EPRI ELECTRIC POWER RESEARCH INSTITUTE

PQ Encyclopedia

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Grounding – A Broad-Spectrum Requirement for Power Quality

Chapter 15

Contents

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Introduction

Grounding is a subject in electrical engineering and power quality that should not be taken lightly. Today, many engineers still overlook the importance of grounding and its critical meaning to power quality. While powering end-use loads is clearly the key element in delivering energy to any system, wiring and grounding serve as the electrical foundations that tie systems together. Before systems can function as designed, wiring and grounding from system to system must be accomplished without compromise.

This chapter of the *PQ Encyclopedia* seeks to provide the reader with the basic, historical, and modern aspects of grounding as it relates to equipment performance, power quality, system compatibility, and electromagnetic compatibility. Several case studies provide background for an analysis of what works and doesn't work and provide a context for the importance of good grounding practices and the consequences of faulty wiring and grounding systems.

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Grounding is one of those technical subjects in power quality that requires the careful definition and application of its terms.

INDUSTRY DEFINITIONS

Although many engineers may not fully appreciate the importance of grounding and its relationship to power quality, proper wiring and grounding provide the foundation that allow electrical systems to perform as designed. Grounding is one of those technical subjects in power quality that requires the careful definition and application of its terms. Listed below are some useful terms related to grounding and its applications for power quality.

Bonding: (a) The electrical interconnecting of conductive parts, designed to maintain a common electrical potential (see the National Electrical Code [NEC] [NFPA 70]). (b) The permanent joining of metallic parts to form an electrically conductive path that will ensure electrical continuity and the capacity to conduct safely any current likely to be imposed. (See the NEC.)

Equipment grounding conductor: The conductor used to connect the noncurrent-carrying metal parts of the equipment, raceways, and other enclosures to the system grounded conductor, the grounding electrode conductor, or both, at the service equipment or at the source of a separately derived system.

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

Ground electrode: A conductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground. (See the NEC.)

Ground electrode, concrete-encased: Also known as a Ufer ground. A grounding electrode completely encased within concrete—located within and near the bottom of a concrete foundation or footing or pad—that is in direct contact with the earth. Note: This term is defined more specifically in Article 250 of the NEC.

Ground grid: A system of interconnected bare conductors arranged in a pattern over a specified area on, or buried below, the surface of the earth. Normally, it is bonded to ground rods driven around and within its perimeter to increase its grounding capabilities and provide convenient connection points for grounding devices.
The primary purpose of the ground grid is to provide safety for workmen by limiting potential differences within its perimeter to safe levels in case of high currents that could flow if the circuit being worked on became energized for any reason, or if an adjacent energized circuit faulted. Metallic surface mats and gratings are sometimes utilized for this same purpose. Note: This term should not be used when referring to a signal reference structure, which is defined in this clause.

Ground impedance tester: A multifunctional instrument designed to detect certain types of wiring and grounding problems in low-voltage power-distribution systems.

Ground loop: A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

Ground potential shift: The difference in voltage between grounding or grounded (earthed) structures such as the opposite corners of a metal building. Generally, ground potential shift increases with distance of separation of ground locations and with the frequency or wave front rise time of the resulting current flow. Ground potential shift problems are generally exacerbated by surge events from lighting and utility power sources.

Grounded: Connected to earth or to an extended conducting body that serves instead of the earth, whether the connection is intentional or accidental.

Grounded system: A system in which at least one conductor or point (usually the middle wire or neutral point of transformer or generator windings) is intentionally grounded, either solidly or through an impedance.

Any electrical device or system that generates electrical energy must provide a path for the return of that energy to the source.

Grounding system: A system that consists of all interconnected grounding connections in a specific power system and is defined by its isolation from adjacent grounding systems. The isolation is provided by transformer primary and secondary windings that are coupled only by magnetic means. Thus, the system boundary is defined by the lack of a physical connection that is either metallic or through a significantly high impedance.

Isolated equipment ground: An isolated equipment grounding conductor runs in the same conduit or raceway as the supply conductors. This conductor is insulated from the metallic raceway and all ground points throughout its length. It originates at an isolated ground–type receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source. Note: This term is defined more specifically in the NEC.

Reactance grounded: Grounded through an impedance, the principal element of which is inductive reactance.

Resistance grounded: Grounded through an impedance, the principal element of which is resistance.

Resonant grounded: A system in which the capacitive charging current is neutralized by an inductive current produced from a reactor connected between the system neutral and ground. By properly "tuning" the reactor (selecting the right tap), a low magnitude of fault current can be achieved. In general, when this occurs the arc will not maintain itself and the ground fault is extinguished or "quenched." In a parallel circuit, consisting of L and C, this happens when,

$$\omega L = \frac{1}{\omega C}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Separately derived system: A wiring system whose power is derived from a generator, transformer, or converter windings and has no direct electrical connection, including a solidly connected grounded circuit conductor, to supply conductors originating in another system.

Golidly grounded: Connected directly through an adequate ground connection in which no impedance has been intentionally inserted.

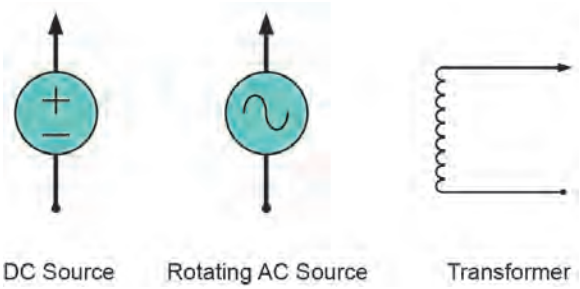
Ungrounded system: A system without an intentional connection to ground except through potential indicating or measuring devices or other devices with very high impedance.

Voltage potential: The level of voltage measured between two points of reference.

PURPOSE AND IMPORTANCE OF GROUNDING

Before discussing the effects of good or poor grounding on equipment performance, on power quality, and on electromagnetic compatibility, the concept of how grounding relates to energy sources and their loads should be presented. The figure below illustrates three types of sources of electrical energy. Any electrical device or system that generates electrical energy (the flow of electrical current) must provide a path for the return of that energy to the source. The reentry point for the return energy is often called the *ground*.

Three Types of Sources of Electrical Energy



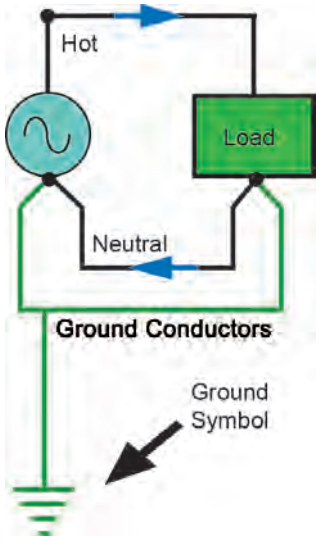
A third conductor in an AC circuit called a ground conductor is used to ensure the safety of nearby humans and to prevent system instability.

Sources of electrical energy provide energy to loads that are connected via conductors, as shown in the figure below. The load determines how much energy is produced by the source—the power that the load requires to operate over time. In a typical circuit, the source has a high side and a low side, with the *high side* having a superior voltage potential to the *low side*. When the load is part of the circuit, higher-potential and lower-potential conductors connect the load to the source, completing a circuit and creating a path for the current to flow. The circuit must be continuous from the point of higher voltage potential to the point of lower voltage potential at the source. Conventionally, current is characterized as traveling from the higher potential, passing through the load, and returning to the source at the lower potential.

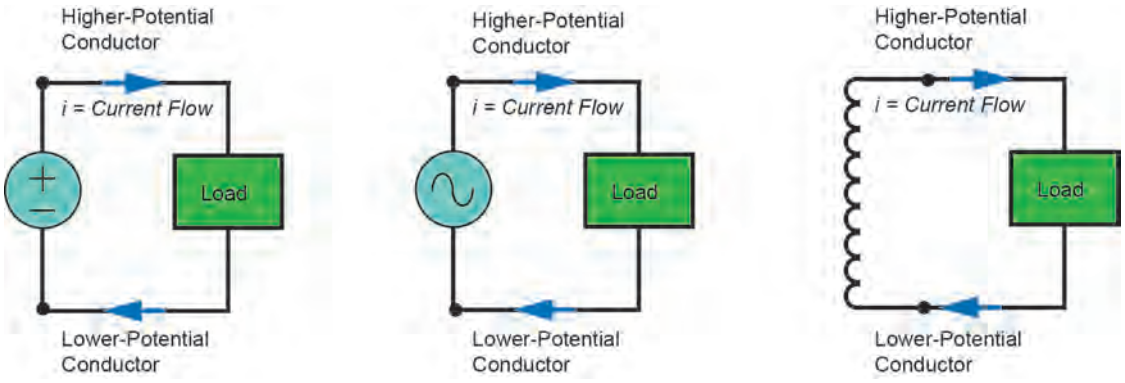
Although the lower-potential conductors in the figure below are at a lower voltage potential, they may not be electrically defined as *grounds*. Instead, they may be defined as a *negative conductor* on a DC source or a *neutral conductor* on a rotating AC source or transformer. The higher-potential conductor is called a *positive conductor* on a DC source or a *hot conductor* on a rotating AC source or transformer. Henceforth, the discussion of grounding focuses exclusively on AC sources.

The diagram below illustrates the use of a third conductor in an AC circuit called a *ground conductor*. This conductor is used to ensure the safety of nearby humans and to prevent system instability, which is the subject of this chapter. The ground conductor is installed in parallel with the neutral conductor, connecting the low side of the load to the current reentry point of the source. Grounding in this way is denoted by the ground symbol shown at the bottom of the figure. All grounds are connected in some way to earth, either through copper rods driven into the ground, connection to metal water pipes, or other means.

A Ground Conductor Added to an AC Circuit

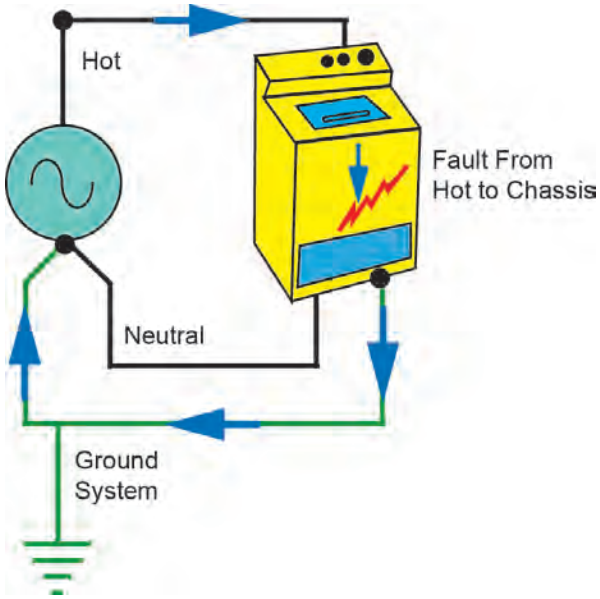


Current Flow from an Energy Source, Through a Load, and Returning to the Source

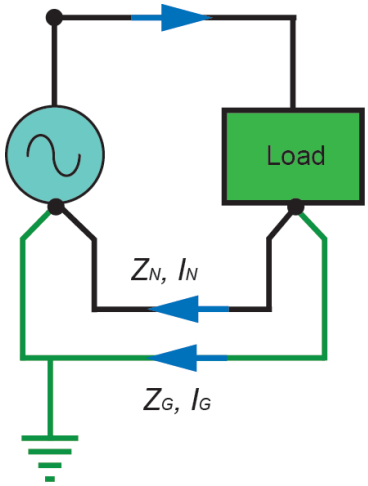


The average layperson does not understand the real concept of what a ground conductor is designed to provide and may think it does not provide any real benefit. This is not the case. The ground conductor is essential for human safety and vital to the performance of the energy source and the load.

Ground Systems Prevent Exposure to Damaging Voltages



Current Flow Through the Neutral Conductor and the Ground Conductor



For example, consider an appliance with a metal cabinet, such as the clothes washer shown in the figure at left. If a fault were to occur between the hot conductor and the metal chassis of the machine, touching of the cabinet could result in a shock when a person completes the circuit with his or her body. However, because the ground conductor is connected to the metal chassis, all fault current is diverted to a grounding system.

As the figure below that shows, the neutral and ground conductors both support current flow. Each has its impedance (noted in the figure as Z_N for the neutral impedance and Z_G for the ground impedance). The size of the neutral conductor is typically the same size or slightly smaller than the hot conductor. The ground conductor is shown as a physical conductor connected from the load to the reentry point of the source. In addition, the ground conductor is connected to the grounding system. The load current that flows from the source through the hot conductor and through the load will still return to the source through the neutral conductor (I_N). However, some current will flow through the ground conductor (I_G). As we will see in this chapter, specific conditions determine how much current will flow through the ground conductor.

Ideally, in a near-perfect world, the impedance of the neutral conductor, Z_N, and of the ground conductor, Z_G, would be purely resistive and zero: $Z_N = Z_G = R = 0$. However, in the field of power quality, it is important to realize that these impedances are non-zero and are not equal for several reasons. Some of these reasons are listed below and are illustrated in the figure on the next page.

- The impedance of both conductors includes a finite amount of inductance and capacitance characteristic of several factors, including the gauge, length, type (whether the conductor is solid or stranded), material (whether the conductor is copper, aluminum, or other), spacing to other conductors, spacing to effectively grounded surfaces

(such as concrete), and dielectric (whether the conductor is insulated [type of insulation] or bare). All of these factors determine the total effective inductive reactance and capacitive reactance of the conductors.

$$Z_N = R_N + jZ_{NL} - jZ_{NL} \text{ ohms}$$

$$Z_G = R_G + jZ_{GL} - jZ_{GL} \text{ ohms}$$

where $Z_{NL} = j2\varpi fL$, $Z_{NC} = j/2\varpi fC$, and f is the frequency.

- The neutral conductor is larger (it has a higher-gauge wire) than the ground conductor. Thus, it is more difficult for current to flow through a smaller conductor than through a larger conductor. Larger conductors have higher conductivities and lower resistivities.

