Grounding Basics: AC & Household

Grounding Made ~~Simple~~ Simpler

The subject of grounding is a complex, multifaceted subject, that is often treated as an after-thought but needs to be considered from the beginning of the design and build process of any DIY Solar/Battery Project.

This is Part 1 of a 4-part series on grounding Basics.

1. **AC & Household (This Paper)**
   Part 1 covers the basics of grounding for household AC systems. Even if you are familiar with house wiring, it is suggested that the reader review this paper to become familiar with the terminology concepts and practices of grounding.
2. **Stationary Systems(Coming soon)**
   Part 2 introduces the grounding principles of DC wiring, inverters and multiple power sources.
3. **Solar Panels (Coming soon)**
   Part 3 is a short overview of how to properly ground the frames and mounting racks of Solar arrays.
4. **Mobile Systems (Coming soon)**
   Part 4 goes through designing the grounding scheme that addresses the unique situations encountered in a mobile system.

Each of the 4 parts are written to be usable and understandable as a stand-alone paper. However, to get a broad understanding of grounding and grounding principles, it is recommended that all 4 papers be read.

Note: This paper only gives a basic overview of grounding concepts and the NEC Grounding requirements.   It is NOT a comprehensive review of the NEC grounding requirements.

International Note: This paper is written with a North-American point of view.   However, many of the concepts are applicable elsewhere even if the implementation is not.

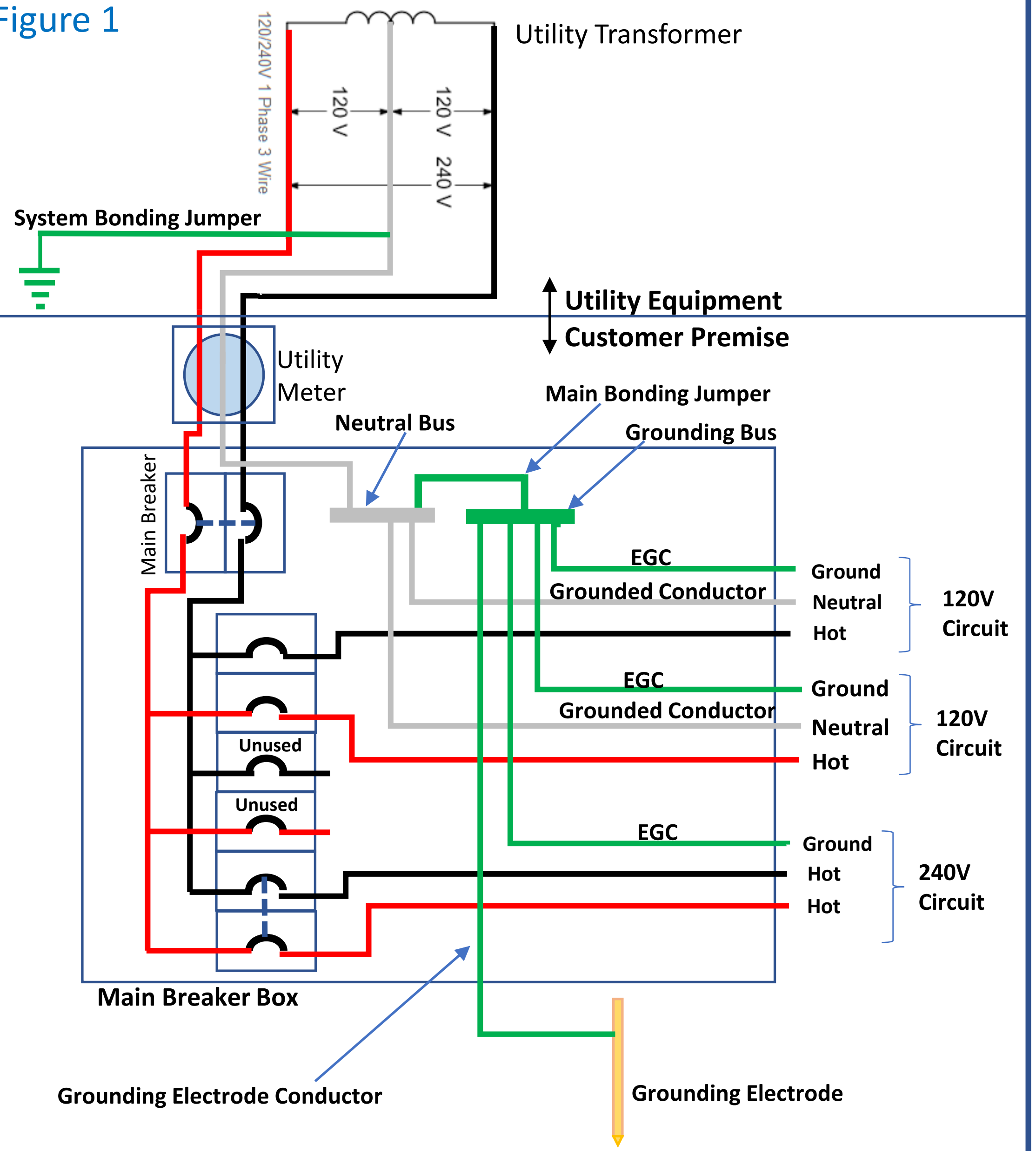
Definitions of Ground (<u>This is important to understand first!!</u>)

The term 'ground' means different things in different contexts and as such, it can cause confusion if precise wording is not used. This paper will use the definitions used by the US - NEC code:

- **Earth Ground -** This is a point that is electrically tied to the earth. This is often done with a copper rod that is driven 8' into the ground but there are other methods.
- **Bonding -** Bonding is electrically tying one conductor or conductive material to another. This term is often used to describe connecting AC Neutral to DC Negative or tying an Equipment Grounding Conductor to a non-current carrying metal component.
- **Equipment Ground<u>ing</u> Conductor** (**EGC**) – A conductive path that is part of an effective ground-fault current path and connects normally non-current-carrying metal parts of equipment together. The EGC system is usually tied to the grounded conductor (neutral conductor) and the grounding electrode conductor.
- **Ground<u>ed</u> Conductor -** This is a normally current carrying conductor that is bonded to ground. In household AC wiring the neutral wire is a Grounded conductor.
- **System Bonding Jumper –** This is a conductor between Ground and a current carrying conductor (Neutral) at the source. For US residential utility power, the source is the Utility transformer, so this is is done by the utility, not on the customer premise.
- **Main Bonding Jumper –** This is a conductor between the AC Neutral and Ground that is typically found in the main breaker box in the US. This re-establishes ground reference with the EGC because the utility does not supply a grounding conductor to the house.

International Note
Terminology for grounding varies significantly from one country to the next. Furthermore, the specific practices vary significantly from country to country but at the highest levels the problems are the same and solutions are often similar

Figure 1



Grounded conductors are current carrying conductors that are tied to ground
Grounding conductors are also tied to ground but do not normally carry current

Best Practices for Grounding.

There are a few basic best practices that, if followed, will go a long way in building a properly grounded system:

1) From any point on the equipment grounding system there should be only 1 path to the point that connects to earth ground. (No ground loops)
2) The exposed metal chassis of equipment and devices must be tied to the equipment grounding system.
3) Metal connection boxes and metal conduit must be tied to the equipment grounding system.
4) The AC equipment ground conductor should be routed with the associated current carrying wires.
5) AC neutral is bonded to ground at only one place in a house at any given time. (See International note).
6) If possible and allowed, the system should tie to the Earth Ground Electrodes at only one place.
7) For circuits that run 30A or less the equipment ground conductor should be the same size as the current carrying conductor. (For higher current circuits, use the NEC chart to look up wire size)
8) DC circuits
    1) NEC requires DC circuits that run at 50V or more must be bonded to ground at exactly one point. (48V LiFePO systems operate at above 50V)
    2) DC circuits less than 50V are optionally bonded to ground at exactly one point.

    Note: It is allowable to bond either the Positive or Negative branch of a DC circuit to ground (not both).

These are from a combination of NEC requirements and best practices. While these sound simple, the implications are not always obvious. The rest of this paper will discuss many aspects of grounding, how they apply to real-world situations and how they result in these best practices.

International note: Some countries do not allow Neutral-ground bonding anywhere in the house (See ‘5’ above)

AC Neutral To Equipment Ground bond.

AC Neutral must be bonded to the equipment grounding system in exactly one place on the customer premise. In the vast majority of US residential systems this is done at the service entrance/Main breaker box (Figure 1).

Neutral and ground must only be bonded together at one point. Otherwise, current would occur on the Equipment Grounding conductors between the two bonded points and create a significant shock hazard to anyone working on the system. (Figure 2)

In addition, if the neutral wire is broken between the two bond points, the full current of the circuit would be flowing undetected through equipment ground. This creates a significant safety hazard for anyone working on the system. (They would naturally assume there is no current or voltage on a ground wire).

One situation where the 'single bond' rule is often accidently broken is in sub-panels. A standard breaker box may not have common and equipment ground isolated or the installer might install equipment grounding conductors or Neutral conductors on the wrong bus bars or even install a jumper between Neutral and the grounding system (Figure 2)

The size of the bonding jumper between Neutral and Ground is determined by NEC Table 250.66 (shown in appendix A)

Note: Special situations around AC neutral bonding arise when there are multiple power sources such as utility, inverter and generator will be discussed in other papers

Figure 1

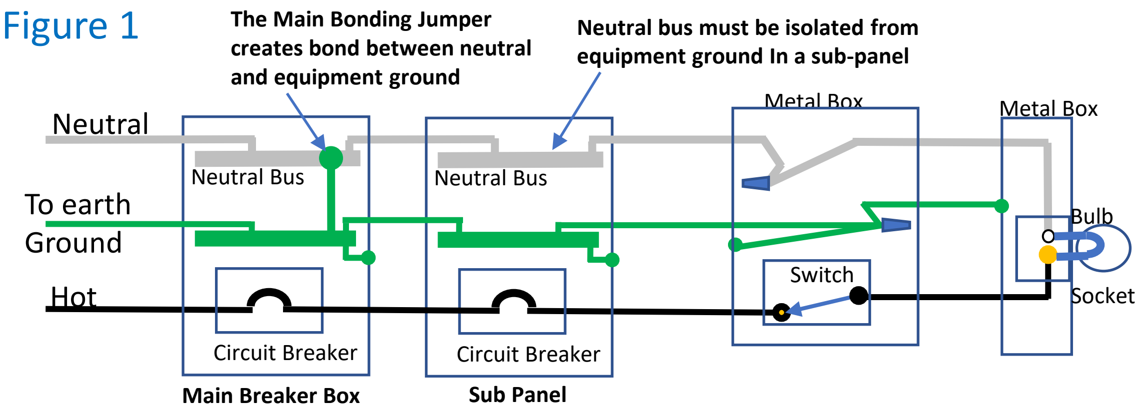
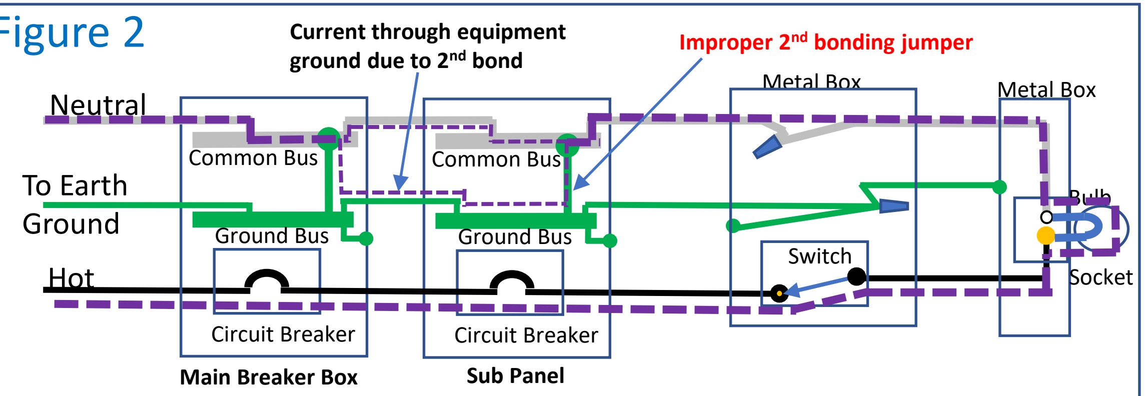


