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White Paper: Electrical Ground Rules

Best Practices for Grounding Your Electrical Equipment

A look at circuit grounding and its importance to you, as well as the US AC power system and its use of earth ground (Part 1 of 3)

8500-993c

This paper is part one of a three part series that takes a look at grounding and its role in protecting personnel, protecting equipment, and ensuring the integrity of electrical signals. In this part, we will review circuit grounding and its importance to you, as well as the US AC power system and its use of earth ground.

Part two of this series will look at Ground as a means of protection, ground faults, and the operation of the ground fault circuit interrupter (GFCI).

Part three of this series will review ground and its role as a voltage stabilizer and transient limiter. It will offer some tips on what you can do to improve your connection to ground to realize benefits to safety and signal integrity.

BACKGROUND

When wiring or connecting circuits, electrical equipment, and electrical instruments, there is a connection that you probably don't give much thought to, and one that consequently reigns as one of the greatest sources of instrument error and malfunction. The connection I am referring to is your connection to Ground. For the purpose of this discussion, unless otherwise specified, the term "ground" will refer to a connection to earth ground, or an extension of a connection leading to earth ground. In some circuits, ground may also refer to a connection to the chassis or frame of the device, which is sometimes used in the absence of a connection to earth ground as a convenient reference point for signal measurement.

Electrical systems must be grounded in order to work properly. The earth often serves as an ideal ground because of its large mass and ability to absorb charge, but ground can be any electrical connection that is able to freely conduct electricity, and grounding a circuit does not always refer to making a physical connection to earth ground. For example, airplanes will connect their conductive metal shells and frame to ground for all the electronic components inside the aircraft, both generated AC and DC. The aircraft is only actually earth grounded when it's on the ground to drain static build-up and during refueling. Parts of an aircraft that are made of plastics or other composite materials are often protected with a metal mesh or fibers to minimize charge buildup. Even some aircraft tires will have a copper mesh molded into the nose-wheel or other conductive material molded into the tire rubber to contact earth and dissipate charge. Helicopters also pick up large amounts of static charge and they often employ an earth-contact lead to contact the ground or water to dissipate charge before contacting personnel, perhaps during an air or water rescue. Likewise automobiles can't pass electrical charge to earth through their insulating rubber tires.

So ground in a car or airplane may be inclusive of its chassis and this is sometimes used as a return path for current, back to the negative terminal of its battery. The battery current flows from its positive terminal through the devices (lights, radio, etc.), then out of the devices to the negative terminal of the battery, which is usually connected in common to the chassis of the vehicle. It is generally not good practice to use the chassis as a return path for load current, as this really isn't a safe practice in most cases, and for vehicles, it would be a source of noise for any devices that happen to make their ground connection via the chassis or frame (instead, the chassis should only connect to ground at one point).

For AC powered devices, earth ground is never used as a return path for load current, except in the case of a ground fault. That is, with modern 3-wire AC powered devices, ground is usually a third conductor to the device that is held in reserve for special situations (ground faults) and it does not normally carry load current (serving to keep its potential the same along it, or "equipotential"). For these devices, AC neutral is the wire used to conduct charge back to the source and complete the circuit during normal operation.

For applications where power to the device is from an isolated source, perhaps via an isolated AC-to-DC converter, a direct path to earth ground may not be present for the powered circuit. Many times, the isolated output power supply will connect earth ground at its output DC minus lead, and it may include a hidden path to earth ground on its AC power side via an isolation capacitor to output DC minus. In cases where an earth ground connection is not evident, ground is usually chosen as the common return path from the power supply to the equipment (isolated output DC minus), and in some applications, it may even be necessary to hard-wire a path to earth ground at the DC minus output of the isolated power supply powering your equipment.

WHAT IS GROUND?

When you first learned about ground, you may have been told something like "…ground in a circuit is a reference point of 0V". While that might represent an "ideal" ground, it is very misleading in practice. It is true that ground in a circuit can refer to a reference point from which all voltages are measured, and for the purpose of simplifying your measurements, it's convenient to think of this ground as having a potential of 0V. This certainly does simplify your voltage measurement and analysis. But the reality is that ground could be any potential. And unfortunately, the simple fact is that all conductors have some impedance, including the conductors used for ground. Once you start pumping charge through any conductor, it's going to look very different than a perfect conductor at 0V.

