Understanding capacitive voltage sensors

How voltage detectors use your body's conductivity

Application Note

Your partner just bought one of those pen-shaped ac voltage detectors. He calls it a "tick-tracer" or a "glow-tip". You've seen him carry it in his shirt pocket wherever he goes. He must like it because he won't loan it out. When you asked him about it, he claimed that it can detect live ac voltage inside an insulated wire. He also says he has used it to quickly detect an open neutral in a branch circuit or in some cases spotted a bad ground connection for a metal enclosure.

How does this thing work anyway? How can it detect voltage without making a metallic contact? Will it detect live conductors inside a grounded metal conduit?

Capacitive coupling

AC voltage detectors work on the principle of capacitive coupling. To understand this, let's return momentarily to electrical circuit theory and recall how a capacitor works. A capacitor has two conductors or "plates" that are separated by a non-conductor called a dielectric. If we connect an ac voltage across the two conductors, an ac current will flow as the electrons are alternately attracted or repelled by the voltage on the opposite plate. There's a complete ac circuit even though there's no "hard-wired" circuit connection. The electrical "field" inside the capacitor, between the two plates, is what completes the ac circuit.

We often think of capacitors as individual circuit components such as motor starting caps, but in reality, the world is full of small "stray" capacitors that we don't normally realize are present. Here's an example. Suppose you are standing on a carpeted concrete floor directly under a 120 V light fixture and the light is on. Your body is conducting a very small ac current because it is part of a circuit consisting of two capacitors in series. The two conductors or plates for the first capacitor are the live element in the light bulb and your body. The dielectric is the air (and maybe your hat) between them. The two conductors for the second capacitor are your body and the concrete floor (remember that concrete is a good conductor, as is shown by the use of concrete encased electrodes as earth grounds). The dielectric for the second capacitor is the carpet plus your shoes and socks. This second capacitor is much larger than the first. A very small ac current will flow because there is 120 V across the series combination. (As an aside, this current must be way below the shock threshold or we wouldn't be living in a world of ac power–we definitely would not be turning on lights in the bathroom.)

Capacitive voltage sensors

But how does the voltage divide between the two caps in series? This answer is critical to understanding how the capacitive voltage sensor works. Let's briefly return to our electrical circuit theory again. In a series circuit, the largest voltage will develop across the largest impedance (Ohm's Law). With capacitors, the smaller the capacitor, the larger the impedance (known as capacitive reactance). It's a little tricky, because it's the opposite of how resistors behave, but keeping this twist in mind, the rest is straightforward. When two capacitors are in series, the largest voltage will develop across the smallest capacitor. In the above example, only a few volts will develop between your feet and the floor (the large capacitor) while the remainder of the 120 V will be between your head and the light bulb (the small capacitor). This may sound bizarre because we normally don't think of the carpet and floor as parts of an electric circuit but in fact they are and they will obey Ohm's Law and Kirchoff's rules if we apply them correctly.

The capacitive voltage sensor works because when you hold the barrel in your hand and place the tip near a live conductor, you are inserting the high impedance sensing element into a capacitively coupled series circuit. As in the previous example, your hand and body form a relatively large capacitor coupled to the floor. The sensor tip is a small capacitor coupled to the live voltage. The sensing circuit detects the voltage and turns on a light or sounds the buzzer.

Try it and see

To prove the theory for yourself, try this simple test: Find a metal desk lamp that has a two-prong power cord, i.e., a lamp that is not grounded. Plug the cord into a live outlet and with the sensor in your hand, touch the tip to the metal frame of the lamp. The sensor should indicate live voltage because the metal frame of the lamp is near (capacitively coupled to) the hot side of the line cord and there is no grounding conductor to "draw down" the voltage. In other words, the sensor detects the "stray" voltage coupled to the light frame by the "stray" capacitance between the frame and the hot side of the line. Now, rest the sensor on a stack of books or other non-conductive object so that the tip remains in contact with the lamp frame while you take your hand away. The sensor will no longer indicate live voltage because its capacitively coupled circuit was broken when you took your hand away!

This test gives us a clue about how the sensor can detect an open neutral in a branch circuit. Let's assume the circuit you are testing is a 120 V wall outlet. When you plug in a load, nothing happens. A quick check of the panel shows that the correct circuit breaker is on and your multimeter measures 120 V between the hot and ground at the outlet. Next, you take out your sensor and insert the tip into the hot side of the outlet – it indicates live voltage. Then, you insert the tip into the neutral side of the outlet with the same results – a live voltage indication. How can this be? If the neutral were in contact with the hot conductor, wouldn't we have a short circuit? Wouldn't the breaker be tripped? If we think carefully about capacitive coupling, the answer will be obvious. The hot and neutral conductors are lying side by side for the complete distance from the outlet back to the panel. In other words, they are capacitively coupled together: each wire is one "plate" of the capacitor and the conductor insulation is the dielectric. If the neutral is open at the panel, and therefore not grounded, the neutral conductor will float up to nearly the same voltage as the hot. That's why the voltage sensor indicates live voltage on the neutral.

Try this yourself with a pair of two-prong extension cords. Plug one cord into a wall outlet and plug the second cord into the first but connect only the hot side leaving the neutral open. Go to the loose end of the second cord and try the voltage sensor in both sides. They both should indicate live voltage.

Under certain conditions we can use the voltage sensor to detect a bad ground connection on a metal enclosure or section of conduit. In fact, this is a good habit to get into before contacting or working on any electrical enclosure. Think of the lamp frame test described earlier. The reason the sensor indicated live voltage on the frame was because the ungrounded metal frame had stray voltage on it coupled from the hot conductor. In the case of the ungrounded metal enclosure, the voltage sensor won't tell you if the enclosure is just "hot" from capacitively coupled voltage, or if it's really hot from, let's say, contact with a live wire (frayed insulation on a phase conductor). The difference can be life or death. It's worth checking out.

Matching ac detectors to applications

Not all ac detectors are created equal. Most ac detectors on the market today have a specific sensing range and sensitivity levels within which they are specified to operate properly. Some are designed to be used on lower voltage control circuit applications such as found in the HVAC marketplace, others specified for residential use and still others specified for use in different industrial environments. Most ac detectors also offer different means of alerting users to whether voltage is present or not. Some use visual stimulation, such as the tip lights when voltage is present, some use an audible tone, some offer both and still others have additional enhancements such as a built in flashlight. The batteries used to power the ac detectors also vary by manufacturer. Some use standard easy to obtain batteries like AA or AAA sizes and others use "watch" style batteries which may be more difficult to find when you need them the most.

So, when selecting your ac detector of choice, be sure to carefully consider what style or type of detector best meets with your job requirement and your application environment.

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