Grounding Power Distribution Systems

High resistance?
Low resistance?
Solidly grounded?
Ungrounded?

Which type should you use?
Ground verb: 1: to bring to or place on the ground: 2: to cause to run aground 3: to throw a football intentionally to the ground to avoid being tackled for a loss: 4: to connect electrically with a ground 5: to furnish a foundation of knowledge.

According to Merriam-Webster’s dictionary, there are many definitions for the word “ground,” but how do we know which one to use? Fortunately the National Electrical Code® (NEC®) Article 100 provides us with a better description:

Ground. A conducting connection, whether intentional or accidental, between an electrical circuit or equipment and the earth or to some conducting body that serves in place of the earth.

The NEC is pretty clear about the definition of an electrical ground. However, when you begin to design an electric power system, you discover that the word “ground” has a few modifiers that describe the type of ground, such as:

- Solidly grounded
- Un(grounded)
- Resistance ground
- Reactance ground

To help further clarify the various types of grounding, the NEC offers additional guidance by providing two other definitions.

Solidly Grounded. Connected to ground without inserting any resistor or impedance device.

Effectively Grounded. Intentionally connected to earth through a ground connection or connections of sufficiently low impedance and having sufficient current-carrying capacity to prevent the buildup of voltages that may result in undue hazards to connected equipment or to persons.

Both of these definitions refer to a connection to earth, or ground, and both refer to the word “impedance.” These two concepts help define the types of grounds available for power distribution systems. Impedance can be comprised of resistance, inductance and capacitance and limits current flow based on the total magnitude of the impedance measured in ohms. When AC current flows through a resistive component (resistor), it will be in phase with the voltage. Current flowing through an inductive element will be 90 degrees behind the voltage (lagging), and current traveling through a capacitor will be 90 degrees ahead of the voltage (leading). Although all three components can make up the total impedance, the most common element used for impedance grounding is the grounding resistor.

The NEC contains specific articles that dictate when you shall ground, when you shall not ground, and when you are permitted – but not required – to ground. These code requirements are based on various factors such as whether or not there are connected phase to neutral loads, whether only qualified persons service the installation, and operating voltage levels.

The main goal of solidly grounding a power system is to provide a low-impedance return path for short circuit current during a line to ground fault. This helps produce a current with a large enough magnitude to enable protective devices to quickly clear the fault. Grounding is also used to stabilize the line to ground voltage during normal operations, and it limits voltage during abnormal surges such as lightning or accidental contact with higher voltage lines.

All of these goals help to improve safety and minimize damage. However, not all power systems are solidly grounded. Depending on the NEC requirements for a given system, there may be a choice between types of grounding so consideration must be given to the advantages and disadvantages of each. Whether the choice is solidly grounded, ungrounded or impedance grounded, the type of grounding used will affect many variables. The single biggest impact is on the magnitude of current that could flow due to a ground fault and the possible damage that the current could create.

Solidly Grounded Systems
The most commonly used grounding configuration for industrial, commercial and institutional power distribution systems is the solidly grounded system. NEC Article 250.20 defines when an AC power distribution system shall be grounded. In general, with few exceptions, systems that operate between 50 and 1000 volts AC with line to ground voltages of less than 150 volts and/or systems with line to neutral loads are required to be grounded. Article 250.21 defines systems that are not required to be grounded but that are permitted to be grounded. Systems 1000 volts AC or greater are permitted to be grounded unless they supply mobile or portable equipment; then they shall be grounded as specified in Article 250.188.

The 150 volt line to ground threshold that requires a system to be solidly grounded is based on laboratory experiments and case studies. If there is less than 150 volts across an arcing gap, the arc rarely can sustain itself. By having a solidly grounded system, there is a greater likelihood of developing sufficient short circuit current so an overcurrent device would trip the faulted circuit off line.
NEC Article 230.95 requires that ground fault protection of equipment be provided for solidly grounded wye electrical services rated more than 150 volts line to ground but not exceeding 600 volts phase-phase for each service disconnecting means rated 1000 amps or more. There are exceptions for fire pumps and continuous industrial process systems where a non-orderly shutdown will introduce additional or increased hazards, but in general this applies to most solidly grounded systems in the 480Y/277 volt range. In addition, Article 215.10 has similar requirements for feeders.