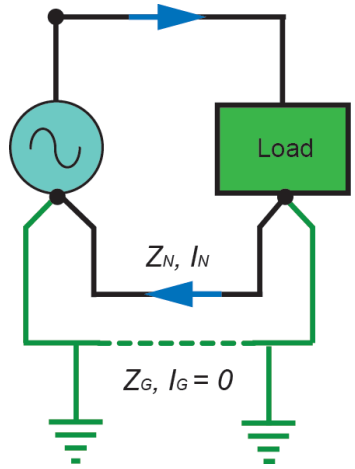
- The connection of a neutral conductor will involve the use of more and different types and sizes of hardware (screws, bolts, washers, nuts, connectors, and so on) than what is used for the ground conductor.

- The neutral conductor will be of a different length and take a different path from the source to the load than that of a ground conductor.

In older facilities (including family dwellings), dedicated ground conductors from service panels to wiring devices and equipment were not required. Paired hot and neutral conductors without grounding conductors were used in early family dwellings. Thus, end-use equipment was not grounded. Ground conductors were also not used in the early commercial and industrial facilities. Although ground conductors were not used, end-use loads relied on the continuity provided by metal piping: electrical metallic tubing (EMT) and rigid (steel pipes threaded together).

Although ground conductors were not used in older facilities, end-use loads relied on the continuity provided by metal piping.

Flow of Ground Current From the Load Back to the Source Without the Use of a Dedicated Ground Conductor



Damage to Electrical Conductors. Any electrical conductors are subject to damage, even if they are contained in metal pipes. Conductors can suffer damage caused by facility renovations. Machinery such as fork lifts can also run into metal piping, causing damage to the conductors inside the piping. Contractors can drive screws and nails into residential wiring, causing a short circuit between hot and neutral conductors and individual conductor breaks without shorting to an adjacent conductor. The shifting of walls and floors and the collapse of ceilings during extreme weather events can also cause major damage to conductors.

Conductors can also be damaged during the electrical-wiring phase of building construction. Electrical contractors push or pull bundles of insulated conductors through metal piping segments during construction and renovation. Contractors do take precautions to prevent skinning the insulation off of conductors; however, conductors can suffer insulation damage during this process.

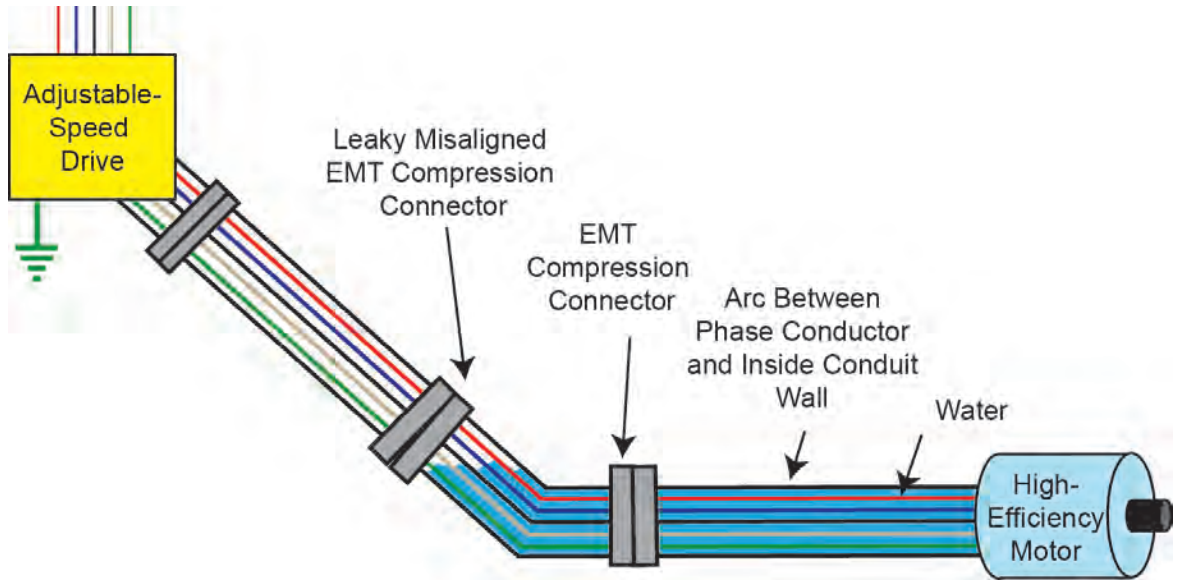
An example of an arc that developed between a phase conductor and grounded conduit illustrates the importance of grounding.

For example, consider the scenario illustrated in the figure below. An adjustable-speed drive (ASD) powered a high-efficiency motor via a three-phase set of ASD output conductors with neutral and ground conductors. The motor was connected to a pump that was used to pump out excess drain water that would gather in an outside area concealed by a short concrete wall where plastic tanks were stored as a part of a food-canning process. All of the conductors were enclosed in EMT joined together with compression connectors. However, as the diagram illustrates, one of the connectors was misaligned during the installation process when the pump was installed. The misalignment caused improper sealing of the conduit. The lack of sealing allowed a small space to develop in the connector.

After several months, shortly after the facility was commissioned, the conduit filled up with rainwater to the connector level. Because the conductors are coated with a plastic sleeve during the manufacturing process, this would normally not cause a significant problem. However, the insulation on one of the phase conductors was damaged during the installation process (see the red conductor in the figure). This occurred as the conductor bundle was pulled through the conduit. A small piece of insulation only 2 millimeters wide allowed the bare copper to be exposed. With the conductor in contact with the water in the conduit, the 277-volt line voltage essentially contacted the inner wall of the conduit. This voltage potential in close proximity to the grounded metal conduit eventually allowed arcing to occur. The intermittent arc was not strong enough to cause the three-pole breaker to trip. The arcing produced a band of radiated emissions high enough in frequency to cause electromagnetic interference (EMI), which affected a piece of industrial process equipment inside the facility.

This example of an arc that developed between a phase conductor and the grounded conduit illustrates the importance of grounding. Because the ASD and the conduit were grounded, the arc still developed and was sustained, but with minimal threat to human safety. The presence of the rainwater acted as a catalyst for the arc to occur. The grounded conduit did help control some of the radiated emissions; however, the emissions were also present on the conductors and the grounding system.

Damaged Phase Conductor Inside a Water-Filled Conduit Arcing to the Inside Conduit Wall



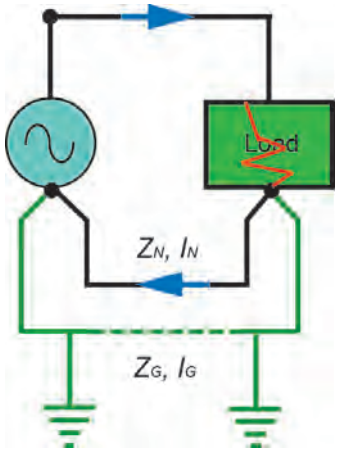
An open neutral condition does not always involve the physical break of the neutral conductor, but may involve a loose connection that is part of the neutral wiring system.

The emissions from the arc were essentially re-radiated into the facility where a multichannel temperature-measurement system was being used to verify the quality of the process used to seal metal cans that contained vegetables. The temperature of the cans had to be verified to ensure that the proper vacuum seal was present inside the can after heating the can. The EMI problem created by this arc caused the temperature-measurement system to malfunction. The malfunction was manifested by the system displaying temperatures with large measurement errors, indicating that some cans were overheated and some cans were not heated to the proper temperature. The food-processing researchers in this facility could not verify the pressure seal of the cans under development. Thus, the process could not pass the quality tests needed before the process was certified for use in an actual food-processing plant. Without the grounding of the conduit, ASD, and motor, this system could possibly have become energized at a voltage level that could present a safety problem for the researchers.

The above arcing problem is an example of a fault, but one that involved a phase conductor of a branch circuit as shown in the figure below. The fault in this example occurred to the grounded conduit not to the neutral conductor. The grounded conduit and the ground conductor inside the conduit, which was connected to the grounding system inside the facility, did support some fault current associated with the arc. If the conduit were not grounded, part of the 277-volt potential could have energized the conduit system inside the building.

Cases of open neutrals have been identified at various points along the electrical systems of facilities. In some of these cases, the open neutral was detected in branch circuit wiring. An open neutral condition does not always involve the physical break of the neutral conductor. An "open neutral condition" may involve a loose connection that is part of the neutral wiring system. For example, a lug connector inside an electrical panel may become loose in an aging electrical system. In other cases, physical stress may be placed on a conduit, causing some of the conductors inside the conduit to also experience stress. If the neutral conductor happened to be the shorter conductor, then the stress imparted on the conduit may cause the neutral conductor to slightly pull away from the neutral lug connector. This pulling action will loosen the set screw in the connector. Regardless, a compromised neutral conductor can result in return current flowing through the ground conductor instead – generally an undesirable circumstance.

Example of a Fault Involving the Branch Circuit (or Load) Where the Fault Current Was Supported by the Ground



Grounding

The 25-Ohm Ground: Myth or Fact?

The NEC promulgates a rule that limits the ground resistance of a single ground rod to a maximum of 25 ohms. What is the genesis of this rule? Is it efficacious? This 25-ohm rule has been adopted by many utility companies and other organizations. However, the basis for this value is not clear to many power quality engineers in the industry.

A thorough investigation of the literature revealed that the 25-ohm rule made its first appearance in the context of electricity in the 1918 NEC, as shown in the figure below. But, where did this value come from? Many stories and unsupported anecdotes and discussion sites can be found on the Internet. A few of them discuss Edison using the earth as a return path, and that it was a requirement to match the impedance of the DC distribution line to ensure proper operation of the DC generators.

The 25-ohm rule made its first appearance in the context of electricity in the 1918 National Electrical Code.

First Appearance of the 25-Ohm Rule

l. The combined resistances of the ground wires and connections of any grounded circuit, equipment, or lightning arrester should not exceed 3 ohms for water pipe connections nor 25 ohms for artificial grounds where these must be used. Where, because of dry or other high resistance soils it is impracticable to obtain artificial ground resistance as low as 25 ohms, two such grounds 6 feet apart if practicable must be installed, and no requirement will be made as to resistance.

Source: NEC 1918

Edison adopted the 25-ohm rule, which was derived from the telegraph industry, an industry where he was once employed. The source of this value does indeed come from telegraph grounding requirements from the 1800s. However, this requirement has been seriously misinterpreted. The following discussion will reveal how the 25-ohm rule emerged and how a different value from 25 ohms was actually preferred for grounding and appeared in print as early as 1884.

Wire Gages and Conductor Material

From the 1884 transactions papers of the American Institute of Electrical Engineers (AIEE, the predecessor of the IEEE), this misinterpretation may be found and explained. As the excerpt in the figure below shows, Count Du Moncel indicated that a *favorable* ground resistance would be equivalent to seven miles of No. 8 line wire. It is this paragraph that some believe is the source of the 25-ohm value.

Seven Miles of Number 8 Telegraph Line

The late Count Du Moncel made observations which tend to show that the resistance of the earth under very favorable conditions is equal to that of a No. 8 line wire of about seven miles in length. When, therefore, the resistance of the line wire is not over ninety or one hundred ohms, it does not seem advantageous if we desire the best electrical results, to use an earth return. By reason, however, of the increased economy in

Source: AIEE Transactions 1884

The seven-mile resistance of a No. 8 copper conductor at 3.315 ohms per mile is 23.21 ohms. This could very well be the source of the 25-ohm rule—and also the source of the prevailing misinterpretation.

At the time of the AIEE publication, the standard wire gage being used by the telegraph company was the Birmingham Wire Gage (BWG). Using this gage method, a No. 8 BWG conductor is approximately equal to a No. 6 American Wire Gage (AWG) conductor in diameter. Calculating the resistance of a seven-mile No. 6 AWG conductor results in 14.64 ohms. Under this assumption, a favorable ground resistance would be 15 ohms—not 25 ohms.

Although it is not clear in the paragraph, it is apparent that the resistance of a *favorable* ground for the telegraph company was one that was less than 91 ohms and not that of 25 or 15 ohms, as discussed here and shown in the figure below. In this paragraph, it is clear that the wire being discussed is of the BWG standard because it calls out the diameter of the wire being 65 mils, which has a resistance of about 13 ohms per mile. An iron conductor of 65 mils is found to be a No. 8 wire under the BWG standard. At 13 ohms per mile, the resistance for seven miles is equal to 91 ohms. This confusion between copper and iron can be attributed to the fact that early telegraph lines were made of hard-drawn copper, but by 1855, the practice was changed to the use of iron because it would not break as easily.

Resistance of No. 8 BWG Iron Wire

iron wire we may assume is No. 8, has a diameter of 165 mils, and a resistance per mile of about 13 ohms per mile. A copper wire of almost an equal degree of conductivity is No. 16, which has a diameter of 65 mils; the diameter of the iron wire is thus about two and a half times that of the copper wire, and its sectional area

Source: AIEE Transactions 1884

A ground resistance of 91 ohms may seem a bit high as a *favorable* ground resistance, but early telegraph systems used the earth as a return conductor. As the resistance of wire increases over a space of a hundred miles to 13,000 ohms, the ground resistance in comparison is small. The primary reason for using the earth as a return path for telegraph systems is simple economics—there is no need for a second conductor to complete the circuit.

By 1869, the BWG wire standard was still used primarily for telegraph lines, but the telegraph companies were beginning to use a copper-sheathed steel cable called the *American Compound Wire* in place of the iron line wire, as shown in the figure below. Again, with the use of what appears to be copper, it would be an easy mistake for someone to think that (1) the telegraph lines are made of copper, (2) the basic line wire is a No. 8 wire gage, and (3) B & S (Brown and Sharp) wire, which is known today as the AWG, is the BWG wire standard.

The American Compound Wire Gauge, AIEE

135. WIRE.—For ordinary lines, galvanized iron wire, of No. 8 or 9, Birmingham gauge, is generally employed. For short lines, No. 10 or 11 will answer very well. The "American Compound Wire," a recent invention, is composed of a combination of a steel core with a sheathing of copper. It has come into extensive use within the short time which has elapsed since its introduction, and has, thus far, been found to answer admirably. A wire of this kind, having a conductivity equal to a No. 8 iron wire, weighs only 80 pounds per mile.