Figure 2



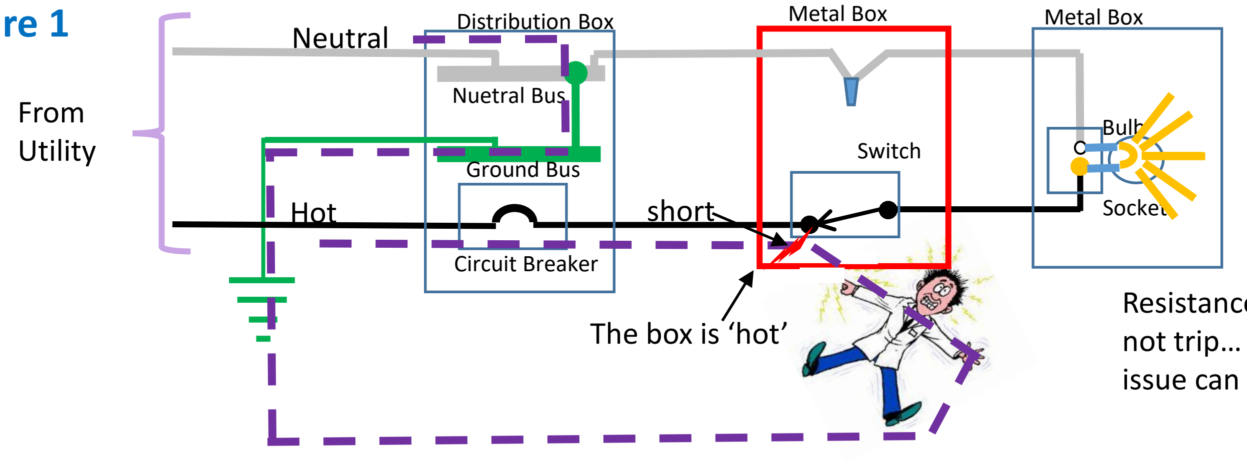
International Note:
Some countries have networks without local bonding of Neutral on the Equipment Grounding Conductors.

Primary purpose of equipment grounding conductor and Bond to Neutral: Clear a fault!

The objective is to trip the Over Current Protection Device (**OCPD**) on a short to non conducting metal

No Equipment grounding conductors

Figure 1

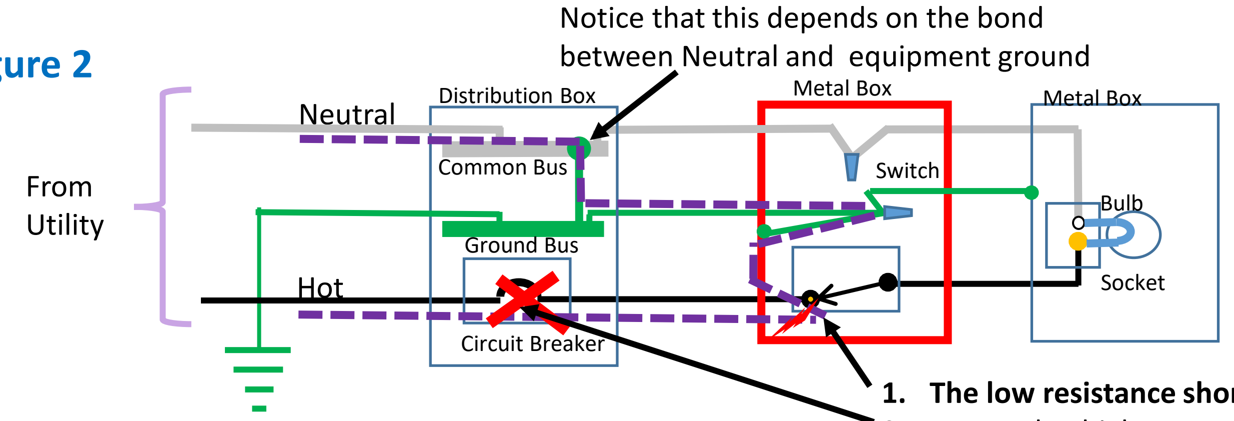


> **Warning:** Equipment ground does not protect against shock from direct contact with a hot wire

Resistance of the body limits current so the circuit breaker does not trip… but there can still be enough current to kill! The same issue can happen with exposed metal of plugged-in devices.