The most common ground fault protection method used to comply with these Code requirements is a “residually connected scheme.” This scheme requires the summation of currents from all three phases, usually from current sensors, at a wye connected summing point. In a fairly balanced system, the sum of all three phases based on the 120-degree phase displacement is zero. If a ground fault occurs on one of the phases, there will be more current flowing on that phase than the others and the sum of all three phases at the wye connection is no longer zero. This results in the residual current flowing through the ground device and tripping the circuit off line. In reality, the ground device is not really tripping directly due to a ground fault but rather in response to an unbalance that is caused by a ground fault. Unfortunately this means that a significant load unbalance could possibly nuisance trip the device as well.

When ground fault protection is used on the service only, a possible problem may exist. This presents the possibility of tripping a facility’s entire power distribution system off line for a localized ground fault, rather than just tripping a smaller downstream breaker. Since ground fault devices tend to be quite sensitive, responding quickly to low levels of ground current in a matter of cycles, they do not always coordinate with smaller branch overcurrent devices downstream. It is quite possible that a lower magnitude ground fault on a smaller branch circuit could trip the main overcurrent device’s ground fault protection instead of one of the smaller downstream breakers. The time-current graph below illustrates coordination between a 2000 amp main circuit breaker and its corresponding ground fault function, and a 225 amp downstream circuit breaker. The graph’s current axis indicates that for ground faults occurring in the range of 500 amps to just below 2000 amps, the main breaker’s ground fault function would trip rather than the 225 amp breaker. The result is a major outage for a minor event.

Ungrounded Systems
Where service continuity is a prime concern and tripping the power distribution system off-line due to a ground fault cannot be tolerated, ungrounded systems are commonly used if they are permitted by the NEC, which includes not having any line-neutral loads. Although an ungrounded system has no intentional connection to...
ground, there is a weak connection via capacitive coupling from the power system conductors and equipment to earth.

Capacitance exists between any energized conductor and ground or between two energized conductors; in each case air acts as the dielectric for the capacitor. Capacitance is an impedance, which restricts current flow depending on its magnitude. In an ungrounded system, the impedance magnitude is extremely high, approaching infinite, but it still allows a very small current to flow, which produces weak coupling to ground in ungrounded systems.

The major advantage of an ungrounded power system is that when one phase shorts to ground, there is no solid return path through which current may flow. There is usually only the very small current flow due to the capacitive coupling and in low voltage systems that is usually only 1 or 2 amps. The absence of any significant current during a ground fault means the power system can remain energized and the process can continue to operate.

However there are disadvantages to using ungrounded systems. When a ground fault is intermittent, which is usually the case, large overvoltages can occur between the phase conductors and ground due to the system capacitance. This causes high voltage transients, which can damage conductor and equipment insulation.

During a ground fault, the phase-neutral voltage increases to a phase-phase voltage. Figure 1 illustrates a comparison of the voltage vectors under normal conditions for a solidly grounded system and an ungrounded system. Figure 2 shows the vectors of the two systems under ground fault conditions. The grounded system’s voltage on the grounded phase goes to zero (in theory, depending on how solid the connection is). The ungrounded system has the neutral point shift and the grounded phase’s voltage goes to zero. The shifting of the neutral point produces phase-phase voltage between the remaining ungrounded phases and ground/grounded phase.

NEC 250.21 requires that ground fault detectors be used in ungrounded AC systems with an exception for voltages less than 120 volts line-ground. Ground fault detection is necessary because if the first ground fault is not found and corrected, a second ground fault on a different phase would produce a phase-to-phase short circuit and substantial current would flow, tripping overcurrent devices and possibly causing damage.

When the ground fault detector indicates a fault has occurred, the system can usually continue to operate, but the fault must be located and cleared as soon as possible. Locating a fault on an ungrounded system is not an easy task. It usually is a matter of trial and error, switching circuits off and on while monitoring the detector’s status to determine which circuit is faulted.