Ground Plates and Lightning Protection

The requirement for a low ground resistance for most lightning-protection systems can be traced back to the early telegraph days as well. Again, we find in the 1884 transactions papers of the AIEE references for lightning rods, specifications for ground resistance, and construction of ground plates, as shown in the excerpt below.

Ground Plate to Measure Less Than 10 Ohms

POLE LIGHTNING RODS.

These are for the protection of poles. They may be led from a point about two feet above the pole, down the side thereof, being secured by staple, and terminate in a plate buried in damp earth at the foot of the pole. Unless, however, good earth is made the pole is safer without any wire. When used, they should have branches running out on the cross arms to within half an inch from each insulator.

Any earth wire can readily be measured for resistance in like manner with any other conductor.

No earth wire and plate should measure more than ten ohms.

Source: AIEE Transactions 1884

It is from these early lightning-protection schemes that the NEC adopted the 25-ohm rule and the practice of artificial grounds, which in today's code is accomplished with ground rods. However, as contained in the 1918 NEC, artificial grounds were not to be less than 4 square feet and were meant to be applied in areas where the level of ground water is close to the surface, as shown in the figure below.

Requirements for Ground Plates

s. Artificial grounds should be located where practicable below permanent moisture level. Each ground must present not less than 4 square feet surface to exterior soil. Areas where ground water level is close to the surface should be used when available.

Where ground plates are used they should be at least No. 16 Stubbs gage copper; when driven pipes are used they should be of galvanized iron and not smaller than one inch internal diameter; and when cast iron plates are used they should be at least one-quarter inch in thickness.

Source: NEC 1918

The use of the 25-ohm rule in the NEC is to ensure a reasonable ground resistance. A ground resistance other than 25 ohms could have been established, but what should be considered is the application of the ground.

Going back to the description of Pole Lightning Rods in the figure on the previous page, requirements for telegraph grounding are shown, with recommendations of a vertical grounding plate and that the hole should be dug until damp earth is reached. The damp earth is a common theme among all of the early requirements for grounding when pipes were not available to use. When using the phrase "damp earth," the intent is to reach a low soil resistivity, taking the soil resistivity to be equal to or less than 50 ohm-meters. Then, the 1/8 inch thick, 3 foot by 4 foot grounding plate would provide less than 25 ohms of earth resistance.

The use of the 25-ohm rule in the NEC is to ensure a reasonable ground resistance. At the time of publication of the 1918 NEC, adequate grounding was established by the telegraph company to ensure proper operation of the telegraph stations and to provide lightning protection. It is apparent that the NEC calculated what the telegraph equivalent resistance of a ground plate would be under reasonable soil resistivity and established its own dimensions, which—when the equivalent earth resistance to the plate is calculated—results in approximately 25 ohms. The overall intent of grounding is to ensure that proper return current for faults is ensured and to reduce step potentials. A ground resistance other than 25 ohms could have been established, but what should be considered is the application of the ground. Is it for safety, lightning protection, or other (in the case of the early telegraph companies)? As it is, the application will determine what the ground resistance should be, except for cases where codes or standards may take precedence.

Results of Computer Modeling for Grounding

With all of the different possible grounding configurations, past practices of grounding with plates should be explored to see whether any correlation exists between the practices and establishing the 25-ohm rule used today.

Using the EPRI Grounding Guide Software program, the resistance was calculated for five grounding configurations (note that the last three configurations are industry standard lengths):

- A vertical ground plate—with an area of 3 x 4 feet and a thickness of 1/8 inch—buried into a damp earth, as described in the 1884 AIEE (labeled "1884 AIEE" in the figure on the next page).
- A horizontal ground plate—with an area of 1 x 4 feet and a thickness of No. 16 gage—buried into the earth to a depth of 8 feet, as described in the 1918 NEC (labeled "1918 NEC").
- A 12-foot ground rod with a diameter of 3/4 inch (labeled "12' GR 3/4"").
- A 10-foot ground rod with a diameter of 5/8 inch (labeled "10' GR 5/8"").
- An 8-foot ground rod with a diameter of 5/8 inch (labeled "18' GR 5/8"").

The results are based on the Dwight method of calculating ground impedance. This method was found to be the most stable for all cases. All calculations are based on 8-foot depths, except for the two ground rods that exceed 8 feet in length.

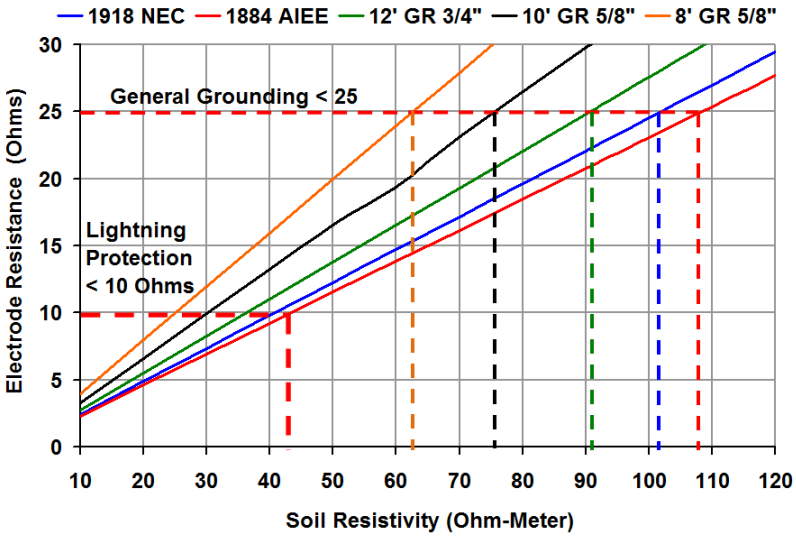
During modeling, there were two targets of soil resistivity (based on calculations in most of the relevant literature):

- To achieve an electrode resistance of 10 ohms or less for lightning protection, the soil resistivity should be 50 ohm-meters or higher.
- To achieve an electrode resistance of 25 ohms or less for general grounding, the soil resistivity should be 100 ohm-meters or higher.

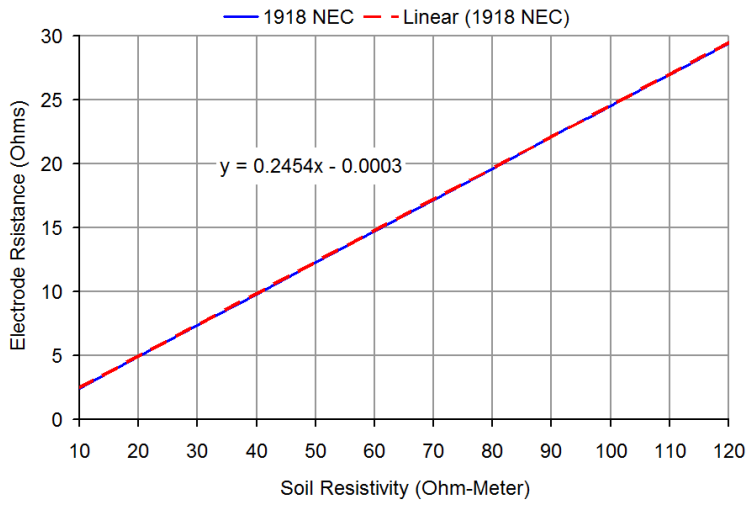
The ground plate of the 1918 NEC would be more effective than an 8-foot ground rod used after 1965 for grounding.

The model determined the values of soil resistivity for each grounding method that intersected the 25-ohm and 10-ohm targets. The higher the soil resistivity for a given electrode resistance, the better the grounding method. Modeling results are shown in the graph below. Using a soil resistivity value of 100 ohm-meters or more in the model resulted in an electrode resistance of 25 ohms or less for only two grounding methods: the vertical ground plate described by the 1884 AIEE and the horizontal ground plate described by the 1918 NEC. The target electrode resistance for lightning protection (10 ohms or less) must be established to ensure adequate protection. None of the grounding methods met the criterion of 50 ohm-meters or higher.

Modeled Ground Electrodes Results



1918 NEC 25-Ohm Ground Plate

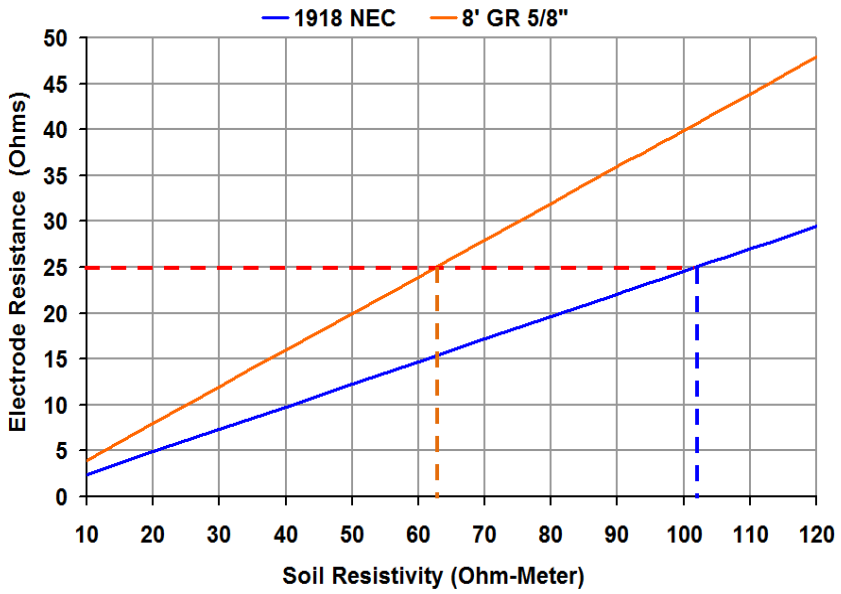


What is interesting and significant is the 1918 NEC ground plate description that is to be used for an artificial ground, meaning that no underground pipe connections are available to ground to. This ground plate provides almost the perfect value of 25 ohms when calculated using the standard 100-ohm-meter value. The line equation developed from the data is almost 25 times the earth soil resistivity, as shown next figure at the bottom of the page.

Furthermore, this is exactly the method that would have been used in the early days of grounding telegraph stations and the use of geometrical objects such as a plate to calculate the surface area in contact with the earth. The figure on the next page shows a close agreement between the specified minimum plate dimension as discussed in the 1884 AIEE transactions papers and that of the ground plate that was called out in the 1918 NEC.

It is apparent that without revisiting the 1918 NEC requirement for (1) a 25-ohm ground impedance, (2) the use of the ground plates for artificial grounding, and (3) allowing for the use of the cold-water pipes for grounding, the 1965 code change states only that if 25 ohms cannot be met, then one additional ground rod should be used. The figure on the next page shows that the ground plate of the 1918 NEC would be more effective than an 8-foot ground rod used after 1965 for grounding.

1965 NEC Ground Rod Versus 1918 NEC Ground Plate



The ground rod recommended in the 1965 NEC would be effective under ideal soil conditions for most cases.

However, the ground rod would be effective under ideal soil conditions for most cases; it should be noted that 100 ohm-meters for soil resistivity is used when no better information is available. The actual soil resistance can differ from this simple assumption and is often higher. As a result, the designs of ground electrodes based on this value are often undersized, hence the need for an additional ground rod. So, it is also reasonable to state that if this additional ground rod in conjunction with the multi-grounded system and the first ground rod does not have an impedance of less than 25 ohms (Rule 096B NESC Handbook), then the chances of achieving this value are unlikely without great economic cost, due to the extensive labor effort and materials used.

Standards and Practices Overview

The table on the next page outlines several different guides, standards, practices, and codes regarding grounding and its purpose. For this review, the following commonalities are found:

- Ground resistance for lightning arrester (LA) protection is less than 10 ohms.
- The typical desired value for a ground is less than 25 ohms.
- An overhead ground wire for lightning protection is based on critical flashover voltage (CFO). Low CFOs are cited for less than 10 ohms; high CFOs are cited for 40 ohms or less.

There appears to be no obvious explanation of the rationale of the derived impedance level, except through basic reasoning that a lower ground impedance is better for effective lightning protection.

Standards Review

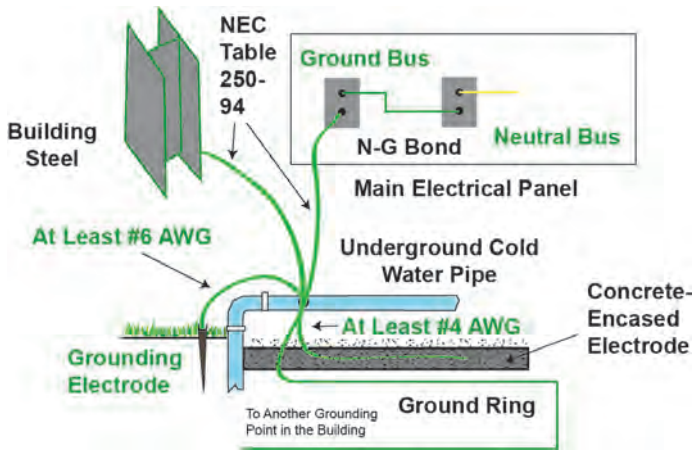
Standard	Ground Impedance	Methods	System	Purpose/Notes
MIL-STD-188-124B	< 10Ω	3m rod 1.9cm diameter copper-clad steel	Long Haul Tactical Communication Facilities	Personnel safety Fault protection Noise reduction
MIL-HDBK-419A	< 10Ω	3m rod 1.9cm diameter copper-clad steel	Fixed Electronic Equipment and Facilities	Personnel safety Equipment and facility protection Noise reduction Lightning discharge 20 kA peak typical
Central Networks	< 10Ω Surge arrester < 20Ω Other	4 each 2.4m rod 1.9cm diameter copper-clad steel	Standard Distribution Earthing	Personnel safety Fault protection
UFGS-33		3m rod 1.9cm diameter copper-clad steel	Unified Facilities Guide Specifications	Requirements for overhead electrical work and utility poles
IEEE 1410	< 10Ω CFO < 200 kV < 40Ω CFO > 300 kV	OHGW	*IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines*	Lightning protection
IEEE C62.92.4	NA	NA	*IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part IV—Distribution*	Personnel safety Fault protection 1.35 overvoltage factor for metal oxide varistor arrester Four grounds per mile Arresters every 1200 feet
EPRI TR 10002021	< 20Ω	Ground Ring and rods	Guide for Transmission Grounding	20-year life cycle
Energy Australia NS 116	<10Ω Equipment <30Ω surge arrester	Ground Rods	Design Standards for Distribution Earthing	Personnel safety Fault protection Lightning protection
National Electrical Safety Code	Unigrounded <25Ω Multiground no spec	3m rod 1.9cm diameter copper-clad steel, butt plate or wire wrap	*NESC Handbook A discussion of the National Electrical Safety Code*	Personnel safety Fault protection Ground rods for equipment, transformers, and four grounds/mile, all others may be butt-plate or wire wrap subject to NESC Rule 094B4a
Tennessee Valley Public Power Association	< 25Ω	3m rod 1.9cm diameter copper-clad steel, butt plate or wire wrap	TVPPA, Distribution Design Guidelines	Ground rods for equipment, transformers, and four grounds/ mile, all others may be butt-plate or wire wrap subject to NESC Rule 094B4a
EPRI TR 1013964	10–25Ω	One 24 foot rod or three 8 foot rods	Examination of Distribution Grounding Electrode Configurations for Optimal Lightning Performance	Soil conditions determine the use of long grounds or the use of multiple shorter ground rods

Tracing the ground conductor through a facility and verifying that it is connected to the grounding electrode is part of a power quality investigation and is vital to proving that the facility is connected to the grounding electrode.