With Equipment grounding conductors

Figure 2



International Note:
Some countries have networks without local bonding of Neutral on the Equipment Grounding Conductor and they do not provide a low impedance path back to the neutral tie at the transformer. For these systems, a Residual Current Device must be used to detect and clear a short from hot to the equipment grounding system.

1. **The low resistance short creates a very high current surge** through the equipment grounding conductor
2. Due to the high current through the short, **the circuit breaker trips and immediately removes the voltage from the box.**

Notice that the tie to earth ground has nothing to do with clearing the fault.

Household GFCI

Household GFCI (Ground Fault Circuit Interrupter) systems have electronics that can detect even small (~6mA) current through ground and will disconnect both Line and Neutral if detected. Detection at such a low current level means that even contact with a hot circuit will likely de-energize the circuit before it harms you.

A GFCI breaker will also trip if there is an improper Ground-Neutral connection in the downstream circuit even if there is no load. (This is sometimes mistaken as a bad GFCI device).

It should be noted that the GFCI can detect current to earth ground even if equipment ground wiring is not present as is often found in older construction. This makes GFCI an easy way to bring older systems up to more modern safety levels. However GFIC circuits have integrated circuits that can and do fail so it is important to test them regularly. The newer models are attempting to design self-checks that, if they fail will not turn on… This reduces the possibility of a hot circuit being 'protected' by a failed GFCI.

Figure 1

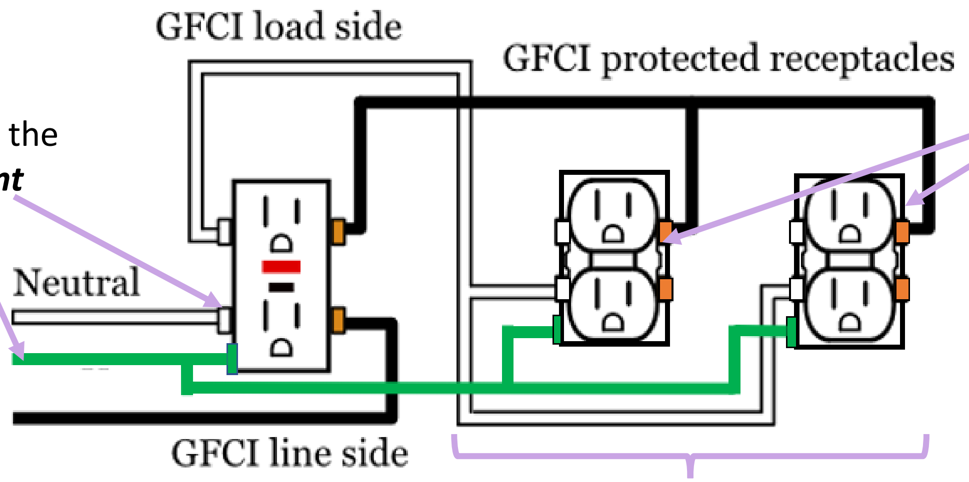
If ground is not available (old construction) the GFCI socket must be marked "***No equipment ground***"

From Main breaker Box

Neutral

Equipment Ground

Line



If ground is not available (old construction) additional sockets must be marked "***Ground Fault Protected. No equipment ground***"

Multiple regular sockets can be added to the load side of a GFCI breaker

Notes:

- The NEC requires GFCI in all outside or wet locations (Bathroom, kitchen, laundry room, etc).
- Many inverters have GFCI circuitry on their AC output.
- GFCI sockets are also known as RCDs (Residual Current Devices) in some parts of the world.
- Household GFCI is very different than Ground Fault Protection on PV Arrays in both purpose and implementation.

240V split phase and grounding.

In North America, residential power is delivered as 120V Split phase. This means that two separate 'hot' lines are brought to the house along with a center-tap neutral. The two hot lines are 180° out of phase with each other. This means that the two hot lines are 240v with respect to each other and 120V with respect to neutral. (Figure 1)

Note:
240V and 120V are RMS measurements. Actual peak voltages are higher.

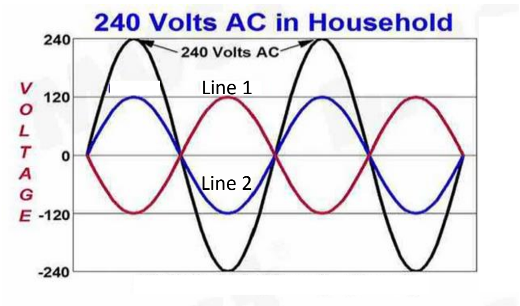


Figure 1

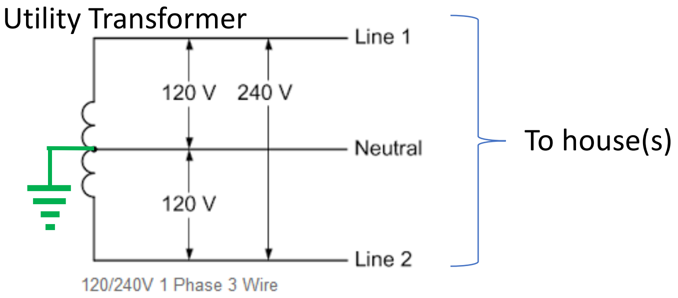


Figure 2

International Note:
Most of the world outside North America uses a single 240V circuit and does not use split phase systems for residential power.