For example, as ground conducts current, a voltage difference will develop across it, forcing each connection to it to occur at a slightly different potential. So in practice, if all connections to ground were really made at 0V, we wouldn't have ground faults or ground loops. And therein lies the problem with ground—your ability to mimic its idealized behavior as a reference connection to 0V really depends on how well you can minimize its effective impedance, chiefly its resistance and inductance. Generally at 50-60Hz power line frequencies, the resistive component of your connection to earth is more significant than the reactive component (inductance). At higher frequencies, the reactive component gains significance, as the inductance of your connection to ground raises its impedance to transient energy. The bottom line is that you need to minimize the effect both components have on raising ground impedance by keeping both the resistance and inductance of your connection to ground to a minimum.

THE IMPORTANCE OF GROUND

A "ground" connection to local earth is normally provided for your AC electrical system and for the equipment owned by the utility. This ground connection must be of low impedance, or with regard to the generally lower frequencies of AC power, its resistance must be low. For example, the US National Electric Code (NEC) specifies an acceptable limit for ground impedance is 25Ω. IEEE Standard 142 recommends a resistance between 1 and 5Ω for the connection between a systems main ground node and earth for commercial and industrial power systems. Your utility will typically target 6-8 ohms for the pole connection to ground. Soil conditions vary widely and will greatly impact ground impedance. In any case, for the protection of yourself and any powered equipment, you want this resistance to be as low as possible, and most electricians will shoot for a measured ground impedance less than 5Ω, typically 2-3Ω. In fact, troubleshooting problematic power systems usually starts with measuring the impedance of the system's connection to earth ground using special equipment, like a Fall-of-Potential Tester. In some cases, the remedy might involve bonding additional ground stakes to the system ground.

The principal purpose of connecting your system to earth ground is:

- To stabilize the voltage to earth during normal operation (think of earth like an anchor to the system voltage).
- To limit the voltage rise created by lightning, line surges, and unintentional contact with higher voltages.

For example, a low-impedance connection to earth will limit the voltage that develops if high voltage conductors fall down onto lower-voltage conductors, which are usually mounted lower to the ground in modern power distribution systems, and this helps to minimize the potential shock to any powered equipment. This low impedance path to earth also helps if a failure occurs within the utility's distribution transformers. When all conductive objects are bonded to the same earth ground system with low impedance, the risk of electric shock is minimized, as the voltage is absorbed by the earth and its energy (charge) is dissipated in its large mass.

However, in practice, there are multiple connections between the utility ground and the ground of system powered equipment that can still lead to "stray voltage" problems. System piping, swimming pools, and other equipment can still develop harmful voltages that can destroy the equipment, or put human life at risk for electric shock. Often these problems can be difficult to resolve, as they may originate from places other than the system premises.

In wiring instruments and electrical equipment, we can derive three main purposes for correctly applying Ground:

- We connect to Ground to provide an alternative path for fault current to flow (safety reason).
- We connect signals to ground to stabilize them & keep them from floating (to limit the voltage and its variation).
- We connect to Ground to limit the voltage-rise induced on powered circuits, typically via lightning, line surges, or unintentional contact with higher-voltages (limiting the induced voltage magnitude).

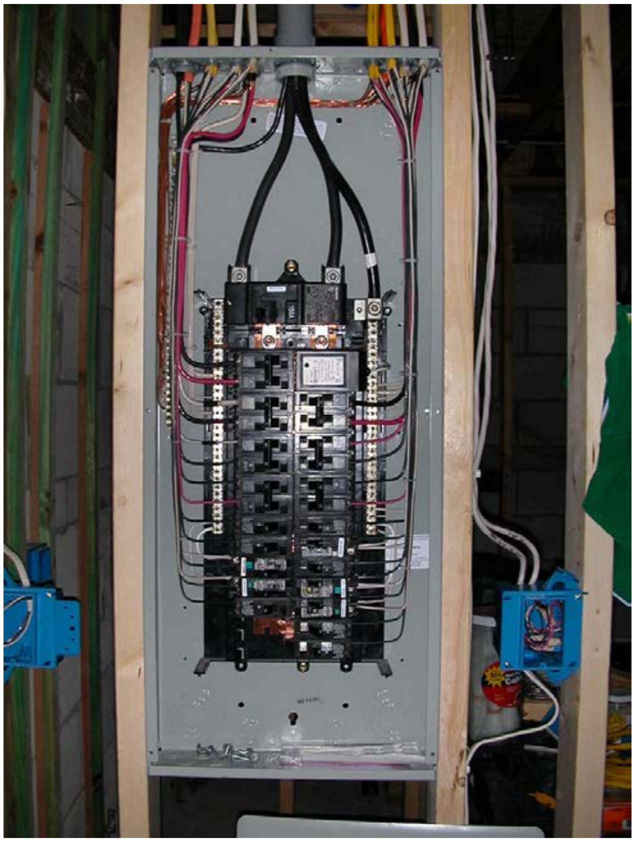
To this I would add another very important side-benefit to providing a good connection to earth ground:

- We ground our circuits to gain EMC benefits that result in lower noise and radiated emissions.

AC POWERED SYSTEMS

To really understand ground, it's important to have a basic understanding of the modern AC power system, as this is where your connection to earth ground is usually established. For example, consider AC power wired to your home. This power is transmitted from your utility over very long distances, using very high voltages to help minimize losses. It is then stepped down using a series of transformers to lower voltage levels before it connects to your home or business.

For power connection right to your home, your utility usually provides three large diameter wires coming from your utility pole to the service entrance of your house—these include two heavily insulated wires from the transformer (two line phases), and a third wire that serves as an earth grounded AC neutral wire. The most common residential service in North America is 240V single-phase (also called 240V split-phase), in which one phase of a higher voltage is stepped down to 240V. This 240V phase winding is center-tapped, which is then grounded and becomes the AC neutral conductor. One line of these windings to neutral powers your 120V loads, and line-to-line they power your 240V loads. The waveforms of each 120V line-to-neutral are offset by one-half cycle, 180 degrees out of phase, although they originate from a single phase 240V secondary. This allows you to power both 120-volt loads in your home (lamp, toaster, etc.) and 240-volt appliances (electric stove, air conditioner, etc.). The two heavily insulated wires typically pass through a watt-meter near your service entrance used to measure your consumption of power. The watt-meter also establishes your premise's connection to earth (from the third utility wire with additional ground stake(s) near the meter). From the meter, two thick wires connect to the service panel, along with a neutral wire (neutral has been bonded to earth ground at your utility pole and one or more earth ground stakes near your meter). The inside of the service panel to your home or business may resemble the following:



Note the three thick insulated wires that connect to your breaker panel. Two thick insulated wires connect to the breakers of your service panel through a lower "mains" panel breaker (the big switch at the top). A third thick wire is the AC neutral wire (the thick white banded cable in the example photo at left). The mains breaker typically consists of two circuit breaker handles joined together as a Double-Pole Service Disconnect. The mains breaker is the switch that controls the utility power from energizing the individual circuit breakers of the service panel. The mains breaker also identifies the amperage capacity of your electrical panel, and will have a number on it like 60, 100, 150, 200, or 400, signifying its total amp capacity. Each circuit of your home or business branches off from the service panel through smaller capacity individual circuit breakers, which will cut off electricity to their branch circuits in the event of an overload.

The two thick hot service wires feeding the mains breaker each carry the 120 volts from the electric meter to two "Hot" electrical bus bars in the panel. Individual breakers contact one or two of these bus bars, according to the voltage of their branch circuit. Connections to these hot bus bars are made in such a way as to balance the load with half the circuits on split phase and the other half on the other split phase.

This is why you may experience some power failures for only a portion of the powered devices in your home--when only one of your two phases loses power. A circuit breaker will connect to one bus bar for 120 volts (a single-pole breaker), or both bus bars for 240 volts (a double-pole breaker). The individual breakers then feed their loads via a black insulated "hot" wire that connects to your power outlet, and energizes the connected electrical device (light bulb, motor, etc.). The circuit returns back to the panel through a white insulated neutral wire that connects to the Neutral bus bar of the service panel, which also connects to all the individual white neutral wires from all the branch circuits and ties them in common.