Established Within a Facility

Certain infrastructures of a facility must be bonded to the grounding electrode. The grounding electrode establishes grounding of a facility to the earth. The grounding electrode as shown in the figure below is a critical part of any facility's grounding system. The ground conductor from the main ground bus inside the main electrical panel is part of the grounding electrode system. This conductor is stranded copper and typically of a large wire gauge like #2/0 (pronounced "two aught"). The length of this conductor will vary from facility to facility. Because this conductor can be long and must be routed from the main electrical panel to a suitable location outside in the earth's soil, it will typically follow a path through the building that may be difficult to trace. In the area of power quality, tracing this conductor through a facility and verifying that it is connected to the grounding electrode is part of a power quality investigation and is vital to proving that the facility is connected to the grounding electrode. This electrode must not be covered up in any way that prevents it from being inspected during a power quality investigation. The connection of the grounding conductor to the electrode must be visible to verify a solid bond. The grounding conductor must be accessible should a ground impedance test need to be carried out.

Grounding of a Facility at the Main Electrical Panel



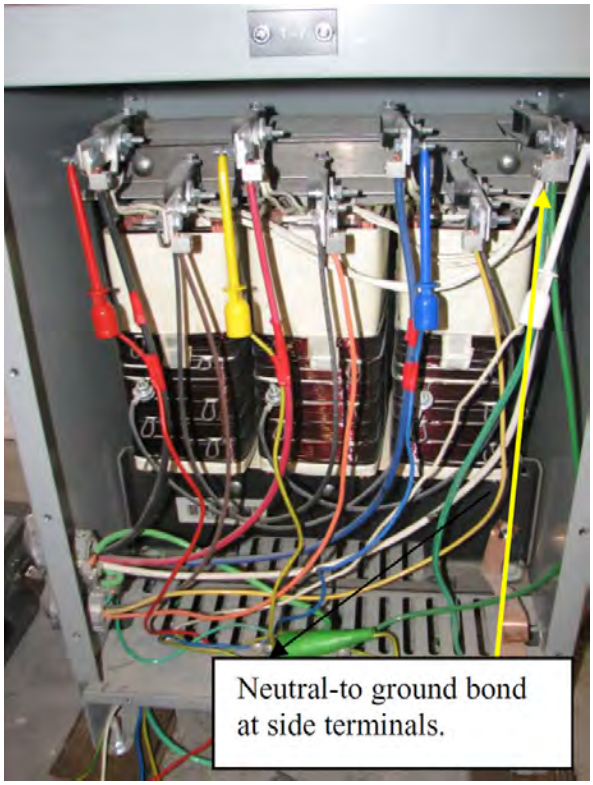
In facilities where concrete is used for floors, a concrete-encased electrode bonds the steel in concrete to the facility grounding system. Ground rings are used outside of a facility and are buried in the soil near the area where the main switchgear is located. The grounding conductor from the ground bus in the main electrical panel (or switchgear) may travel hundreds of feet to reach the incoming main water pipe. A grounding conductor is also connected from the building steel to the water pipe where the ground conductors are bonded together. Grounding the building steel helps to ensure that the steel members and the other metallic components of the building connected to it throughout the building remain at an equipotential close to the earth's near-zero voltage. This is especially important should the building suffer a direct or near-direct lightning strike. If the building steel is not grounded to the grounding electrode, members of the steel system further away from the grounding electrode could become biased at high positive or negative potentials for brief moments in time during a lightning transient event. Grounding the steel also prevents stray charges from building up on the steel and prevents the steel system from becoming energized should a phase conductor get in contact with any steel member. Grounding the steel system in a facility also provides a low-impedance path to ground should the facility suffer a lightning strike. Facilities that have metal roofs are bonded to building steel.

In the figure at left, one will notice that there is a *neutral-to-ground bond* between the ground bus and the neutral bus in the main electrical panel. This bond forces the potential of the neutral conductor to be the potential of the grounding conductor at the point where the two buses connect to the grounding electrode. A neutral-to-ground bond is required at each separately derived source. In power quality, the presence of this bond *at the main electrical panel (or switchgear) or at the output of a voltage source* is critical to the performance of the electrical system.

Faults in the wiring and grounding system can occur at any point along the circuit.

A transformer is another example of a separately derived voltage source. A neutral-to-ground bond at the secondary of a transformer is also critical to the quality of voltage for loads downstream of a transformer. The figure below illustrates the presence of a neutral-to-ground bond in a dry-type transformer that is providing power to the loads in an industrial roofing materials plant.

Example of a Neutral-to-Ground Bond at the Secondary of a Dry-Type Transformer



Requirements for an Effective Grounding Path

There are four requirements for an effective grounding path. The path to ground from circuits, equipment, and conductor enclosures shall:

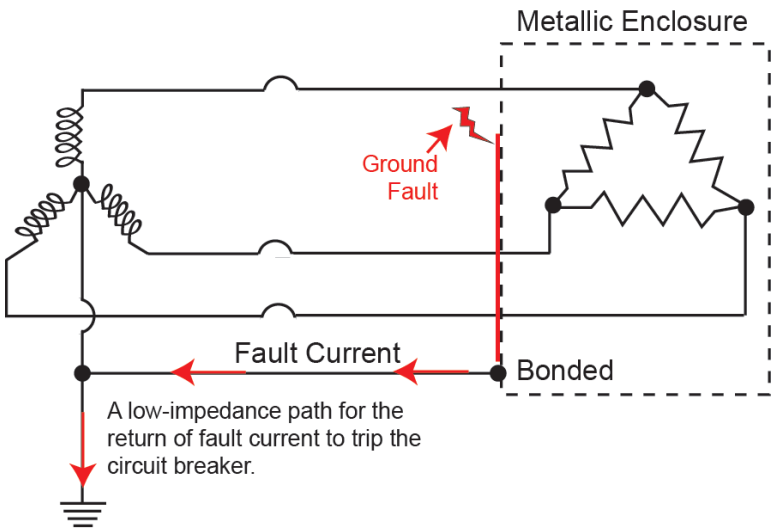
1. Be permanent and continuous.
2. Have capacity to safely conduct any fault current likely to be imposed on the ground path.
3. Have sufficiently low impedance to limit the voltage to ground and to facilitate the operation of the circuit-protection devices (such as fuses and circuit breakers) in the circuit.
4. Finally, the earth shall not be used as the sole equipment ground conductor.

Faults

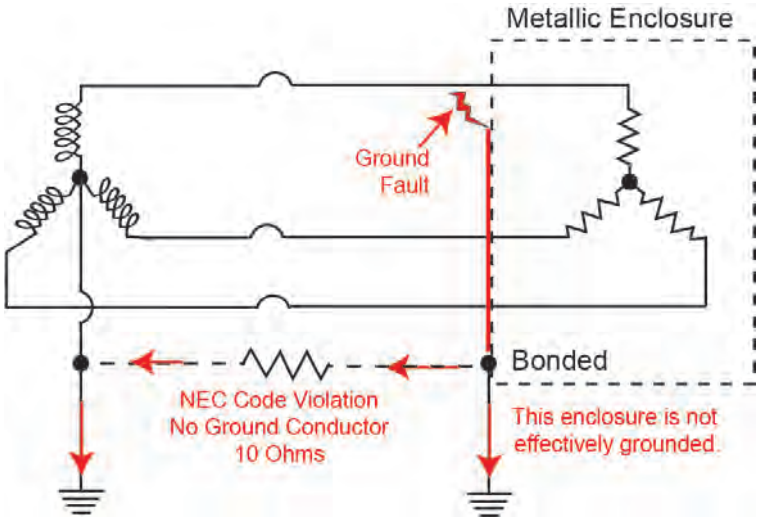
Grounded Faults. Faults in the wiring and grounding system can occur at any point along the circuit. Power and ground conductors are often bundled together in the same conduit or raceway as they leave one cabinet and enter another. Faults involving the power conductors are not uncommon. When a fault does occur, the voltage potential is looking for a lower potential to maintain the flow of current. The potential will find the nearest conductive surface of lower potential and establish a fault condition.

The figure at the top of the next page illustrates a fault occurring on one of the phase conductors that completed the fault circuit to the side of a metallic enclosure. This fault initiates an arc that creates a fault current that flows through the metallic enclosure to the point where the enclosure is bonded to ground. The ground conductor is connected to the grounding electrode. Thus, the fault current flows through the ground conductor and to earth ground. The presence of the ground conductor that supports the fault current from the enclosure prevents the enclosure from becoming biased at a voltage above 0 volts. This ensures the safe operation of the enclosure and the live wiring and components inside it.

Example of a Faulted Phase Conductor Creating a Ground Fault Current to Earth Ground



Example of an Ungrounded Fault to an Ungrounded Metallic Enclosure



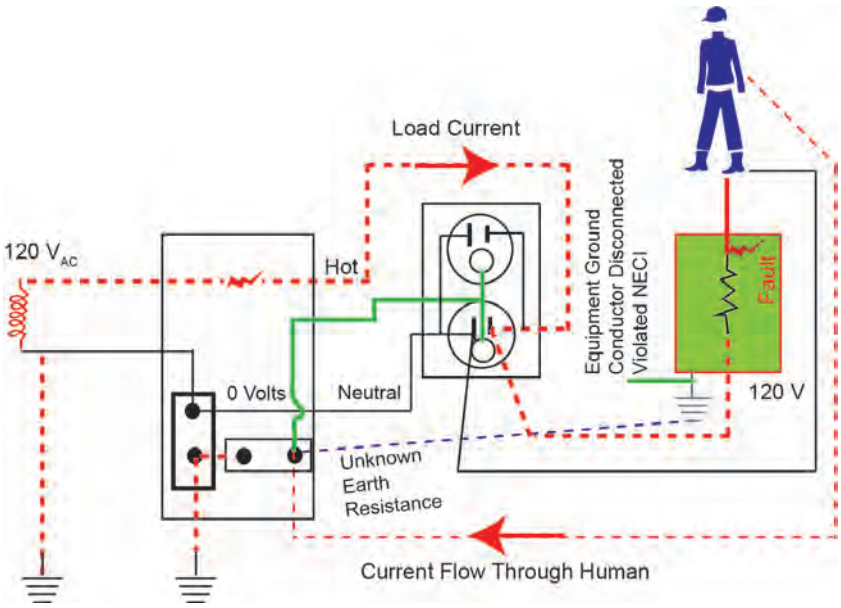
Ungrounded Faults. Errors in ground and bonding enclosures and equipment inside of enclosures as well as metallic conduits and raceways can cause ungrounded fault conditions when a fault occurs. Figure 21 illustrates a fault on a phase conductor involving a metallic enclosure. In this case, the enclosure was not properly grounded or not grounded at all.

Improper grounds may form as a result of loose bolts, screws, and terminals as well as through corrosion of bonds that were once good low-impedance bonds. When corrosion occurs in an electrical bond, a higher impedance occurs in that bond. In the figure at bottom left, an impedance of 10 ohms formed through degradation in the grounding conductor between the enclosure and the grounding electrode. In power quality when this condition arises during a lightning strike (or nearby strike) or during the propagation of an electrical disturbance (such as voltage surge or transient), the equipment inside the metallic enclosure will experience a difference in grounding potential. A disturbance at the source will cause a disturbance (or fault) current to flow through the 10-ohm path, simulating the "grounding conductor" and thus forcing the ground at the "bonded" point to be different from the ground at the grounding electrode (earth). In many cases, this difference potential will cause equipment to fail.

Faults Enabled by Disconnected Equipment Grounds. The NEC requires that equipment be grounded via a ground conductor as part of the building wiring system. In addition, equipment frames and housings are required to be grounded as well. However, equipment grounds can become disconnected for various reasons. Many types of equipment vibrate during operation or are frequently moved from one location to another. Vibration or movement of equipment can deteriorate the bonding of the equipment to the grounding conductor. Deterioration can also be caused by environmental effects, including exposure to various types of chemicals that may be a part of the process for which the equipment is used. As one can see from the figure on the next page disconnection of the equipment ground can present unsafe operating conditions for end users. The frame or enclosure of a piece of equipment can become biased to an unsafe voltage.

In the area of power quality, a missing equipment ground is a recipe for equipment failure when a voltage surge, transient, or internal equipment

Example of Disconnection of Equipment Ground from Grounding Conductor



Good power quality performance depends not only on the presence of proper neutral-to-ground bonds but also the quality of the bonds.