This is implemented by the utility using a split-phase transformer (Figure 2). The Neutral line will always be grounded and, in North America, there is no Ground Wire routed from the utility to the residence.

When dealing with 240V in a split phase system, both of the power lines are hot. Since both lines are hot, the circuit breakers must be dual pole breakers that open both lines if either pole exceeds the breaker current limit.

Notice in Figure 3 that even though the 240V appliance does not use neutral, the bond between neutral and ground carries the short circuit current that trips the breaker. Since it is a dual pole breaker, both hot circuits are opened if either side trips. (Not using ganged dual pole breakers for split phase 240 is an extreme safety hazard.)

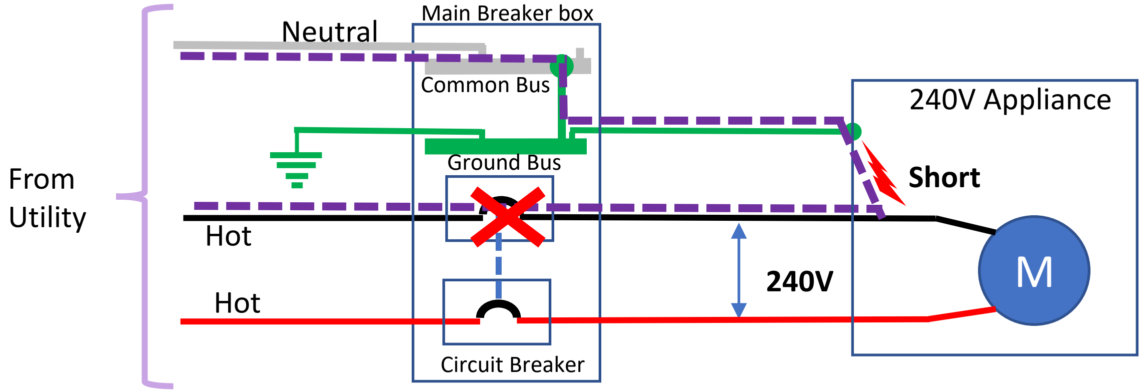


Figure 3

In the rest of this presentation, only 120 circuits between one of the Hot lines and Neutral is shown, but nearly all residential houses in north America use 120 V circuits from both of the hots to neutral. The principles are the same for 240V circuits and 120 volt circuits.

Creating Earth Ground.

A common method for creating the connection to earth is by driving a copper rod at least 8 feet (Or below the frost level) into the ground and attaching to it with a weld or an approved ground clamp device. (For US Utility supplied power, this bonding is required to be done at the service entrance of the power grid and be no more than 25 ohms resistance to earth ground. It is possible to get adequate grounding with a single grounding rod, but a second rod is often needed. Many inspectors will just expect two electrodes. (There is a complex set of requirements around earth-grounding rods that is beyond the scope of this paper)

A building or structure may have many items that act as an electrical connection to earth ground. Some of these include metal water pipes, concrete re-bar, and structural steel. The NEC code requires all of these to be tied to the grounding system in new construction. However, due to the unreliable nature of using plumbing as the electrode, plumbing is no longer considered sufficient, and a separate grounding electrode must be installed. (Building structural steel can be the primary grounding electrode if it meets all of the NEC requirements)

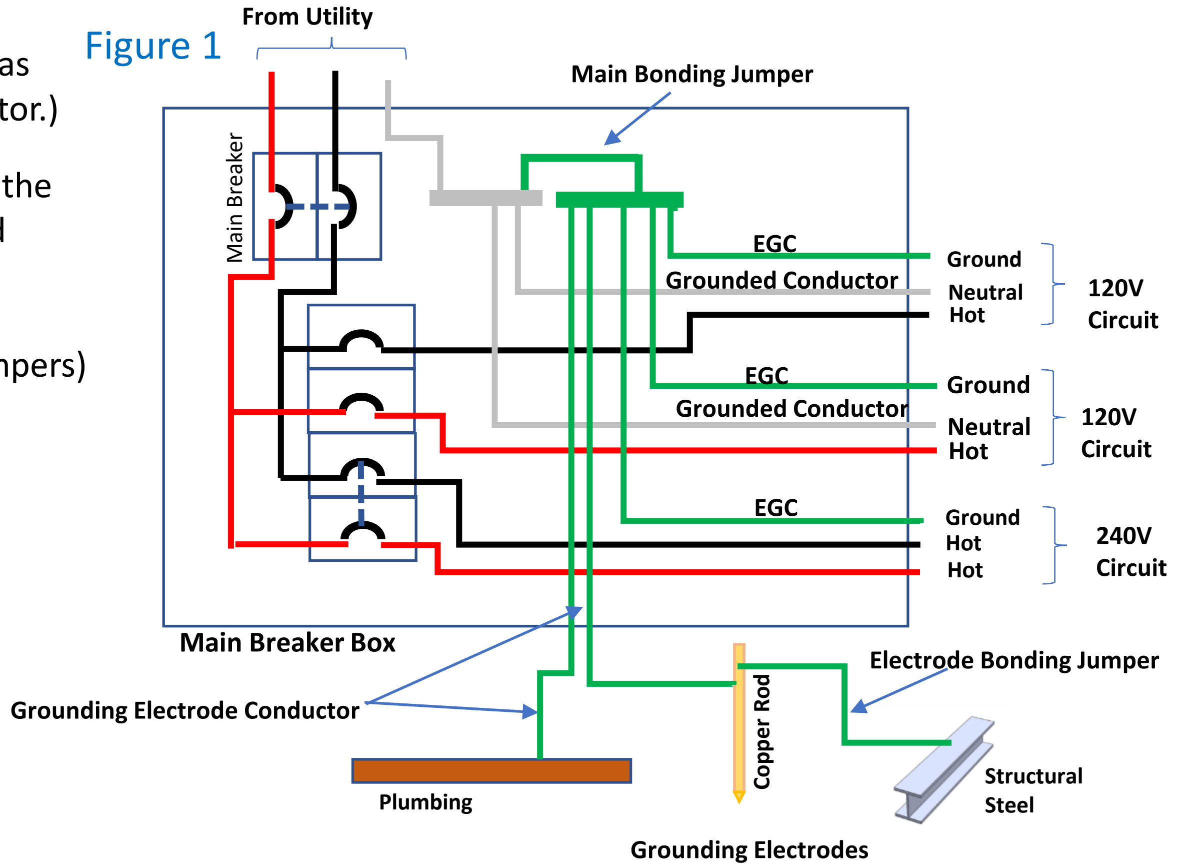
Once ground is established, it is tied to the Equipment Grounding conductors (EGCs) as well as the Grounded Conductors. (In this diagram AC Neutral is a Grounded Conductor.)