**Resistance Grounding to Reduce Ground Fault Current**

Think about the last time you or a colleague experienced the effects of a short circuit. How bad was it and was there much damage to equipment? What caused it and how long did the outage it created last? If the power system was grounded, chances are it was a line to ground fault where only one phase was involved. Statistics show that ground faults make up the great majority of all short circuits, since it is more likely that one phase will fail rather than multiple phases failing
together. In fact, a three phase short circuit usually requires a little “additional help” like a backhoe or overhead crane.

A ground fault frequently begins as an intermittent low magnitude arcing current that does not produce the extreme mechanical forces found with higher magnitude faults. That sounds like a ground fault does not produce much damage but as it turns out, ground faults can be even more destructive than bolted (solid contact) faults. The extreme heat of the arc can cause fires, and voltages can create safety issues. An arcing ground fault could even produce a current with a magnitude so low and intermittent that phase overcurrent devices might not be sensitive enough to respond quickly, if at all.

At the other end of the spectrum it is possible to have extremely high magnitude currents produced by bolted ground faults. Depending on the location of the fault and the impedance of various circuit elements such as the source, transformers and conductors, the ground fault current could be larger than the three phase fault current at the same location. An example of where the ground fault current sometimes is larger than the three phase current is at the secondary of delta-wye connected transformers.

It is possible to intentionally limit the magnitude of current that flows due to a line to ground fault in a solidly grounded system by adding impedance to the ground return path, typically connected between the transformer X0 terminal and ground. This can be in the form of an inductor or resistor although it is much more common to use a resistor.

Resistance Grounding
Resistance grounded systems are broken into two sub-categories:

- High-resistance grounding
- Low-resistance grounding

The NEC, service continuity requirements, and the system voltage, together dictate which type of resistance grounding system to use.

Although other locations and configurations exist, the most common location for a grounding resistor is at the wye connected secondary of transformers, connecting the X0 terminal to the resistor and then to the grounding electrode system. They are also used to connect the neutral of a generator to the grounding electrode system through the resistor. If the system does not have an accessible neutral point, grounding transformers can also be used to derive a neutral point. All neutral grounding resistors must be designed and factory tested to IEEE Standard 32-1972

High-Resistance Grounding
NEC Article 250.36 states that:

250.36 High-Impedance Grounded Neutral Systems
High-impedance grounded neutral systems in which a grounding impedance, usually a resistor, limits the ground fault current to a low value shall be permitted for 3-phase AC systems of 480 volts to 1000 volts where all of the following conditions are met:

1. The conditions of maintenance and supervision ensure that only qualified persons service the installation.
2. Continuity of power is required.
3. Ground detectors are installed on the system.
4. Line-to-neutral loads are not served.

A high-resistance grounded system is an alternative to the ungrounded system. Both provide improved service continuity by allowing continuous process systems to remain on line during a ground fault. However, the high-resistance grounded system has several additional advantages. High-resistance grounding requires selecting a resistor to limit the ground fault current to slightly higher than the capacitive charging current, but typically no more than 10 amps. The power system can usually continue to operate at this level of current since it is not in a damaging range. In some respects, the high-resistance ground system behaves like an ungrounded system since process continuity can be maintained. However, with a properly selected resistor, high-resistance grounding can also reduce the transient overvoltages that are characteristic of ungrounded systems. The connection to ground through a resistor provides an additional, more direct connection to ground rather than only through the weak capacitive coupling found in the ungrounded system. Similar to the ungrounded system’s requirements, the high-resistance grounded system requires a ground fault detection scheme, since a second ground fault on a different phase would produce a phase-to-phase fault.
A typical ground fault detection scheme for an ungrounded system uses lights connected in a wye configuration as shown below. If a ground fault occurs on an individual phase, that phase’s light will now be between the grounded phase and ground with zero volts across it, resulting in the light going out.

