws and that's Joule's Law. Joule's Law expresses how heat develops in an electrical circuit. Heat is the enemy of electrical circuits. Heat breaks down insulation and sometimes the wires themselves. When insulation and wires fail, short circuits, ground faults, and fires are usually not far behind. Many of the deficiencies we call (over fusing, for example) have some of their basis in Joule's Law. Joule's Law is:

$$\text{Heat} = \text{Current}^2 \times \text{Resistance} \times \text{Time}$$

Joule's Law has some interesting features; the first being that voltage is not a factor in generating heat in an electrical circuit. A 1 ½ volt battery, under the right conditions, could generate enough current to start a fire. Ever see melted insulation on a neutral wire? The neutral wire is a current-carrying wire with no voltage (if everything is working as it should). Joule's Law explains why heat is generated when no voltage is present.

Another interesting feature is that heat increases exponentially as current increases. Two amps generates four times more heat than one amp (22 = 4), three amps generates nine times more heat than one amp (32 = 9) and so on. Joule's Law helps explain why over fusing can be so dangerous.

Resistance is an important factor in generating heat in an electrical circuit. Aluminum wire has a higher resistance than copper wire so more heat is generated in aluminum wire at a given current. Heat, as described by Joule's Law, helps explain why aluminum wire must be larger than copper wire. Resistance at loose or corroded connections can be much higher than at tight and clean connections. Heat, as described by Joule's Law, helps explain why loose and corroded connections are a problem.

Hot Boxes

Ever look inside a panelboard cabinet or a junction box and see it filled to the brim? Did you say anything about it? Joule's Law tells us that perhaps you should have said something.

Wires and devices get hot, as decreed by Joule's Law. More wires or devices equal more heat. Less free space in a cabinet, box or conduit equals less space to dissipate that heat. All this heat with no place to go could end in one of those fires you see on the evening news. You can't tell by looking whether a box or conduit is filled beyond its allowed limits. But if you see a cabinet or box that appears uncomfortably full, calling for evaluation might keep a TV news crew away from a home you inspected.

Beware of General Rules

We learned in inspector school that the upper ampacity limit for circuits using copper wires is 15 amps for #14, 20 amps for #12, 30 amps for #10, 40 amps for #8, and 55 amps for #6. Limits for aluminum wires are 5 amps less than for the same size copper wire except that #14 aluminum wire may not be used, and #6 aluminum wire is limited to 40 amps. So any circuit using these wires should be protected by an overcurrent protection device at or below these limits, right? That's right in many cases. What the instructor probably didn't tell you is that wire upper ampacity limits are valid only under prescribed conditions. The allowed ampacity of wires can be more or less than these limits depending on the circuit they protect, how they're installed, and on the type of wire insulation.

These upper ampacity limits apply to most of the wiring we see in most modern homes. These upper ampacity limits are almost always valid for #14, #12 and #10 wires. These wires are covered by special rules that apply only to these wire sizes. The upper ampacity limits are almost always valid for wires that are part of NM cables (usually referred to by the trade name Romex). NM cables are also covered by special rules that apply only to NM cables. These cables are what we usually see for most branch circuits in modern homes, with the notorious exception of the Chicago area.

These upper ampacity limits do not apply to wire sizes #8 and larger that are not part of an NM cable. A common example is individual wires pulled in conduit or tubing. To find the upper ampacity limits of these wires, you need to know the wire size, wire material and insulation material. Knowing this, you go to IRC Table E3705.1 or NEC Table 310.15(B)(16). Here you find that the upper ampacity limit for #8 copper wire with THHN insulation is 55 amps. That's quite a bit more than the same wire contained in NM cable.

Now if you want to go way beyond the scope of a home inspection, you need to take the upper ampacity limits of wires (and NM cables) and reduce them based on the number of wires run close together and the air temperature where the wires are run. This is called derating for proximity (number of wires) and ambient temperature. Derating gets complicated. Let's leave it to the electricians and code geeks.

Before we leave this topic, let's address a common point of confusion. Wire size and overcurrent protection for circuits serving air conditioning and heat pump condensers are based on the minimum and maximum circuit ampacity ratings on the condenser's label. The maximum rating is usually larger than the limit for the size of wire serving the equipment and allows for the current surge required to start the compressor.

Photo 1 is of the label on The Word's shiny new heat pump condenser. The circuit serving this condenser could use wires as small as #12 copper as shown by the minimum circuit ampacity. The overcurrent protection device should be no more than 30 amps as shown by the maximum overcurrent protection device. The upper ampacity limit for #12 copper wire is usually 20 amps, but rules allow the circuit to be protected by up to a 30-amp device.

Full Circle

We've learned that heat is the enemy of electrical circuits. We want to avoid creating heat when possible, and when it's not possible, we want to dissipate the heat so it doesn't damage the insulation or the wires. We put limits on the current a wire can carry because heat increases exponentially as current increases. We put limits on the number of wires and devices that may be installed in close proximity because wires and devices in close proximity have less air around them to dissipate heat.

Photo 1: The label from a new heat pump condenser.

The Bottom Line

What we've discussed in these last three columns goes beyond what you need to know to perform a competent inspection; but The Word believes that ASHI members want to do more than a competent inspection. Those who go above and beyond will be rewarded, and now you have some tools to go above and beyond mere competence.

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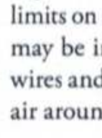

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