Notice in the diagram that there are multiple ties to earth ground, but they all tie to the same point for connecting to the equipment grounding conductors and the grounded conductor. This can be done with multiple Grounding Electrode Conductors and/or with daisy chained Electrode Bonding Jumpers. (It is best to have a single Grounding Electrode Conductor and daisy chain all of the electrodes with Electrode Bonding Jumpers)

The size of the grounding Electrode conductor is determined by the NEC table 250.66 (See Appendix A)

International Note:
In some countries the earth-grounded wire is provided by the utility company and not created on the customer premise. The implementation seems quite different but the purpose of tying to Earth Ground remains the same.

Figure 1



Why tie to Earth Ground at all??

In electrical systems, metal components can build up a significant electrical charge without actual contact with an energized wire. This can happen for a couple reasons:

- Static Charge
- Lightning strike

This may seem like an unlikely problem in DIY solar systems but think about times when you have touched something and got a static shock. The voltage from the shock was quite high. Even though it did not hurt you, the voltage from that shock was high enough that it could damage electrical components. In extreme cases the shock can be strong enough to injure you. In addition, wires running outside to solar panels are particularly susceptible to static build up and electrical storms even if they are not directly hit by lightning.

By tying Equipment Ground and Neutral to earth ground, these induced charges do not build up in either the current carrying circuits or any of the non-current carrying metal that is connected to earth ground. The helps prevent electrical shock as well as equipment damage from these induced charges.

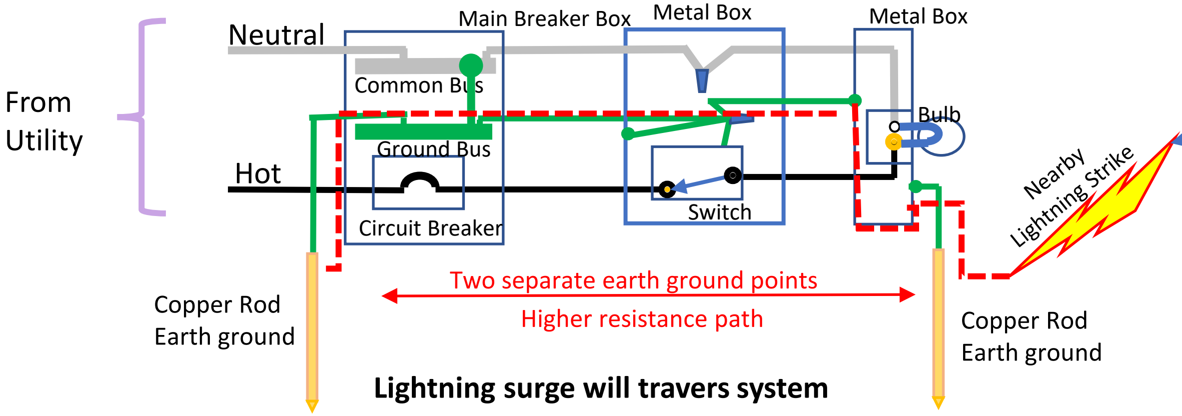
Note: Despite what you might have heard, tying the system to earth ground is not about making the system safe from short circuits. It is only about draining the induced voltage/charge. Furthermore, it does not protect against a direct lightning hit. It can only help prevent problems from nearby strikes.

Note: Something that is not tied to earth ground is considered ‘floating’ and is susceptible to these built-up charges.

Multiple ties to Earth Ground should all be at a single point.

The NEC allows and sometimes requires multiple points in the system to be tied to earth ground, but it should be avoided where it is not required. In a lightning strike the equipment grounding conductors could see a high voltage surge of current trying to equalize the two separate earth ground points(Figure 1). By having all earth ground points go to a single common grounding point, any surge current is limited to the Grounding Electrode Conductors (Figure 2). Having a single Grounding Electrode Conductor going to daisy chained Grounding Electrodes is best. (Figure 3)

Figure 1 BAD



In the event of a lightning strike, there is an earth voltage gradient. The voltage difference between two separate earth grounds can cause extremely high surge currents through the low resistance equipment ground

Equipment grounding conductors should NOT be tied to earth ground at multiple points!