Manufacturers of high-resistance grounding systems can provide a fault detection system that indicates when the first ground fault occurs. A common method is to monitor the voltage across the resistor and when a ground fault occurs, the ground current flowing through the resistor will produce a voltage across it that can be sensed by a relay to initiate a warning signal.

Locating a ground fault on the high-resistance grounded system can be much easier than on the ungrounded system. Many high-resistance systems can be equipped with a fault location system that switches a portion of the resistor in and out, developing a pulsing current. A sensitive clamp-on current meter can be used to track the fault, beginning at the source and following down the branch circuit that has the pulsing current on it, leading to the faulted circuit.

Although other current and voltage ratings may be available, 5 amp and 10 amp resistors rated 277 volts line-neutral are the most common. The current rating is continuous, since the system is designed to operate under ground fault conditions.

To illustrate the impact that the type of grounding has on the ground fault current, several computer simulations were performed with results tabulated below. The simulations involve bolted short circuits at the secondary bus of a delta-wye connected 2500 kVA transformer that has an impedance of 5.75% and a secondary voltage rating of 480Y/277 volts. A total of three cases were developed for the following grounding configurations:

- solidly grounded secondary
- ungrounded secondary
- high-resistance grounded secondary

The results of the solidly grounded case show the maximum three-phase short circuit current is 49,431 amps and the ground fault current is 50,350 amps. This is a case where the ground fault current is greater than the three phase current in part because the fault is located right at the secondary bus of a delta-wye transformer.

The ungrounded case indicates that being ungrounded has no effect on the three phase fault current, but since there is no ground return path, the ground fault current goes to zero.

For the high resistance grounded case, a 5 amp resistor was used to connect the neutral of a 480Y/277 secondary to ground. The impedance of the resistor is 277 volts/5 amps or 55.4 ohms. This large impedance is many orders of magnitude greater than the equivalent impedance of the rest of the power system, so the fault will be limited predominantly by the grounding resistor. With the high resistance in the ground return path between the neutral and ground of the transformer secondary, the ground fault current is limited to 5 amps, which would be low enough to continue operating.

<table>
<thead>
<tr>
<th>Transformer Secondary Configuration</th>
<th>Three Phase Fault Current</th>
<th>Ground Fault Current</th>
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</thead>
<tbody>
<tr>
<td>Solidly Grounded</td>
<td>49,431</td>
<td>50,350</td>
</tr>
<tr>
<td>Ungrounded</td>
<td>49,431</td>
<td>0</td>
</tr>
<tr>
<td>High Resistance Grounded</td>
<td>49,431</td>
<td>5</td>
</tr>
</tbody>
</table>
Low-Resistance Grounding

During a ground fault, high-resistance grounding can be very effective in maintaining service continuity on lower voltage systems. This may not be the case at higher voltages, typically above 5kV, where corona (electrical discharge) can occur at the fault location and can cause more current to flow. At higher voltages low-resistance grounding should be used.

Low-resistance grounding is not generally used on low voltage systems (i.e. less than 600 volts) because when a ground fault occurs, the ground fault current flowing though the grounding resistor creates a substantial voltage across it. At lower voltages, with the significant voltage occurring across the resistor, there is often not enough voltage across the fault to sustain the current flow and trip an overcurrent device off-line.

Ungrounded or high-resistance grounded systems are preferred to low-resistance grounding at lower voltages since they do not require tripping an overcurrent device.

Ratings of Low-Resistance Grounding Resistors

The neutral grounding resistor should be sized to limit the ground fault to a low enough level to minimize damage, yet allow enough current to flow so ground fault devices can operate and clear the fault. In addition, to dampen transient overvoltages, the resistor should allow a minimum current to flow that is greater than the capacitive current. The grounding resistor is usually sized to limit current to between 100 and 1000 amps, although manufacturers have resistors rated for lower and higher currents.

A computer simulation was developed to illustrate the effect that low-resistance grounding has on ground faults. Using a 5,000 kVA delta-wye transformer with a 4160Y/2400 volt secondary as an example, selecting a grounding resistor rated 600 amps at 2400 V line-neutral would be a reasonable choice. 600 amps would provide sufficient current for the operation of ground fault devices yet would minimize damage.