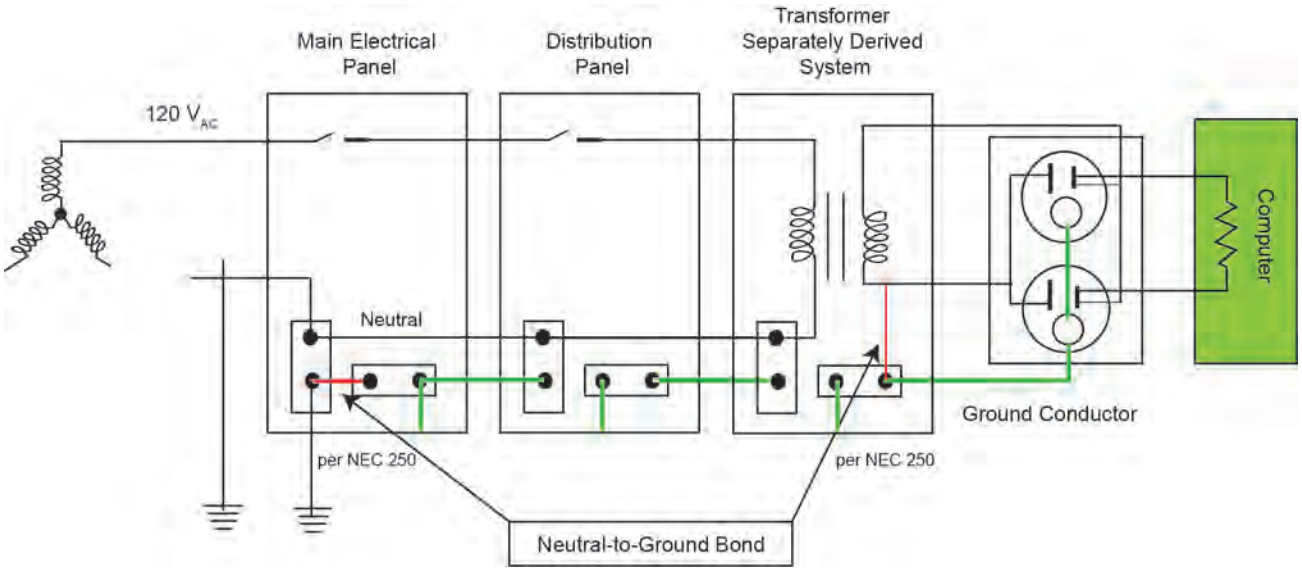
failure occurs. When a surge occurs on the AC power input of a piece of equipment, a surge current is going to occur somewhere inside the equipment. If the equipment contains a surge-protective device (SPD) across the AC line, then a surge current will flow through the SPD. Depending on where the SPD is connected—from hot to neutral, from hot to ground, or from neutral to ground—some of the surge current will flow through the equipment ground. However, if the equipment ground is missing, then that current will take the path of least resistance—whatever that may be. In many cases, the path of least resistance does lead to the development of an undesired potential difference involving the ungrounded equipment. This undesired potential can be a few thousand volts and will likely damage the equipment or another piece of equipment connected to it.

Proper Neutral-to-Ground Bonds. Providing the proper neutral-to-ground (N-G) bonds is critical to life safety, power quality, and equipment performance. N-G bonds are required by the NEC at main electrical panels and at all separately derived sources such as transformer secondaries, as illustrated in the figure at the top of the next page. Without proper N-G bonds, the wiring and grounding system will resonate when a ringing frequency associated with a voltage transient or surge occurs. This will result in the development of an undesired potential difference at the load voltage point, which can damage electronic equipment. Re-establishing the voltage reference (the neutral) at a separately derived source (like at the secondary of a transformer) will keep the reference from "moving around" with respect to voltage. Good power quality performance depends not only on the presence of proper N-G bonds but also the quality of the bonds.

Improper Bonding of Ground Terminals. The performance of grounding systems is not only important to life safety but also to equipment performance at frequencies other than 60 hertz. Electrical disturbances not only occur at 60 hertz but also contain high-frequency phenomena. The electrical disturbances—voltage surges, voltage transients, and electrical fast transients—are high-frequency events that contain high-frequency content. Combination-wave surges are microsecond events. The front wave of a combination-wave surge voltage rises within 1 to 2 microseconds. Ring-wave surges oscillate at a few hundred kilohertz to a few megahertz. Electrical fast transients (EFTs) are even faster events. They occur in the few tens of nanoseconds. The oscillatory nature of these events, which are typically destructive to equipment, can be magnified by grounding systems that break down at high frequencies. To ensure low impedance grounding at high frequencies, each segment of the entire grounding system must maintain its impedance well beyond 60 hertz.

When the events discussed above occur in a facility where a poor grounding system exists, the system will essentially develop small segments of high impedance as the events occur. This breakdown in impedance slows down the flow of the high-frequency energy associated with these events and sets up reflections within

Examples of Proper Neutral-to-Ground Bonds in an Electrical System

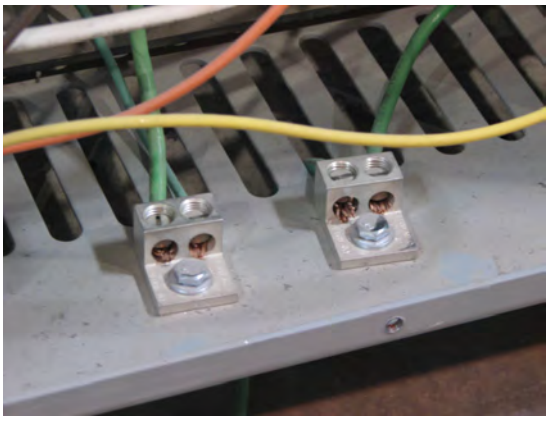


Use of additional ground rods further downstream of the service entrance to solve power quality problems typically results in undesired power quality performance at the equipment level.

the grounding system. The protection offered by mitigation devices such as SPDs and EMI filters will be compromised when grounding techniques like the one shown in the figure at right are used in facilities. The two grounding conductors shown are affixed to the inside surface of the casing in a dry-type facility transformer. As one can see, the grounding terminals are simply bolted to the metal casing without removing the paint on the surface of the casing. The paint under each terminal acts as an "insulator" at high frequency and presents a capacitance between the conductors at high frequency. The ideal solution to this problem would be to grind off an area on the casing such that the bare metal is exposed and then bolt the two terminals together with one bolt on top of the bare metal.

Improper Use of Ground Rods. Ground rods should be used only at service entrances like that shown in the figure on the next page, where the grounding electrode is used to ground the facility's electrical system and the water pipe to earth ground. The use of additional ground rods further downstream of the service entrance to solve power quality problems typically results in undesired power quality performance at the equipment level. Use of multiple ground rods to augment the performance of the grounding system seeks to establish a second path to earth ground, especially when the existing grounding system cannot perform as required. For example, when grounding problems like that shown in the figure on the next page exist and are not rectified, the addition of a ground rod at a distribution panel, transformer, or at the point-

Example of Poor Bonding of Two Ground Conductors Inside a Dry-Type Transformer Case



of-use at the end-use equipment, ground current (including fault current) will try to take the path of least resistance. This path may be through the ground rod and may be shared by the originally compromised grounding system. Multiple paths with above-zero impedances at high frequency will set up undesired potential differences along the grounding system. These potential differences will show up at the inputs to sensitive electronic equipment and cause equipment malfunctions and failures.

Example of Improper Use of External Ground Rod at a Dry-Type Transformer

All exposed metal parts of structures and electrical equipment should be effectively grounded for electrical safety.

Equipment Performance

The use of proper grounding techniques that establish low-impedance paths to earth ground for life safety will also establish low-impedance grounds for equipment performance. The table on the next page provides a correlation between some equipment malfunctions, electrical phenomena, and grounding errors.

Power Quality

Power quality is the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment. On the load side of power quality, grounding is one of the primary areas of concern with respect to proper design for facility electrical systems. If good grounding techniques are not followed, conditions for ground-related power quality problems will exist in facilities. While the purpose of the NEC is to define the requirements for safe electrical systems in the prevention of electrical shock and fire, following NEC requirements—combined with good power quality–related wiring and grounding practices—is essential in establishing good power quality and compatibility in facilities and between the public power system and sensitive electronic loads and equipment.

According to the NEC in NFPA 70, all exposed metal parts of structures and electrical equipment should be effectively grounded for electrical safety. Such parts—including the structural framing; chassis; piping; heating, ventilation, and air conditioning (HVAC); ducting; and electrical conduit/raceways—should be bonded to the local grounding electrode system using direct means. For lightning protection, additional metal structures such as wire fences, steel columns, metal towers, and some concealed systems might also require bonding and grounding according to ANSI/NFPA 780-2004: *Standard for the Installation of Lightning Protection Systems.*

The following excerpts from ANSI/NFPA 780 detail lightning-related grounding requirements.

Article 4.16.4 Ground Terminals. Each down conductor shall terminate at a ground terminal dedicated to the lightning protection system. The design, size, depth, and number of ground terminals used shall comply with 4.16.4.1 through 4.16.4.2 (p. 780-17)

Article 4.14 Common Grounding. All grounding media in or on a structure shall be interconnected to provide a common ground potential. This shall include lightning protection, electric service, telephone and antenna system grounds, as well as underground metallic piping systems. Such piping systems include water service, well casings located within 25 ft (7.6 m) of the structure, gas

Examples of Correlation of Equipment Malfunctions, Electrical Phenomena, and Grounding Errors

Equipment Malfunction or Failure	Electrical Phenomena	Grounding Error Causing the Problem
Computer power supply failure	Surge energy was not absorbed by metal-oxide varistor; undesired potential differences migrated to bridge rectifier and switching transistors in power supply, causing components to experience overvoltage conditions.	Equipment grounding conductor not connected to proper grounding terminal on equipment AC input.
Indication error on medical infusion pump	Continuity of equipment grounding conductor interrupted by too frequent bending of AC line cord at rear of infusion pump; electrical noise generated by on-board battery charging system was not injected into ground; noise was recirculated on main printed circuit board and caused microprocessor errors leading to indication errors.	Failure of equipment grounding conductor.
Failure of electronic high-intensity discharge ballast	High-impedance ground at AC power connection (ground was not continuous but relied on connection of ground terminal inside industrial receptacle to metal box providing mechanical support to receptacle) to electronic HID ballast caused development of high-frequency voltage potential between ballast case and facility ground; caused premature ballast failures due to instability in high-frequency inverter circuit, which caused failure of power transistors.	High-impedance ground.
Failure of printer	Reversal of neutral and ground conductors at receptacle caused power supply failure; bridge rectifier failed when surge occurred.	Ground conductor reversal.

Single-point grounding of the power system greatly reduces the amount of steady-state current in the grounding conductors of appliances.

piping, underground conduits, underground liquefied petroleum gas piping systems, etc. Interconnection to a gas line shall be made on the customer's side of the meter. Main size lightning conductors shall be used for interconnecting these grounding systems to the lightning protection system (p. 780-16).

Article 4.14.2 Common Ground Bonding. If electric, telephone, or other systems are bonded to a metallic water pipe, only one connection from the lightning protection system to the water pipe system is required, provided that the water pipe is electrically continuous between all systems. If it is not electrically continuous, due to the use of plastic pipe sections or for other reasons, the nonconductive sections shall be bridged with main size conductors or the connection shall be made at a point where electrical continuity is assured (p. 780-16 and 780-17).

The NEC grounding practice for electric power services at residential buildings is called "single-point grounding." This single-point connection is the bond between the service neutral conductor and the grounding electrode system made by the "main bonding jumper" inside the service-entrance panel. For safety reasons not related to surge protection, the NEC requires that the neutral conductors of the branch circuits inside a residence never be grounded beyond the initial

The required grounding electrode for communication systems is typically "borrowed" from the power system by connecting a grounding conductor directly to the nearest accessible location on the power grounding electrode system.

bonding point. Single-point grounding of the power system greatly reduces the amount of steady-state current in the grounding conductors of appliances. As a result, the AC voltages at different points in the ground tend to remain at the same level as the grounding electrode system, which is considered to be at 0 volts or ground during steady-state or power-frequency faults. This requirement, when implemented with surge protection in mind, takes the form of the intersystem grounding illustrated in the figure below.

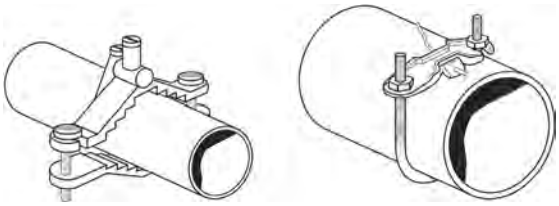
The NEC grounding practice for communication systems at residences is not specifically defined to be single-point. However, the requirements for grounding given in NEC chapter 8 favor the single-point grounding concept. For example, Article 800 mentions only one (a single) grounding conductor to the grounding electrode.

Grounding for communication systems at residences focuses on metallic paired and coaxial cables and primary protectors; masts and metal structures supporting antennas; antenna discharge units; and unpowered equipment and enclosures. The required grounding electrode for communication systems is typically "borrowed" from the power system by connecting a grounding conductor directly to the nearest accessible location on the power grounding electrode system. This location is often the power grounding electrode conductor or the power grounding electrode itself, such as a ground rod. In this configuration, the required intersystem bonding is automatically accomplished. The figure above shows the typical devices used to make this grounding connection.

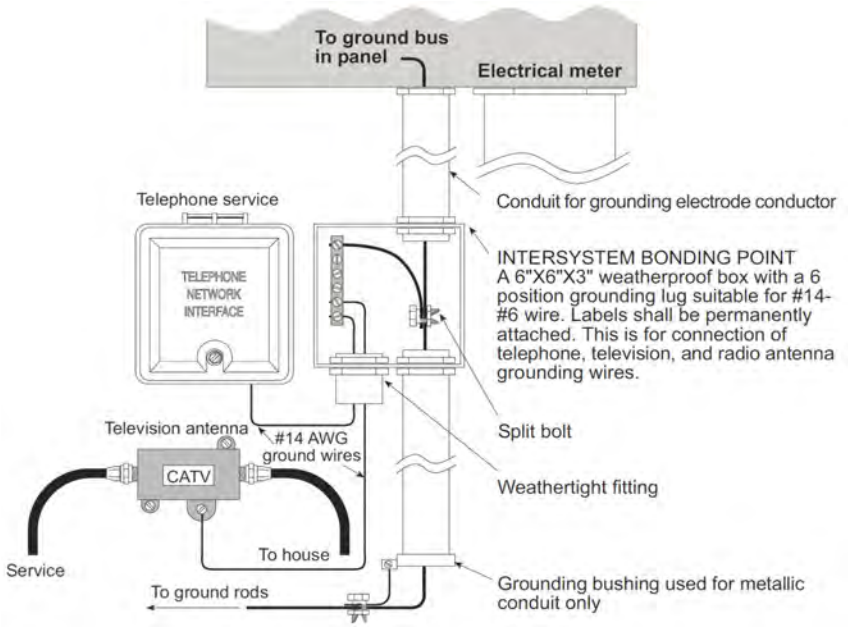
In certain locations, it may be deemed impractical to prevent a considerable separation between the power service entrance and the communication service entrance. The typical grounding method for this type of configuration is to place an electrode, such as a ground rod, at the communication service entrance as part of the intersystem grounding. In addition, an intersystem bonding conductor is required to connect the power grounding electrode system to the communication grounding electrode system. In combination, both grounding electrode systems make up the building grounding electrode system.

