

Best Practices for Grounding Your Electrical Equipment White Paper

Part 2 of 3:

**Examining our use of ground as protection,
and how ground fault circuit interrupter devices operate to protect us from severe shock.**



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Preface

This paper is part two of a three-part series that examines grounding and its role in protecting personnel, protecting equipment, and ensuring the integrity of electrical signals. In this part, we will examine our use of ground as a means of protection from ground faults, and how ground fault circuit interrupter (GFCI) devices operate to protect us from severe shock.

[Part one of this series](#) addressed the concept of grounding, the AC power system and its use of ground, and gave three main reasons why we ground electrical equipment: for safety, to stabilize electrical signals, and to limit transient voltages and current.

[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.

Grounds as a Means of Protection

In Part 1 of this series, we said that one reason we connect to ground is for safety because it provides an alternative path for [fault current](#) to flow. The voltage in a circuit will force current to travel all available conductive paths back to the source. Most of this current will follow the path of least resistance. We normally provide an earth ground connection as an alternative low-resistance path for this current flow to limit shock (as an alternative path to using your body to return current to AC neutral and earth ground). For AC powered circuits, a ground fault is any event that causes an imbalance in current flowing in the AC hot lead with current flowing in the AC neutral lead. The ground fault current refers to the difference in current flowing between AC hot and AC neutral, and it could be the current flowing in the earth ground lead or the current taking another path back to the AC source, like through a body to earth ground (because AC neutral and earth ground are tied together at the source).

For AC powered devices, appliance manufacturers go to great lengths to make sure that you do not become the path of least resistance for a fault condition, which allows current to flow from AC hot back to AC neutral/earth ground via your body (Remember that AC neutral and earth ground are held in common at the source of the AC voltage). They do this by properly insulating their product and/or by providing a remote connection to earth ground at the product (via that third rounded conductor at your power outlet). That is, a conductive enclosure or housing of the device will typically connect to earth ground. Then if the AC hot or AC neutral wire to the device should fray or break, it could contact earth ground and complete the circuit, allowing the breaker to trip when its rated limit is reached, possibly preventing a fire, and hopefully without electrocuting yourself in the process. Of course, some appliances are constructed using insulating materials and do not connect their chassis to earth ground (they connect to AC using two-prong power cords). Under normal operation, the current to the device flows from between AC Hot and AC Neutral, through your load, and returns to your breaker box and utility meter power connection. The third wire, or earth ground wire, will become the return path for at least part of that current, should a fault occur at the powered device. Without this third conductor or alternate path held in reserve, your body could become the return path of least resistance to earth ground, and this could drive serious injury. Thus, for most 3-conductor AC wired equipment, its connection to earth ground is primarily to provide a safe path for current to flow in the event of a circuit fault, and normally, no current flows in the ground wire. By limiting current flow in the ground wire to only under certain conditions (ground faults), this helps to ensure that there will be no potential difference across this conductor, and it can better act like an extension of earth ground itself (i.e. nearly 0V).

So, what does a wired earth ground really protect you from? Does it protect you from electrocution? And what if your appliance does not include a connection to earth ground and you become the path of least resistance for some sort of ground fault? The answer to these questions is that a wired ground does not protect you from fatal shock. Rather, a GFCI can protect you from fatal shock.



The GFCI and its use of Ground as a Means of Protection from Ground Faults



To further illustrate how earth ground works as a means of protection, let's examine the behavior of a device that you may already be familiar with--the GFCI outlet. It looks similar to the picture at left, and usually includes a "Test" and "Reset" button. However, a GFCI protected outlet may look identical to a standard outlet if it happens to be connected downstream to the load side of a GFCI outlet.

You probably have several of these in your home, perhaps in your kitchen, laundry room, basement, bathroom, garage, or at an outdoor outlet. You probably know that these outlets are used to help protect you from severe shock, and are generally required in "wet" areas, but you may not have given much thought to how this device actually works with ground to help protect you from harmful levels of shock.

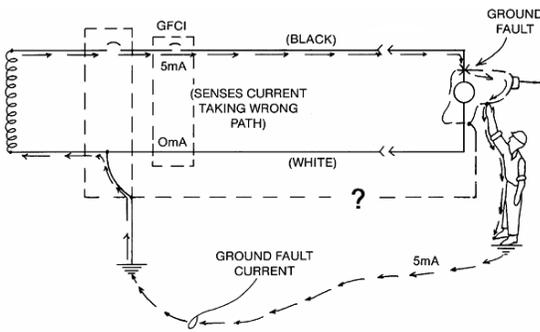


In addition to GFCI outlets, there are Ground Fault Circuit Interrupter (GFCI) Breakers similar to the examples shown at left. These act similar to GFCI outlets, but will protect an entire circuit from ground faults, while the GFCI outlet only protects at its outlet and any downstream outlets for daisy-chained "load" outlets. The advantage of a GFCI Breaker is that you do not need local GFCI outlets. GFCI Breakers are typically used on circuits where the likelihood of fatal shock is much higher (like a public swimming pool), and like a GFCI outlet, they can typically stop current flow within 25ms of detecting a ground fault condition on their branch circuit.