Figure 2 BETTER

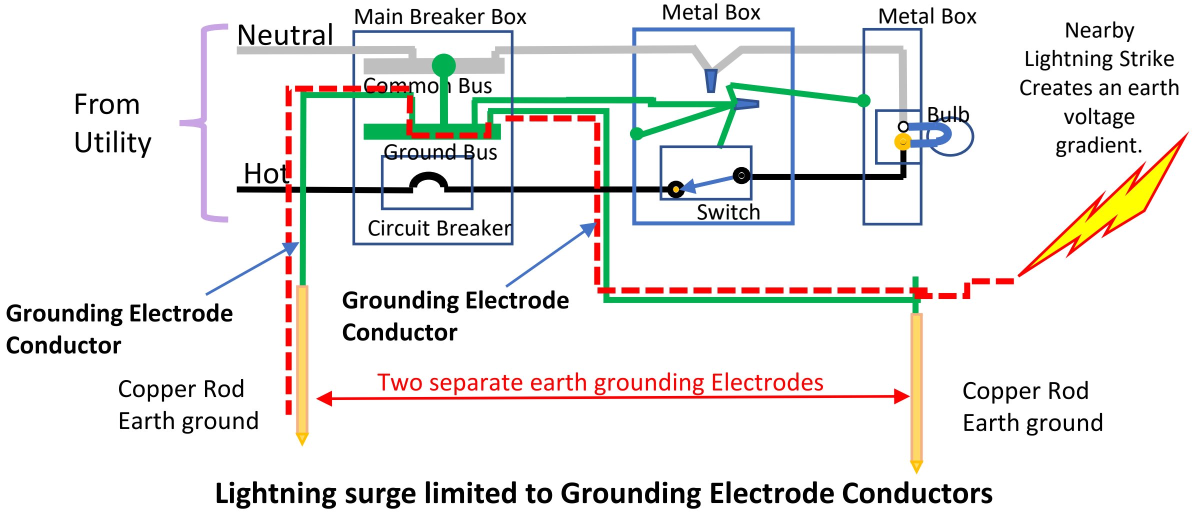
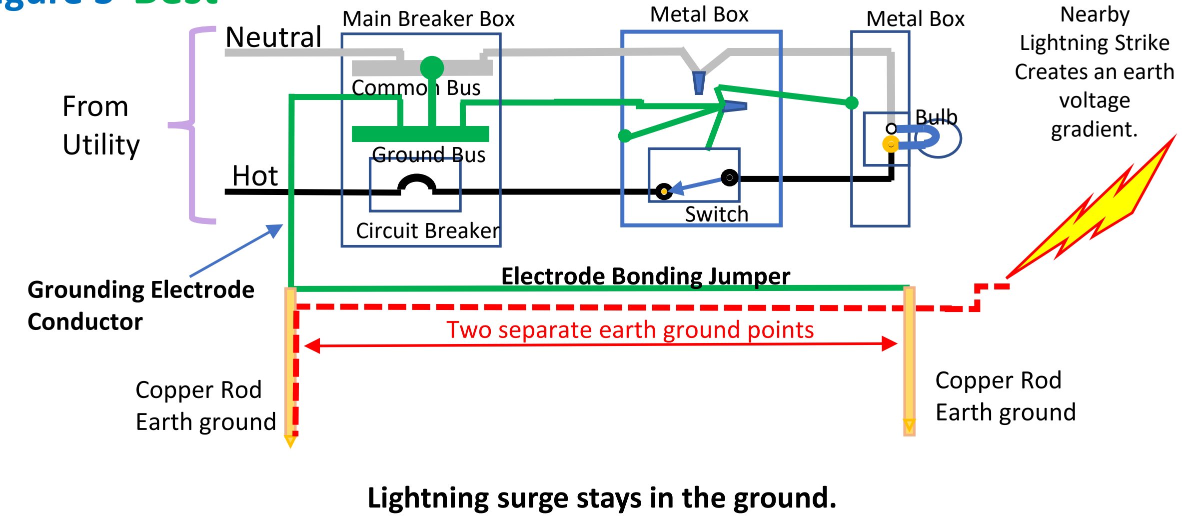


Figure 3 Best



Equipment Grounding Conductor Wiring guidelines

- The equipment ground conductor (ECG) should be routed with the current carrying conductors for the circuit.
- In order to minimize RFI issues, there should be only one path from anyplace on the equipment ground conductor back to the common grounding point. If there are multiple paths, it creates ground loops that form antennas and cause difficult to diagnose problems.
- For most US household wiring (30A or less), the equipment ground conductor will be the same gauge as the circuit it is protecting. For currents, above 30A, see the NEC table 250.122 in Appendix B.

  Notice that in Table 250.122, the ground conductor is often sized for ampacity lower than the Over Current Protection Device. This is because the surge current of a short circuit will be very short in duration.
- A single Equipment Grounding Conductor may be used in a conduit carrying multiple circuits. The Grounding Conductor must be sized for the largest Over Current Protection Device (OCPD) of the various circuits in the conduit.
- Earth Ground can not be used as an Equipment Grounding Conductor. Doing so can create dangers in both lightning and short circuit scenarios because the connection to earth can be a high impedance path.