Earlier versions of the NEC allowed making use of a full length of metallic water pipe to perform this safety bonding, but now a 1.5 meter (5 feet) limitation is prescribed for the conductor that bonds the protector (network interface device or cable protection block) to the pipe. If this condition is not met, the grounding conductor must go all the way to the power system ground.

Bolted Clamp-Type Connectors for Ground Connection to Electrodes



Recommended Service Grounding for Enhanced Surge Immunity



While this prescription is significant for safety reasons, it makes no difference from the point of view of surge protection because the length of the bond, not its nature, determines shifts in differences between ground potentials. For this reason, the use of a surge reference equalizer is recommended.

Correlation of Electrical Phenomena with General Effects of Improper Grounding

Electrical Phenomena	General Effects of Improper Grounding
Low steady-state line voltage	None: No increased ground current flows when steady-state voltage is low except when an end-use equipment failure occurs.
High steady-state line voltage	None: No increased ground current flows when steady-state voltage is high except when an end-use equipment failure occurs.
High inrush current	None: Inrush current does not involve ground current except when neutral and ground conductor are reversed. Then, inrush return current will flow through ground conductor.
High radiated emissions	Noise currents can be coupled into ground conductors and thus increase flow of high-frequency noise currents.
High low-frequency conducted emissions	Increased flow of low-frequency ground currents from EMI filter.
High high-frequency conducted emissions	Increased flow of high-frequency ground currents from EMI filter.
Voltage distortion	None
Voltage notching	None
Voltage sags	None
Voltage swells	None
Voltage fluctuations (flicker)	None
Electrical fast transients	High-frequency current anomalies in ground conductor.
Ring-wave voltage surge	Flow of high-frequency surge current in ground conductor.
Combination-wave voltage surge	Flow of higher-amplitude high-frequency surge current in ground conductor.
Temporary overvoltage	Flow of temporary fault current in ground conductor resulting from failure of components in AC line input network.
Capacitor switching surge	Flow of low- to medium-frequency surge current in ground conductor coincident with capacitor switching voltage.
Ground noise	Compromised flow of ground noise currents due to high-impedance ground conditions.

To alleviate the problem of shifting ground potentials, it is recommended that all utility services enter the house at the same location, within 1.5 meters (5 feet) of each other, and be grounded and bonded to the same grounding electrode system. Typically, then, the grounding at the service entrance requires the interconnection of the grounding conductors of all services.

System Compatibility

System compatibility is the ability of a device, equipment, or system—generally a load—to function satisfactorily with respect to its power-supply electrical environment without introducing intolerable electrical disturbances to anything in that environment. The functionality of end-use equipment depends heavily on the state and performance of the ground system. The table at left lists a series of electrical disturbance phenomena that can occur on the utility side or customer side of the revenue meter. These disturbances can be caused by utility events and electrical events inside the customer's facility. In many cases when a disturbance occurs, a disturbance or fault current looks for a ground path. If a ground path is not present at the equipment, then the effects of the disturbance can be pronounced, possibly leading to a more serious equipment failure. The table shows that the most concerning disturbances for which compatibility problems can become more serious are those that relate to high-frequency and high-voltage phenomena.

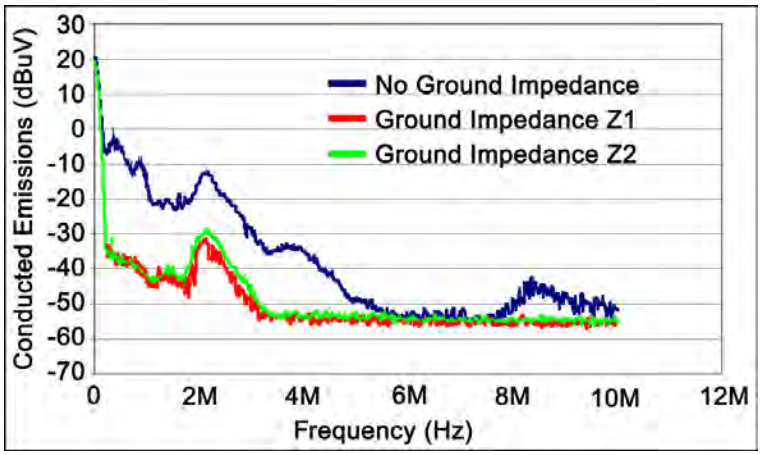
Electromagnetic Compatibility

Electromagnetic compatibility (EMC) is the one area that cuts across all electrical sectors of the energy industry. The control of radiated and conducted emissions is very dependent upon the state and performance of grounds and grounding systems. In power quality, ground performance is critical at the power frequency (50 and 60 hertz). The critical nature of this performance in power quality extends up to about 3 kHz and can extend well beyond this point, depending upon the nature of the power quality problem. In EMC, ground performance covers a very broad

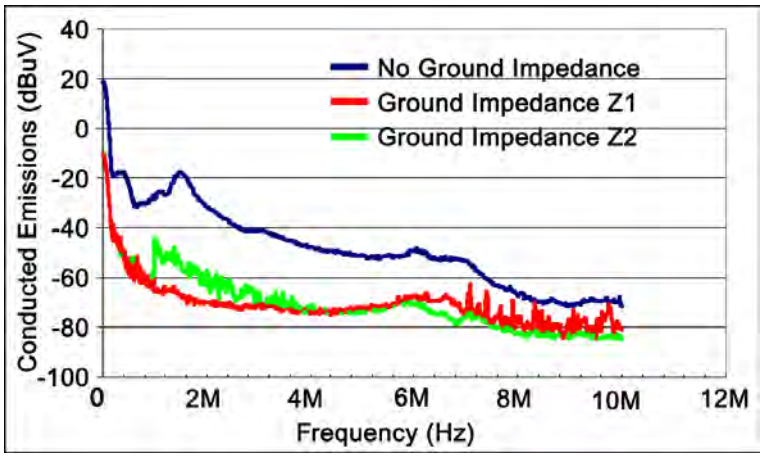
Frequency is not the only variable that affects the level of emissions; the impedance of the ground also has a dramatic effect.

frequency range—from DC to tens of gigahertz. To maintain the control of emissions, which helps to prevent electromagnetic interference (EMI) problems, ground systems must perform across much of the frequency range. To help illustrate this point, three conducted emissions plots are provided below. From these plots, one can see that the frequency is not the only variable that affects the level of emissions. The impedance of the ground also has a dramatic effect.

Ground Emissions from a 15-Horsepower Adjustable-Speed Drive with a 5- and 20-Amp Ground Noise Filter



Ground Emissions from a Fractional Horsepower Drive With a 1- and 5-Amp Ground Noise Filter



15-Horsepower Adjustable-Speed Drive

The figure at top left illustrates the ground noise emissions from a 15-horsepower adjustable-speed drive. As shown, significant noise occurs in the ground in the lower frequencies up to about 5 MHz. The use of the 5-amp (Ground Impedance Z2) and 20-amp (Ground Impedance Z1) ground noise filters significantly reduces this noise, with most of the reduction being in the area around 1 to 2 MHz and 3.5 to 4 MHz to the reduction of about 10 to 20 dB. This plot was taken with the drive fully loaded.

In this emissions plot, the Ground Impedance Z1 provides a higher inductance in the ground than the Ground Impedance Z2. The significant drop in emissions seen by inserting an impedance in the equipment ground of the drive provides better tuning for the EMI filter inside the drive.

Fractional Horsepower Drive

The figure at bottom left illustrates the ground noise emissions from a fractional (<1) horsepower adjustable-speed drive. The emissions are quite high and present across the spectrum out to about 10 MHz. At the lower frequencies, the 1-amp ground noise filter does not perform as well as the 5-amp filter because of saturation. At these frequencies some appreciable current flow in the ground circuit reduces the effectiveness of the filtering that the 1-amp filter can provide. Note that this effect is reversed at the higher frequencies above about 5 MHz, where the red trace crosses the green trace. However, both filters provide a suitable level of reduction in ground noise. At 1 MHz, this equates to about 50 dB. Such filters could be used on these smaller drives to reduce the likelihood of ground noise from corrupting the control data to and from these drives.

Notice that the emissions signatures of these three end-use devices are all different, and the effects of inserting the same impedances (Z1 and Z2) into the equipment ground conductors are also different. Aside from the fact that the emissions signatures without any ground

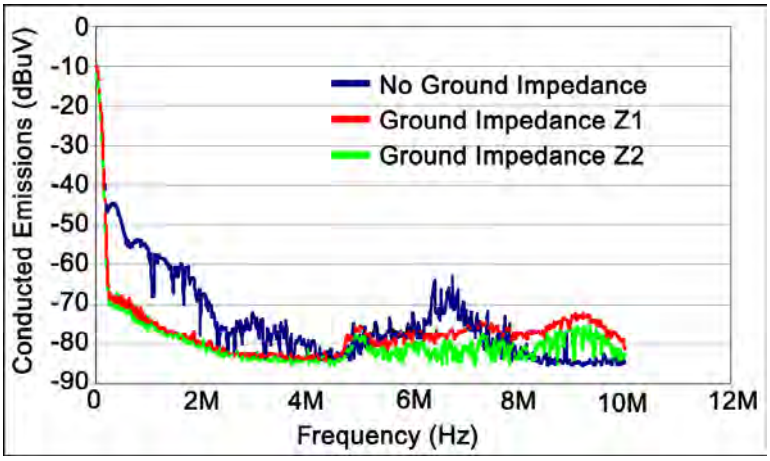
Using a filter on the ground conductor of a solar system may be especially useful to keep emissions from the DC inverter from flowing back into the building's electrical system.

impedances are different, the effects of adding the same impedances to the ground are different for a number of reasons. First, the impedances of the ground conductor looking back up into the EMI filters are different. This is because the filter elements referenced to ground are different. Second, the overall change in ground impedance when the impedances are added is different. This causes a change in the emissions signature when the impedances are added.

DC Inverter for a Solar Cell

DC inverters are commonly used in a variety of equipment that is used to convert stored energy into AC power. Solar cells are one prime example, and their use is growing in the renewables markets. EPRI has done extensive work in this area and had the opportunity to measure ground noise. The figure below illustrates the ground noise emissions from a DC inverter of a solar system measured in the main ground cable. The unfiltered emissions (upper trace) generated by the inverter are characteristic of the inverter's operation and driving frequencies. The use of the 5-amp and 20-amp ground noise filter significantly reduces the emissions up to about 450 kHz. Some reduction in emissions is accomplished around 500 to750 kHz, but an increase occurs from about 750 kHz to 1 MHz. Using a filter on the ground conductor of a solar system may be especially useful to keep emissions from the DC inverter(s) from flowing back into the building's electrical system.

Ground Emissions from a DC Inverter Used in a Solar Cell With and Without Ground Noise Filter



CASE STUDIES IN GROUNDING

Case Study 1: Ground Bonding in Flexible Drop Cord Wiring Systems

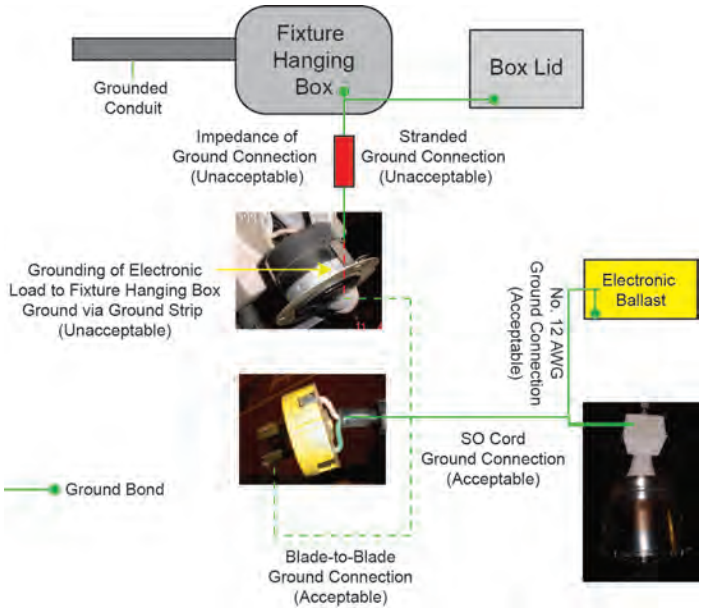
High-frequency electronic lamp-ballast systems are being used more frequently in commercial and industrial facilities to provide a source of energy-efficient fluorescent and HID lighting. Lamp and ballast manufacturers have designed many of these systems to provide high-efficiency lighting systems. A well-known state college in Pennsylvania recently installed universal-voltage electronic HID ballasts in its basketball arena, replacing existing 400-watt high-pressure sodium magnetic ballasts. However, the college experienced component-related ballast failures and replaced all of them. Nevertheless, the new ballasts continued to fail. The manufacturer suspected wiring and grounding issues inside the facility.