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.

As we noted in Part 1, the AC outlets in your home commonly provide 3-wires or conductors for connection to your appliance—a line hot connection (typically via a black insulated wire that connects to the shorter vertical slot of the outlet), a line neutral connection (typically via a white wire that connects to the taller vertical slot of the outlet), and a ground connection (typically via a green insulated or bare copper wire that connects to the round hole of the outlet at the top or bottom between the two vertical slots). In any circuit, current will seek all conductive paths back to its source, but most of this current will flow the path of least resistance. In your home, when you plug an appliance into an AC outlet, you give current a low-resistance path to flow through and power your appliance, and then return via the outlet to its source. The source in this case is where your home or business connects to the power line, usually at your power meter and service entrance. Remember, although AC neutral and AC ground are separate conductors at your outlet, they do connect at your service box and connect to earth ground near this box, usually via one or more grounding rods driven into the earth. Load current normally flows out the line/load hot conductor, through your appliance, and returns to earth ground via the neutral conductor, and doesn't normally flow in the ground conductor.

GFCI refers to a type of power outlet called a Ground Fault Current Interrupter. The GFCI outlet will usually provide a second pair of screws for a load cable connection to allow it to connect to additional non-GFCI outlets in daisy-chain fashion, connecting them through itself to power (making it act like a GFCI breaker for downstream loads). This type of outlet can trip and quickly stop the flow of current through it and downstream from it to prevent serious injury if a Ground Fault occurs anywhere in the circuit. A Ground Fault would occur if the electricity (current) is allowed to take some other path back to the source, than neutral (including through a person's body), as the source is where neutral, and ground connect to the earth. A GFCI outlet works to protect you by measuring the amount of current flowing out the "Hot" wire circuit into the appliance and monitoring the return current flowing out of the appliance back through the "Neutral" circuit.



If the current returned in neutral does not match the current in the hot line, the GFCI will trip and interrupt the current flow out of the hot wire. Of course, the “lost” current doesn’t really go “missing,” but has temporarily found some other path back to the source, perhaps through yourself to earth. This errant path is the ground fault we refer to and the GFCI feeding this circuit will trip very quickly to prevent serious shock or electrocution via current in this errant path.

The figure at left depicts one example of a ground faulted circuit. It shows one phase of an AC line (like that sourced from a service panel) powering a hand drill through a GFCI outlet or breaker. The black AC hot wire to the hand drill makes contact with its metallic housing (causing a ground fault), and a workman standing

on the ground and holding the drill completes a path to earth for a portion of the circuit current. Because this circuit was made through a GFCI outlet or breaker, the small leakage current triggers a relay in the black hot lead to the drill to open and stop the flow of current, protecting the workman from severe shock.

It's important to recognize that a GFCI does not protect against circuit overloads (too much load current), short circuits between hot and neutral, or minor electrical shocks. The man in the example above would still feel a small shock when he makes contact with the hand drill. And, even with a GFCI protected circuit, you can still be shocked if you touch bare wires while standing on an insulating surface, such as a wood floor, and you happen to complete the neutral current path. The GFCI only protects against current flow that does not completely follow its normal safe path along neutral to earth ground at your service panel but uses some other errant path to reach the earth instead. The other path could be through a person's body to earth ground, or even through the ground wire to earth (perhaps via a hot or neutral short to the grounded chassis of the load device, like in the example above).

Because the GFCI outlet trips to interrupt current when it detects a ground fault (a mismatch in hot and neutral current), it also contains a reset button used to reset its trigger mechanism. This reset has a lockout feature that keeps it in reset for any of the following:

- There is no power being supplied to the GFCI.
- The GFCI has been mis-wired by reversing the line-in (source) and line-out (load) lead connections.
- The GFCI fails an internal test, indicating that it may not be able to provide protection from a ground fault.

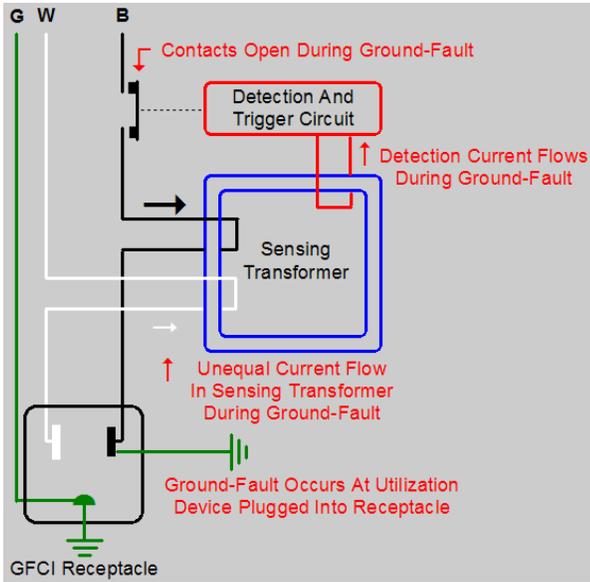
The appliance that you plug into your AC outlet typically connects its other metal parts to the ground connection (any other conductive parts other than its AC hot and neutral circuits). It does this so that if its own AC Hot circuit was to break or fray and accidentally come in contact with another of its metal or conductive surfaces (like its shell or chassis), that surface would instead become a path to ground. This path to ground essentially shorts AC hot to AC ground and causes the circuit breaker or fuse to quickly overheat and open the circuit, interrupting the current flow. The normal level of current to cause a typical breaker to trip is 15A or 20A, but the amount of current that can put the human heart into fibrillation is less than 100mA. So even if a person handling that faulty appliance happened to be barefoot and standing on wet ground, a portion of that branch current would also flow through that person to ground and this could still be fatal.