Figure 1

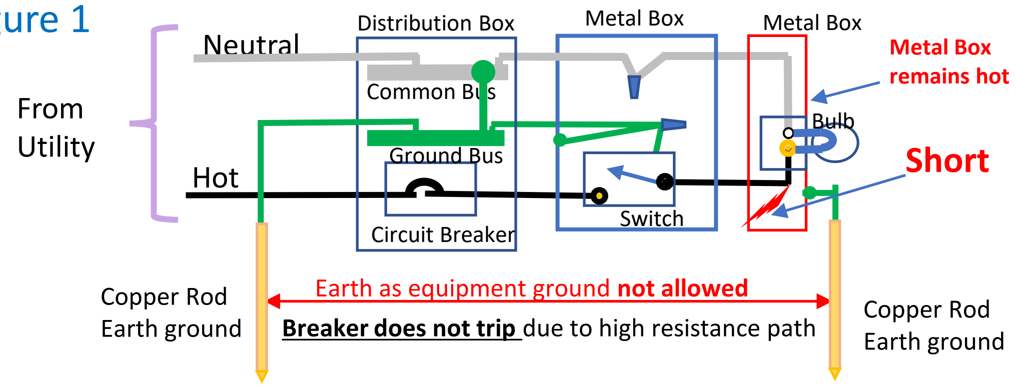
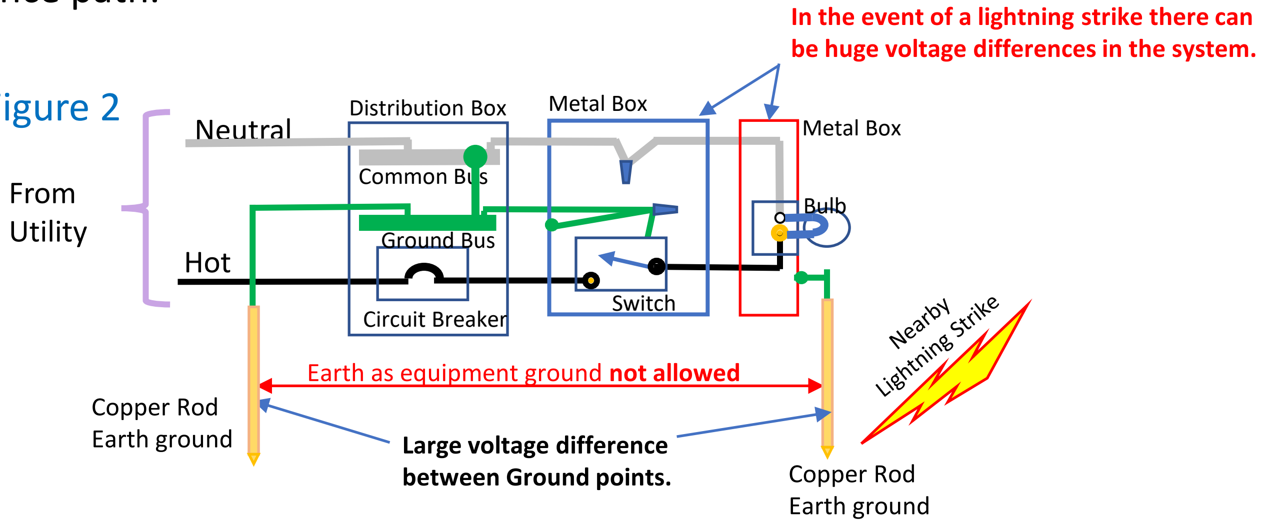


Figure 2



Appendix A: NEC Table 250.66

International Note
The sizing requirements for the grounding electrode conductor may be different outside the US

Grounding Electrode Conductor for Alternating-Current Systems Alternating-Current Systems

Size of Largest Ungrounded Conductor or Equivalent Area for Parallel Conductors (AWG/kcmil)		Size of Grounded Conductor or Bonding Jumper* (AWG/kcmil)	
Copper	Aluminum or Copper-Clad Aluminum	Copper	Aluminum or Copper-Clad Aluminum
2 or smaller	1/0 or smaller	8	6
1 or 1/0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250	4	2
Over 3/0 through 350	Over 250 through 500	2	1/0
Over 350 through 600	Over 500 through 900	1/0	3/0
Over 600 through 1100	Over 900 through 1750	2/0	4/0
Over 1100	Over 1750	3/0	250

1. If multiple sets of service-entrance conductors connect directly to a service drop, set of overhead service conductors, set of underground service conductors, or service lateral, the equivalent size of the largest service-entrance conductor shall be determined by the largest sum of the areas of the corresponding conductors of each set.

2. Where there are no service-entrance conductors, the grounding electrode conductor size shall be determined by the equivalent size of the largest service-entrance conductor required for the load to be served.

This table also applies to the derived conductors of separately derived ac systems.

For Aluminum GEC conductors, see installation restrictions in 250.64(A).

Appendix B: NEC Table 250.122

International Note
The sizing requirements for equipment ground may be different outside the US

Table 250.122 Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size (AWG or kcmil)	
	Copper	Aluminum or Copper-Clad Aluminum*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	1/0	3/0
1000	2/0	4/0
1200	3/0	250
1600	4/0	350
2000	250	400
2500	350	600
3000	400	600
4000	500	800
5000	700	1200
6000	800	1200

Note: Where necessary to comply with 250.4(A)(5) or (B)(4), the equipment grounding conductor shall be sized larger than given in this table.

*See installation restrictions in 250.120.

Corrections

Feedback, Corrections and suggestions are welcome.   You can post them in the comment section for the resource at the following link.

< Fill In Link>

Updates to this document can be found there as well.

About the author

I am *not* a licensed electrician.

I have a degree in electrical engineering.   I know a lot about electrical wiring, solar systems and batteries from both personal experience and on-line research.   I have studied a lot of the NEC code but do not consider myself an expert on it.

I gladly share my knowledge for free to the DIY community, but you should not consider my information as 'professional advice’.