Analysis of the Fixture and Ballast Grounding System

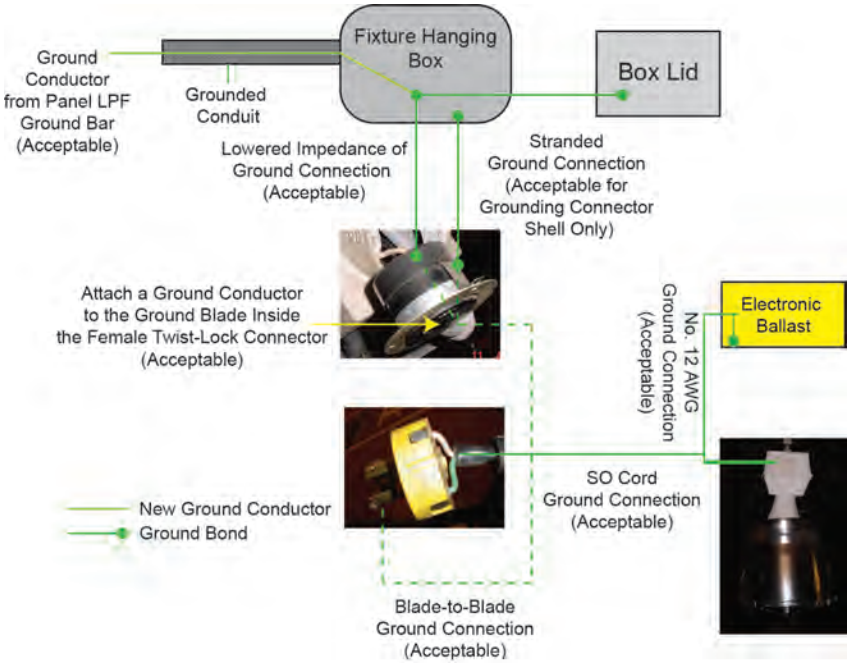
The figure at the top of the next page illustrates the grounding of the present electronic HID ballast system. From the investigation, it was found that grounding of the fixture and ballast system was being established through an unreliable ground conductor system. This system used the ground conductor inside the flexible drop cord, the ground blade of the male twist-lock connector, and the blade of the female connector, which were all acceptable. The system also used the ground strip of the female connector assembly, which attempts to establish a solid and reliable ground to the frame of the fixture hanging box.

The use of this ground strip in connection with the frame of the fixture hanging box presented an unreliable ground connection between the fixture-ballast-male connector and the conduit-fixture hanging box ground. This ground was found to have a high impedance on the fixtures that contained failed ballasts. The impedance of this ground varied with temperature, humidity,

Grounding System of Existing Electronic HID Ballast Installation



Recommended Grounding System



and age of the components. The present age of the connectors contributed to its high impedance. Moreover, the use of the ground strip to establish a solid ground for the fixture-ballast system resulted in the ballast failures that occurred in the basketball arena.

Recommended Grounding System for Existing Electronic HID Ballast Installation

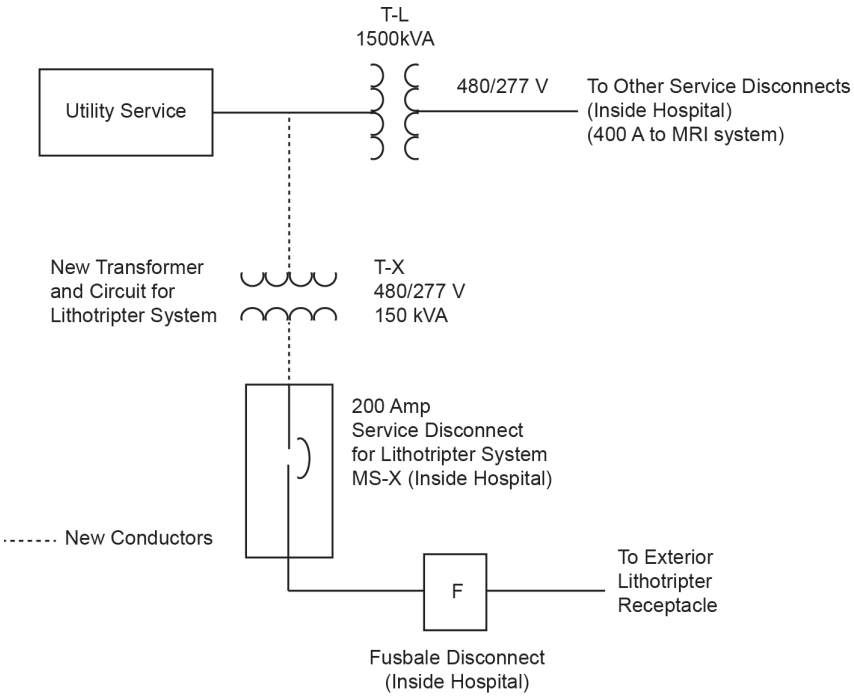
The figure at bottom left illustrates the recommended grounding system for the existing electronic HID ballast installation and any electronic HID ballasts installed in the arena. From this figure, one can see that the grounding system improvements can be made (1) by pulling a ground conductor from the ground bar inside Panel LPF through the conduit to each fixture hanging box, (2) connecting a ground conductor to the ground blade inside the female twist-lock connector, and (3) bonding the ground conductor from Panel LPF to the ground conductor to the twist-lock connector. This method of ground is standard for installations of this type and will ensure a reliable low-impedance ground for the fixture-ballast system.

Case Study 2: Wiring and Grounding Deficiencies Magnify Typical Lithotripter Power Disturbances

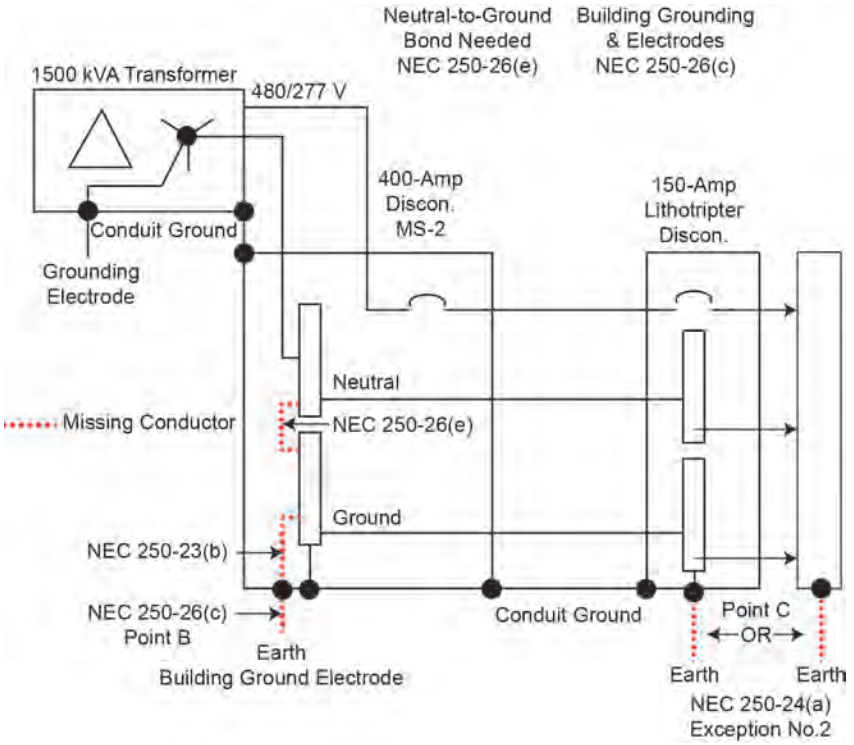
A mobile lithotripter system used to treat patients suffering from kidney and gall stones operated erratically at one of several hospital stops. Circuits controlling small electric motors used for positioning patients in the system's warm-water bath and for targeting a 30-kV arc-generated shock wave to the kidney stone would occasionally malfunction. As a result, the lithotripter could not be used and was taken out of service at the problem site, forcing patients to reschedule their treatments for the mobile system's next visit one month later.

Moving on with the investigation, EPRI power quality engineers inspected the hospital's one-line diagrams, which showed that the same circuit powered the lithotripter and a nearby magnetic resonance imaging (MRI) system. The electrical system powering the lithotripter is shown in the figure on the next page.

One-Line Electrical Diagram for Providing Power to Lithotripter



Wiring and Grounding Diagram for Outside Receptacle for Lithotripter Showing Grounding Errors



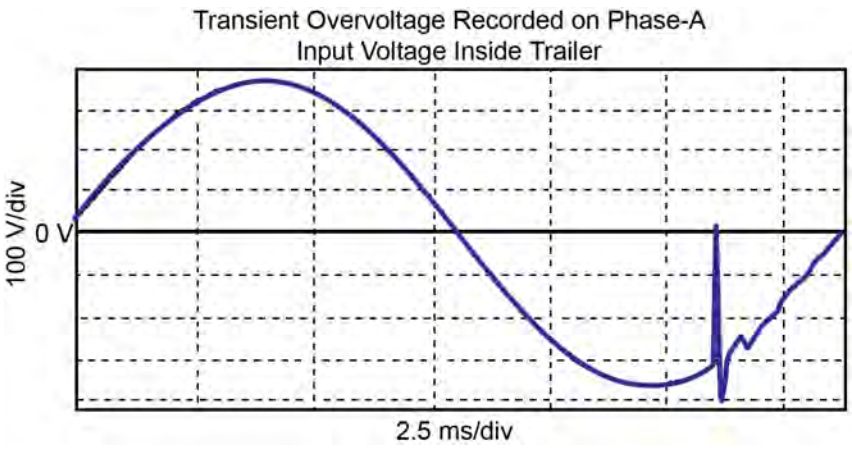
An on-site investigation of this wiring revealed that the main disconnect for the lithotripter circuit inside the hospital had no neutral-to-ground bond, as shown in Figure 34. The investigation also showed that the disconnect outside the hospital for the lithotripter system contained no ground bond and that the enclosure for this disconnect was not grounded to earth at the trailer pedestal.

To record a history of any power disturbances that may have affected the lithotripter, a power-line monitor installed in the hospital indicated the presence of oscillatory transients at the problem site, which were the result of normal day-to-day capacitor switching by the utility. A second power-line monitor was installed in the trailer and was set up to record disturbances as it made its way from hospital to hospital. This data showed that neutral-to-ground voltage transients and oscillatory transients occurred and were incident on the lithotripter system at all hospital sites, as illustrated in the figure on the next page.

However, because the lithotripter system produced its own power disturbance as each shock wave was generated and because the problem site contained neural and ground wiring problems, severe (150 volt peak-to-peak) neutral-to-ground voltage transients occurred and correlated with failures of the patient-positioning system within the lithotripter system at the problem site. Low-level (less than 50 volt peak-to-peak) neutral-to-ground voltage transients, as shown in the figure at the bottom of the next page, were also recorded at the other sites, but these caused no problems for the lithotripter.

Therefore, oscillatory transients were ruled out as a unique problem at the problem site, but the intensity of the neutral-to-ground voltage transients recorded inside the trailer at the problem site were attributed to neutral and ground wiring deficiencies within the circuit providing power to the trailer at the problem site. With the mobile trailer at the problem site, excessive ground currents, as illustrated inthe figure on the next page, were measured at the

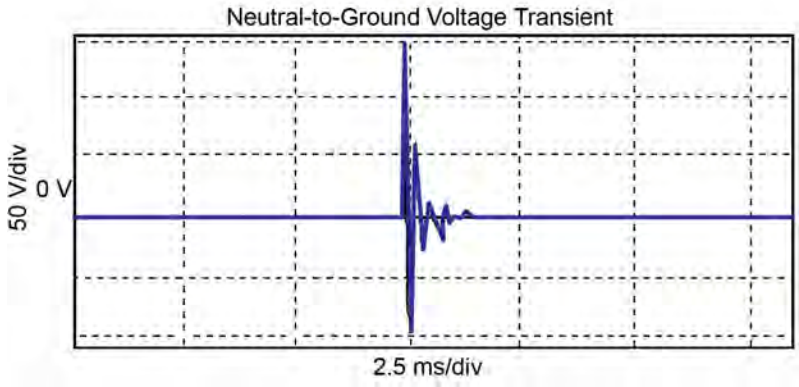
Transient Overvoltage on the AC Power Input to the Lithotripter



lithotripter disconnect outside the hospital while the lithotripter was operating. This indicated the presence of reversed neutral and ground conductors inside the trailer, which would also magnify any power disturbances incident upon the lithotripter system at any site.

Solutions. For the grounding problems, power quality engineers recommended bonding neutral to ground at the lithotripter-circuit main disconnect, installing a ground rod at the trailer outdoor power-supply pedestal at the problem site, and correcting the neutral-to-ground reversal inside the trailer. To further protect the lithotripter system, which was recommended by the lithotripter system manufacturer as well, power quality engineers also recommended the installation of an isolation transformer at the problem site as close to the trailer as possible. This would isolate the lithotripter from any power disturbances or conducted emissions that could result from operating the MRI equipment. The hospital was also advised to add surge protection at the trailer in case of nearby lightning at any of the sites. These changes were made, eliminating all failures at the problem site. To address the radiated interference problems, power quality engineers recommended that the MRI system at the problem site be inspected for adequate radio-frequency gasketing and designed to attenuate radiated emissions from the MRI system. An ideal trailer site should be relocated farther away from the "noisy" MRI system and always be placed on an isolated and dedicated circuit with a stiff source (short run) from the hospital's electrical distribution room.