Generally, in a ground fault situation, the body path would provide a higher resistance path to earth than the grounded chassis and would only take a portion of this current. And just like two different resistive loads in a circuit, current is distributed along both resistive paths, but mostly along the path of least resistance. In the example of a grounded chassis, one path is through the ground wire and another through the body. But, even only a small portion of that 15A or 20A of branch current that flows just before the breaker trips is enough to stop the human heart. In the example of the hand drill, without GFCI protection, the workman may be killed. However, if the branch circuit happens to be passing through a GFCI protected outlet, the workman might still feel a momentary shock, but at a much lower current and of a shorter duration, as the GFCI will interrupt the hot current flow much more quickly than a circuit breaker alone.

In fact, a GFCI protected outlet or breaker will trip if the measured difference in current between the “hot” and “neutral” conductors is as little as 4-6mA. Momentary contact with 120V at 6mA will shock you, but will not likely put your heart into fibrillation, as the GFCI typically trips within 1/30th of a second as soon as it detects a hot/neutral imbalance, a small enough duration to protect you from fatal levels of shock.



Also note that for the purpose of discussion, we tend to think of and talk about AC current as flowing from the hot lead, through the device, and then returning on the neutral lead. However, AC current does not really flow in one direction or with respect to one polarity. Rather “AC” denotes Alternating Current and alternating current actually flows back and forth through the load (alternating its polarity), 50-60 times a second.



A GFCI outlet typically uses a differential or toroidal transformer to couple the line to the load, similar to the illustration at left. The current of the hot wire is magnetically coupled to the toroid and then passes to the load. The neutral wire from the load also passes through the toroid in the opposite direction and back to the service entrance of the house, where the line originates. These two wires are mutually coupled via the toroid or transformer magnetic material, such that for normal operation, the current that flows through the hot wire balances with the current that flows back through the neutral wire. But if these currents do not balance, this imbalance triggers a sensor circuit that drives relay contacts to open the Line hot circuit (black wire), interrupting its flow. Of course, the only way the hot and neutral line currents would not balance is if an external source is adding current to the circuit, or the line current is being leaked through some other external path (perhaps if line current is leaking to earth ground). A hot/neutral imbalance as small as 5mA is enough to quickly interrupt the flow of line current to the load, potentially protecting you from fatal levels of electric shock. In this way, the GFCI interrupts the flow of current much more quickly than the service entrance fuse or circuit breaker, in as quickly as 1/30th of a second.

Do not be fooled into thinking that a fuse or breaker alone can protect you from electrical shock. Rather, it's the purpose of a GFCI to protect you from electrical shock, while the purpose of a fuse or breaker is to protect its premises from electrical fire by limiting the maximum current and duration of excess current to a lower level, but not a low enough level to protect you from shock. Consider that there are many scenarios that could cause a hot wire to accidentally come in contact with the neutral or ground wire, causing a large amount of excess current to flow from hot to neutral. For example, an animal might chew through the wire insulation, a person might accidentally drive a nail or screw through the wire, or the cord connecting to an appliance might get chewed up after being pinched in a doorway or sucked up by a vacuum cleaner. The potential fault modes are endless and difficult to prevent. These faults will all cause excess current to flow and heat up the fuse or breaker and cause it to burn or break open, interrupting the flow of current, possibly preventing the wire from starting a fire. The problem with relying on a circuit breaker or fuse for shock protection is that they are tripped at much higher levels of current (15 or 20A typical), and after longer periods of time, both of which could be fatal if you happen to be in the path of this fault current.

We started this discussion by trying to show how a GFCI outlet works with ground to protect yourself, but the reality is that a GFCI outlet would still protect you from electrical shock due to a ground fault, even without a hard-wired connection to earth ground. That is, if the GFCI happened to be wired using 2-wire AC cables (hot and neutral but no earth ground), it still provides ground fault protection. This is because a GFCI outlet monitors for current imbalances between hot and neutral, not ground. The only possible difference in a 2-wire GFCI powered application is the ground fault current along the errant path could potentially reach a higher level without the third wire ground path present, but the outlet would still detect the hot-neutral imbalance and break the hot wire connection in time to protect you from severe shock.

We spent a lot of time talking about ground as a “safe” path for current, and this is because personal safety should be your number one priority, but we stated at the beginning of this paper that we have two other important reasons for connecting to ground: to stabilize signals and to limit transient voltage and current. In Part 3 of this series, we will discuss the other two reasons we connect to ground and give some tips for improving your connection to ground to realize the benefits of increased safety and signal integrity for your wired equipment.



Grounding Resources

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