The simulation of the solidly grounded transformer produces a three phase fault of 10,815 amps and a ground fault of 11,202 amps. Again, since the fault is at the secondary of a delta-wye transformer, the ground fault current is greater than the three-phase current.

Using a 600 amp resistor between the transformer neutral and ground would theoretically limit the current to 600 amps. The equivalent resistance would be 2400 volts/600 amps or 4 ohms. Although 4 ohms is large for a power system, it is not as large as the earlier high resistance case. In this case, the impedance of the system plays a more significant role since the resistor impedance is smaller. In fact, during computer simulations that were performed, the calculated ground fault current using a 600 amp resistor is actually 596, slightly lower than 600 amps due to the additional impedance of the system including the transformer.

<table>
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<th>Transformer Secondary Configuration</th>
<th>Three Phase Fault Current</th>
<th>Ground Fault Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solidly Grounded</td>
<td>10,815</td>
<td>11,202</td>
</tr>
<tr>
<td>Low Resistance Grounded</td>
<td>10,815</td>
<td>596</td>
</tr>
</tbody>
</table>

Low Resistance Grounding

Due to a substantial voltage drop that occurs across the grounding resistor during a ground fault, a low voltage system might not have enough voltage across the arc to sustain it.
The simulation illustrates the dramatic reduction in ground fault current from 11,202 amps to a very manageable 596 amps, which would greatly limit damage but be large enough to trip a correctly set ground fault protective device.

Grounding resistors used for low-resistance grounding are not usually designed to carry the rated current continuously, 600 amps for this example, but rather for a limited time such as 10 seconds. The time rating is the duration that the resistor can carry rated current without exceeding its temperature rating. Both time and temperature ratings for grounding resistors are defined by IEEE Standard 32-1972 and have time ratings from 10 seconds to continuous, and temperature ratings from 385 ºC to 760 ºC for their allowable temperature rise as shown in the table below. Since the current rating of low-resistance grounding resistors is not for continuous operation, it is important that ground fault protection be set to trip off-line before the combination of time and current allows the resistor to exceed its temperature rating.

<table>
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<tbody>
<tr>
<td>Time Rating</td>
<td>Duration</td>
</tr>
<tr>
<td>Short Time</td>
<td>Typically used where protective devices will clear the fault quickly</td>
</tr>
<tr>
<td>Extended Time</td>
<td>Used where fault currents can last an extended period of time but not more than 90 days per year</td>
</tr>
<tr>
<td>Continuous</td>
<td>Can carry the rated current for an indefinite period of time</td>
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Since the resistor is connected between the neutral and ground, the voltage on the ground side of the resistor should normally be zero. However when there is a ground fault, the return current will develop a large voltage across the resistor that raises the voltage on the neutral side of the resistor. According to NEC Article 250.186 (B), the conductor insulation rating for the neutral conductor of a grounding resistor used in systems greater than 1000 volts must have the same insulation rating as the phase conductors. This is a different requirement than if an insulated neutral was part of a solidly grounded system. In the case of a solidly grounded system, Article 250.184 (A) (1) allows a minimum insulation level of the neutral conductor to be 600 volts for solidly grounded systems.

**The Design will use a Grounded System**

Just fill in the blank. Solidly grounded, ungrounded, high-resistance grounded, low-resistance grounded; there are so many options available for grounding power distribution systems. Most of the time, solidly grounded systems are used and work quite well. However, when service continuity or minimizing damage due to ground faults are of paramount importance, options other than solidly grounded systems should be explored.

Selecting the correct grounding scheme for a power distribution system is a function of economics, reliability, and Code requirements. When allowed by the NEC, resistance grounding schemes can reduce ground fault current, voltage transients and damage. High-resistance grounded systems are becoming more widely used as an alternative to traditional ungrounded systems offering the same continued operation during a ground fault. Unlike the ungrounded system, the high-resistance system also minimizes transient overvoltages and provides easier fault location capability.