Neutral-to-Ground Voltage Transient Occurring at the AC Input to the Lithotripter

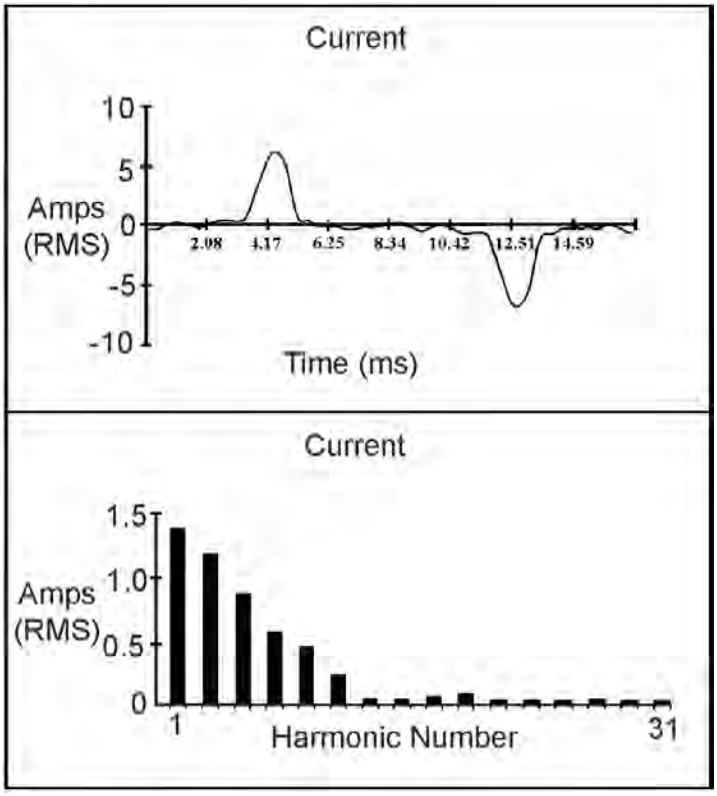


Case Study 3: Common PQ Problems in Medical Imaging Systems

Any power quality professional or auditor with auditing experience knows the basic types of problems that are encountered in a power quality investigation. Quality power containing even minor everyday electrical disturbances can cause significant problems on a medical imaging system—such as MRI, computed tomography (CT), and X-ray systems—if the electrical system is plagued with wiring and grounding errors. Wiring and grounding systems with errors will make any electrical disturbance at the source worse at the load, thus imparting more damage to a system.

Audits on imaging systems and their electrical-system infrastructures typically reveal many of the same types of problems. These problems are usually associated with the techniques used to design and install the wiring and grounding systems that are used to power and protect an imaging system. Some examples of typical errors from two case studies are included in the sections below.

Waveform and Harmonic Spectra of Current on the Ground Conductor at the AC Input to the Lithotripter



Grounding

Grounding methods and practices are extremely important to the reliable operation and life of an imaging system. Grounds for imaging systems are required for safety and help to protect the sensitive electronics inside the imaging system. Electrical disturbances that are created inside or outside the imaging system require low-impedance ground paths back to the voltage source to prevent ground currents from creating high potentials across electrical devices where they can cause damage to the system's electronics. Power quality auditors who investigate imaging systems are consistently interested in the integrity of the grounding systems.

Some manufacturers of imaging systems are now requiring pre-installation power quality audits for all new MRI, CT, cardiac X-ray, and vascular X-ray imaging systems. With such programs in place, trends of service records began indicating that many of the damaged and shutdown systems involved grounding errors inside the imaging suite and associated with the grounding system all the way back to the service entrance.

Auditors have found that ground conductors were missing from the branch circuits feeding the imaging systems. In some cases, the conduit ground (ground continuity established by the connection of the conduit system) was the only return path for ground. In the event of an electrical disturbance such as a voltage surge or voltage sag, the ground current would find it difficult to return to the source when it depended upon the conduit as a ground conductor. In cases where a grounding conductor was available, most of the time it could be traced back to a grounding point in the facility other than the ground point associated with the phase conductors.

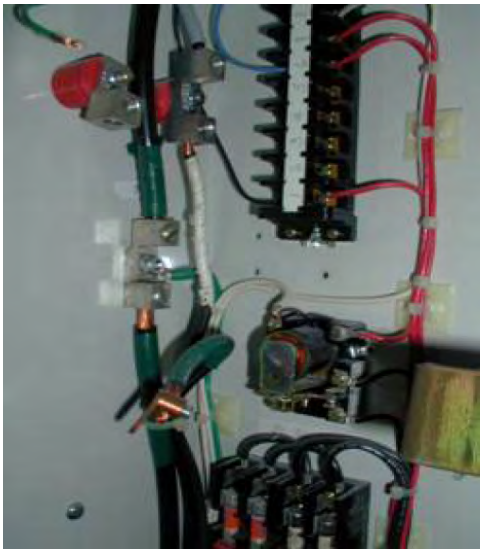
Older healthcare facilities are known for multitudes of renovations, additions, and changes to the electrical system. These activities take their toll on the electrical systems. Some facility engineers in older facilities are unable to locate their earth-grounding electrode (ground rod) because it had been installed for a very long time and no one ever needed to examine it. When electricians are unable to identify a reliable ground, they are inclined to install an additional grounding electrode for each new piece of imaging equipment. In cases like this, a facility with several grounding electrodes in different locations cannot establish an equipotential ground reference during an electrical disturbance. This often results in failed equipment caused by potential differences developed across the various grounding electrodes.

A facility with several grounding electrodes in different locations cannot establish an equipotential ground reference during an electrical disturbance.

In other cases, auditors found that the ground for an imaging system had not been connected to the grounding system of the facility. Some architects, electrical system design engineers, and facility engineers even recommend that isolated grounds be used when installing new imaging systems. The use of isolated grounds is not recommended for these types of installations. Grounding errors can cause many types of problems with imaging systems, including:

- Randomly appearing, intermittent software errors
- System lock-ups that require imaging system operators to reset or reboot the equipment
- Random imaging artifacts that come and go in intensity and frequency
- Hardware failures
- Interaction with or interference from unrelated imaging systems in the facility

Example of Grounding Errors Found in a Main Disconnect Panel of a CT Imaging System



The figure at left illustrates an example of multiple grounding errors found in a main disconnect panel for a CT imaging system. Notice that there are multiple grounding conductors, with some not connected to any ground bus. In addition, the facility-side and load-side grounding conductors are connected together through the use of two lugs. However, these lugs are mounted on top of a painted surface inside the disconnect panel. Mounting grounding bars on top of painted surfaces is not good practice. This creates a capacitive effect between the ground bars and the metal of the panel. Such effects prevent high-frequency voltages and currents in the grounds from finding a low-impedance path back to the source. This type of grounding error would make a voltage transient developed at the source more damaging for the front-end electronics at the imaging system.

Transformers

In providing power to imaging systems, transformers are often necessary to match the source voltage to the input voltage required by the system. Some of the imaging systems are designed for multiple input voltages ranging from 200 to 480 volts, 50 and 60 hertz. Requirements of 120 volts are also included but usually derived from separate sources. Systems that provide a range of input operating voltages should be powered from the higher voltage (such as 480 volts). Using the higher voltage will result in the use of phase and neutral (if needed) conductors that have lower current ratings. Important to power quality, utilization of the higher voltage will result in fewer shutdowns caused by voltage sags and momentary interruptions.

In some imaging suites, the higher voltage of 480 volts is not readily available, meaning that no 480-volt circuit is within supporting equipment areas of the imaging suite where distribution subpanels are located. If a new imaging system is specified for such suites, then a problem in supplying the correct voltage to the area is encountered. Most suites have three-

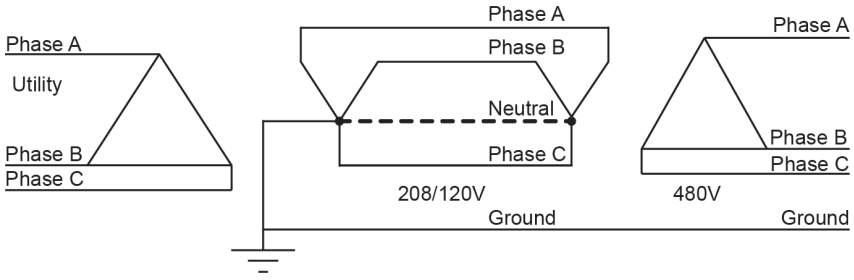
Systems that provide a range of input operating voltages should be powered from the higher voltage.

phase 208/120-volt circuits available with the appropriate ampacity ratings.

The options for providing 480 volts to an imaging suite are: (1) install a new 480-volt circuit from the main switchgear, possibly requiring a long run; (2) install a step-up 208-volt delta to 480/2770-volt wye transformer, requiring a special-order transformer; or (3) install a step-down 480-volt delta to 208/120-volt wye transformer with the 208/120-volt side connected as the primary and the 480-volt side as the secondary. Options 1 and 2 are the most costly and present the longest installation times. Option 3 is the most cost-effective and most widely used but can present significant power quality problems if the neutral and ground conductors are not configured correctly.

The figure below illustrates an example of a step-down transformer used as a step-up transformer to provide a 480-volt source to an imaging system. The commonly provided 208/120-volt secondary voltage throughout the facility is used as the primary voltage for this transformer. However, a neutral conductor is pulled from the secondary of the 480-volt delta to 208/120-volt wye transformer and connected to the "primary" of the 208/120-volt wye to 480-volt delta transformer. The use of this neutral conductor should be avoided to prevent power quality problems with imaging systems.

Transformation of Utility Voltage to Secondary Voltage to Imaging System Voltage with Improperly Connected Neutral Conductor Between the Two Transformers

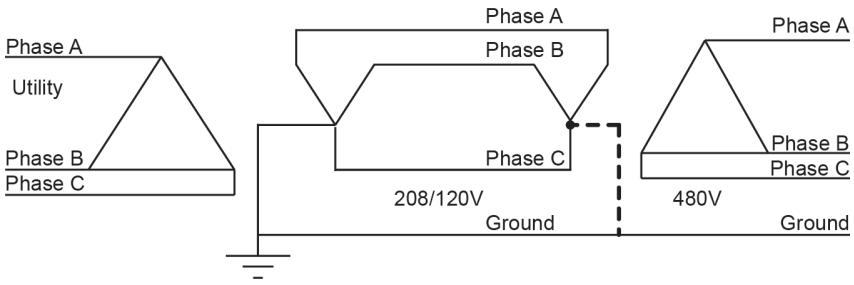


The figure on the next page illustrates an example of a step-down transformer used as a step-up transformer to provide a 480-volt source to an imaging system. The commonly provided 208/120-volt secondary voltage throughout the facility is again used as the primary voltage for this transformer. However, a conductor is attached from the neutral of the primary side of this transformer to the ground. The use of this neutral-to-ground conductor (or bond) should be avoided to prevent power quality problems with imaging systems.

These types of installations can burn up phase, neutral, and ground conductors during a fault condition. How does this happen? The neutral on the primary side of the transformer provides a path for the fault current as illustrated in the figure on the following page. This current in the primary windings of the transformer sets up a current in the secondary windings of the transformer, which in turn tries to drive the load. Then these secondary circulating currents try to "pull up" the primary phase that is down, and the neutral current rises too high. You can avoid this problem by eliminating the neutral connection on the primary winding of the transformer.

In other cases, an isolation transformer is used in a facility to isolate the primary from the secondary. This type of installation seeks to isolate incoming voltage transients from reaching the output. In many of these installations, a neutral conductor is carried from the primary side of the transformer to the secondary side. The use of this neutral conductor should also be avoided to prevent power quality problems with imaging systems.

Transformation of Utility Voltage to Secondary Voltage to Imaging System Voltage with Improperly Connected Neutral-to-Ground Conductor at "Primary" of the Reversed Step-Down Transformer

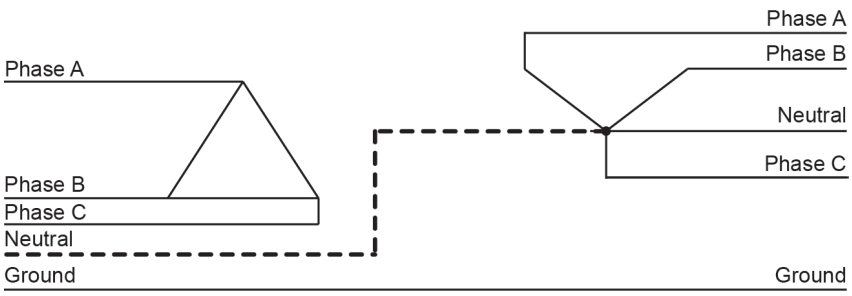


The nature of the use of electricity and the nature of the electrical and electromagnetic environment necessitate stringent requirements for quality grounding systems.

Here are a few more precautions to consider:

- Do not use three transformers to create a wye-wye transformer bank. Because the transformers do not share the same iron core, the circulating magnetic fields rich in third harmonics do not cancel out, creating a pseudo voltage of more than 300 volts and damaging any system or piece of equipment connected to it.
- Do not use an ungrounded delta transformer to power diagnostic imaging equipment. This configuration can actually act like a voltage doubler. In this type of installation, auditors have documented phase-to-ground voltage measurements as high as 960 volts on a 480-volt system. To eliminate this problem, use a wye or corner-grounded delta transformer to power all diagnostic imaging equipment.

Use of an Isolation Transformer in an Imaging System Installation with Improper Use of a Neutral Conductor from the Primary to the Secondary Side of the Transformer



CONCLUSION

Grounding provides a critical component necessary for the safe use of electricity and the compatible use of sensitive electronic equipment. The performance of grounding systems spreads across the frequency range from low-frequency to DC and high-frequency to gigahertz values. The nature of the use of electricity and the nature of the electrical and electromagnetic environment necessitate stringent requirements for quality grounding systems. One of the trends taking place in power quality is the growing need for reliable and high-performance grounding systems as the electrical environment becomes more complex and must support more types of electrical and electronic equipment as modern society continues to progress. The material included in this chapter on grounding provides the basic, historical, and modern justifications for grounding energy sources, electrical systems, and loads.

REFERENCES

AIEE, Transactions of the American Institute of Electrical Engineers, Vol. I, May – October, 1884, copyright 1885. http://antiquesockets.com/nec.html.

ANSI T1.318, *Electrical Protection Applied to Telecommunications Network Plant at Entrances to Customer Structures or Buildings.*

Tagg, G. F., *Earth Resistance*. New York: Pitman, 1964.

IEEE Std 142, *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems* (IEEE Green Book).

IEEE Std 1100, *IEEE Recommended Practice for Powering and Grounding Electronic Equipment* (IEEE Emerald Book).

Modern Practice of the Electric Telegraph, 1869, http://antiquesockets.com/nec.html.

NFPA 70. *National Electrical Code.* Quincy, MA: National Fire Protection Association, 2011. *Protecting Structures and Equipment from Surges*. Palo Alto, CA: EPRI, 2000.

NESC Handbook: A Discussion of the National Electrical Safety Code, Standards Information Network, Fifth Edition. New York: IEEE Press, 2001.

National Fire Protection Association, NFPA 70E®: Standard for Electrical Safety in the Workplace®, 2012 Edition (National Electrical Code)

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