The neutral bar connects to the main circuit neutral wire from the power meter and returns the current back to the electric utility from each of the branch circuits. Likewise, the bare copper ground wires of each branch circuit (assuming that your home or business is wired using 3-wire cable) similarly connect to a ground bus bar in the panel which also connects in common to the neutral bar. The grounding bus bar may be part of the Neutral bar, or separate from it, and collects all the ground wires from the various branch circuits and ties them back to the Neutral bar. <u>This is an important point—that ground is connected in common with neutral at the service entrance</u>.

The neutral/ground connection also connects to one or more earth ground rods driven into the ground near the service meter similar to the Australian example grounding rod shown at left. The ground circuit may additionally connect to the cold water pipes that service the building. This is how each branch circuit gets its connection to earth ground (the AC neutral coming from the utility pole is also earth grounded near the pole).

Do not be fooled into thinking that by grounding the water pipes to your premises, you are somehow protected from electrocution if an AC appliance were to fall into your bath tub while you were bathing. Consider that many homes utilize plastic piping for portions of their plumbing, making this an unreliable connection to ground. The reality is that if there is no path to earth ground or neutral completed by your body, no electrocution can occur. In this "hot tub" scenario, the water would likely cause a short between the AC hot wire of the appliance and AC neutral and excess current would flow and trip the breaker that connects to that circuit. However, if the pipes to the tub were metallic and also earth grounded, and you happened to be touching the faucet or drain while in the water, there is the possibility that you could complete the hot-neutral path for at least a portion of the fault current and be electrocuted. If the appliance were connected to a GCFI outlet, then this could protect you from electrocution (more on this in Part 2 of this series).

Each circuit of your house includes a circuit breaker that connects in series to the black hot lead of your AC wiring. The circuit breaker of each branch hot lead is designed to fail safely. Without a breaker, when a circuit draws more current than it is designed to handle, the wiring will get hot and could start a fire. The breaker curbs this potential for fire by preventing excess current from flowing. It does not protect you from potential electrocution. A **Single-Pole Breaker** provides 120 volts to the branch circuit and typically comes in ratings of 15 amps (for household lighting) to 20 amps (household outlets). **Double-Pole Breakers** provide 240 volts to the branch circuit and come in ratings from 15 amps to 50 amps. Double-pole breakers like the example shown at left usually serve circuits dedicated to a single load, such as large appliances, electric dryers, stoves, or air conditioners.

Electricity must have a complete conductive path to flow. When you look at an AC power outlet, you generally see two vertical slots and a rounded hole between them. The larger vertical slot is AC neutral, and it usually connects to your service entrance via a white insulated wire from your service panel. The smaller vertical slot is AC hot, and it connects to your service entrance via a black insulated wire. The rounded hole between the slots is AC or safety ground and it connects back to your service entrance via a bare copper or green insulated wire. Note that AC neutral and AC ground are separate conductors at your outlet/load, but are actually bonded together at your service entrance.

In the circuit wiring to your load device, you would measure a voltage between AC hot and AC neutral and both lines will carry current to/from your load. AC neutral carries the load current back to your service panel during normal operation, but AC ground does not normally return load current. AC ground only returns current for fault conditions. Thus, you would not measure much voltage between AC neutral and AC ground, as only a small IR voltage drop would exist as a result of AC neutral conducting load current through its resistance. In practice, bonding AC neutral to ground at your service entrance is what allows a circuit breaker to de-energize the entire circuit by simply interrupting the AC hot wire connection upon an overload condition. If AC neutral was not bonded to earth ground, you would have still have a potential for shock by simply changing a light bulb, even with the light switch off, as a path to neutral remains with the switch OFF. Opening the AC hot line via the light switch allows all the conductive wires and fixture metal past the switch to rest at AC neutral, which is "anchored" to the potential of earth ground (nearly 0V), making these conductors safe to handle with the light switch OFF.

This is an important point, that <u>AC neutral is the return current wire</u> of a loaded circuit and it connects to ground at only <u>one point</u>—at the service panel or breaker box. AC ground is a safety wire that normally carries no current. The AC ground wire generally makes contact to the appliance shell or chassis, and may also be connected to other grounds in the facility, such as water or gas piping. If a hot wire to the appliance (AC hot or neutral) breaks and makes contact with a grounded metal chassis, then load current would travel in the AC ground wire back to its source at the service panel (a ground fault). In the American 3-wire system, the white AC neutral wire is held in common to earth ground for 115V power wiring, and also held at earth ground for 230V wired loads (driers, stoves, air conditioners, etc.). The power company supplies 115V on a black insulated wire, 180 degrees out of phase with 115V on the other hot wire (typically a red-insulated wire), so that a voltage between them measures 230 volts. Note that this hot-neutral voltage is nominal and appliances generally work from 110V to 125 VAC, such that the same voltage is sometimes referred to as 110V, 115V, 120V, or 125V.

To reiterate, the AC neutral wire is a return wire for the load current in an electrical circuit. AC neutral does connect to AC ground at the service entrance. But do not confuse neutral with the ground wire, which is also a return wire, but only returns current in the event the connected appliance shorts out, and in this way acts to protect the user from electrical shock (an inadvertent hot connection to ground will cause the load current to quickly rise and trip the hot breaker, shutting off current flow). In the wiring to your home or business, the neutral comes from the power plant via the utility pole and is also earth grounded at the utility pole, AC ground comes from a ground rod, typically below your power meter. In many older homes, the ground and neutral were connected to the same bus bar in the breaker box. But in newer homes, they have their own separate bus bars, but these bars actually connect in common at some point at your service entrance.

An interesting thing about AC neutral, is that if you were to test a live circuit using a static charge meter to measure charge, neutral would not show any charge accumulation (it is charge "neutral"), while the hot wire would show charge present. If you had this circuit controlling some device (maybe a light fixture) and the light fixture was in the ON position, and you cut neutral open, you would notice the two neutral wires would spark when you touch them together, suggesting that charge is present. Likewise, if you were to complete this neutral circuit, perhaps with your body, you would also get shocked, maybe even electrocuted. But if the device's switch (perhaps the light switch) is in the OFF position, you would be safe. This is because the neutral circuit is essentially "anchored" to ground (nearly 0V). Still, never take chances when working with electrical equipment and always turn power OFF before working on its circuitry.

AC Power Outside the US: We have been focused on AC power systems of the US, where American appliances are generally powered from 115V, 50-60Hz. You should note that European outlets deliver 230V at 50Hz. Many modern AC appliances in the US will still be compatible with both voltages, and may run from 115-230V, or will include a switch to optionally power them from 230V. Still, European outlets do not accommodate the two flat prongs of the US plugs and will require an adapter to connect to power. For example, British and Irish outlets use three rectangular prongs, and Continental European outlets utilize two round plugs. Likewise, if your appliance does not accommodate 230V AC power, you will need a voltage converter with an adapter, otherwise the 230V, 50Hz European power outlet would likely reduce your 120V AC appliance to junk very quickly, and could even start a fire. Other countries have other AC standards and these should be checked if travelling abroad with US appliances (some example outlets and plugs are shown below).

THE GROUND LOOP

In an electric circuit, potential difference or voltage is the force that drives current flow. A ground loop refers to unwanted current flow that occurs when a circuit is grounded at more than one potential. Specifically, it is the unwanted signal pickup that results from a shared path to ground. In a way, you could say that a ground loop results when you have too much ground (specifically more than one connection point to ground). In any circuit that covers some distance, the chance that more than one ground point could be made is very high, as all conductors have some resistance, and current flowing through this resistance will always produce a voltage difference along that conductor. The important thing to remember about ground loops is that they usually result in unwanted noise and interference, and also drive measurement error. Severe ground loops can even create the potential for electric shock. There are only two remedies for combating the negative effects of ground loops: signal isolation and/or the use of star grounding in wiring multiple ground paths (more on this later). Usually, ground loops are created accidentally and extra connections to earth ground are not always obvious. For example, devices that connect to a USB port of a personal computer will make a connection to earth ground through the computer, which has earth ground of its power plug connected in common to its chassis and to the USB signal and shield ground. Likewise, double-shielded Ethernet Cable may also connect to earth ground at the network interface of a personal computer. You may inadvertently connect earth ground at more than one point in your circuit via a grounded scope probe.

Ground loops are covered in more detail in another Acromag whitepaper, **The Importance of Isolation (8500-988)**. You can download this and other information at **www.acromag.com**.

In Part 2 of this series (**see document 8501-020**), we will look at the aspects of earth grounding as a means of protection from shock and fire via ground faults. Part 2 will also review how ground fault current interrupters (GFCI) work to protect you from fatal electrical shock.

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