

## Grounding Methods in Mission Critical Facilities

### Abstract

Many factors must be considered when designing the electrical system for critical facilities, not the least of which is the type of ground system used. Proper grounding reduces overvoltages, improves uptime and isolates faults.

### Introduction

Grounded systems offer many benefits over ungrounded systems [1][2][3]. High resistance grounding (HRG) is a specialized type of grounding that offers unique benefits in mission critical installations, when properly applied.

### Grounded System Types

Since a properly grounded system is important, the question becomes “what type of ground system should be installed?” While many variations exist, the most common types of grounding system are:

- Ungrounded
- Corner Grounded Delta
- Solid (or effectively) Grounded
- Low-Resistance Grounded (LRG)
- High-Resistance Grounded (HRG)
- Hybrid-High Resistance Grounded (HHRG)

### Ungrounded

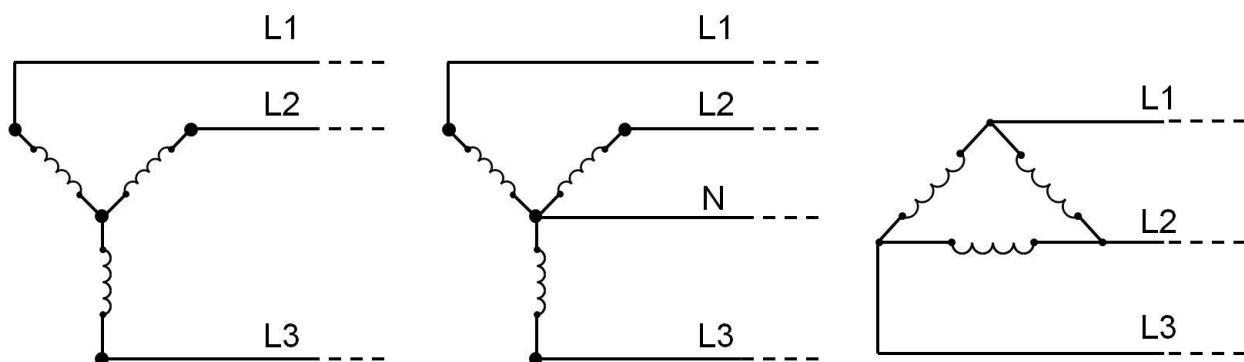
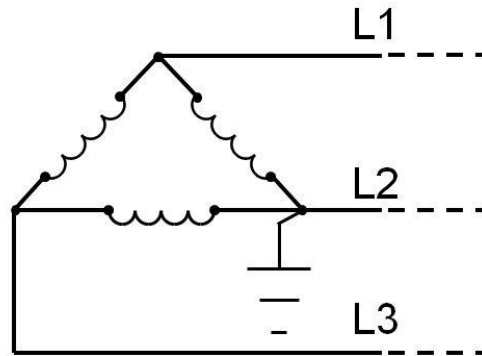


Figure 1: Representative 3- and 4-wire ungrounded wye and ungrounded delta systems

Once a common solution, unground systems have several problems and are not recommended for most modern electrical systems [4].

## Corner Grounded Delta (CGD)



**Figure 2:** Corner Grounded Delta

As the disadvantages of ungrounded systems became better known, a simple, low-cost method of establishing a ground reference on an ungrounded delta system was sought out.

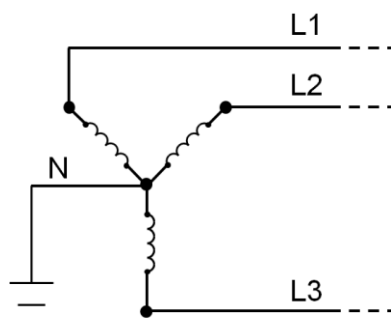
The advantages of CGD are:

- Establishes a ground reference for each current carry conductor
- Low-cost
- Eliminates the problems (overvoltages, transients) of an ungrounded system

The disadvantages of CGD are:

- Need to mark grounded phase throughout distribution system
- Cannot use lower cost 'slash-rated' (i.e. 480/277 or 240/120) circuit breakers.
- Ground fault sensing is undefined for the grounded phase, so typically cannot be used where GF is required such as healthcare facilities.

## Solidly (Effectively) Grounded

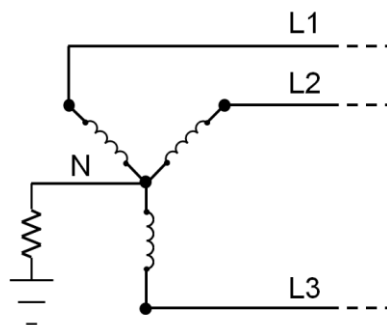


**Figure 3:** Solidly grounded system

Solidly (or “effectively”) grounded systems connect (bond) the system neutral directly to earth ground. This helps insure that the neutral voltage is essentially equal to ground<sup>1</sup>. With a grounded neutral, each individual phase (or line) to neutral voltage is fixed with a reference to ground.

Because of this fixed reference, solidly grounded systems help insure that phase-to-ground overvoltages do not occur. Properly installed solidly grounded systems will bond the neutral ground at only one point. Failing to pay attention to the location of neutral-to-ground bond points can disrupt ground fault sensing systems. Also, the very large amounts of current that can flow during a ground fault on such a system require that the source be disconnected immediately upon the detection of a ground fault. This reduces system reliability and load availability compared to other grounding methods. Since ground faults are 100x more common than any other type of fault [8][9], having such a vulnerable design may not be the best choice for mission critical applications.

### Low Resistance Grounded



**Figure 4:** Resistance grounded system (both low and high resistance)

Low-resistance grounding is used to reduce damage caused by high currents flowing during ground faults. While more common on medium voltage systems, they can be used on low voltage systems. Even though current is reduced (100’s of amperes versus perhaps 1000’s), the fault current magnitude still is sufficiently large that the source must be disconnected immediately. As a result, unless there are overriding reasons, as with the solidly grounded, a low-resistance grounded system may not be the first choice for mission critical applications.

### High Resistance Grounded

High resistance grounding is similar to low-resistance grounded system, except that a neutral grounding resistor with a higher resistance is chosen. This reduces the ground fault current to even lower values, typically less than 10 A, and frequently less than 5A on low voltage systems. Such small currents eliminate the need to trip immediately, giving time to locate and clear the ground fault. Also, as will be discussed later, HRG systems can include features that assist in locating the ground fault, speeding repairs and improving safety and reliability. Therefore, in certain applications, HRG systems are recommended for mission critical applications.

One issue though is that while a ground remains in the system, the neutral voltage will rise above ground potential. Some UPSs systems will view a neutral to ground voltage as a fault and inhibit transferring to and from

<sup>1</sup> Offset by any voltage drop flowing through the N-G conductor due to ground fault current that may be flowing at the time.

bypass. For this reason, HRG systems may not be recommended for powering UPS or other information and communication technology (ICT) loads. With an HRG system the system designer will need to weigh the benefit of increased availability of power into the UPS (due to GFs not causing a source trip) with the potential problem where certain UPSs switch to bypass while a GF is present.

However, in all cases, HRG systems still can be configured to trip the upstream breaker, in effect mimicking a solidly grounded system, while providing the extra benefit of reduced arc flash incident energy releasing during a single GF event since the neutral resistance limits the GF current to very modest levels.

While ground faults can occur anywhere, a somewhat more common location in data centers is within motors. The thinness of the winding insulation, the proximity of the winding to the stator, the high (and cycling) temperatures, the (likewise cyclic) vibrations, all stress the windings and create an environment conducive to ground faults.

Having a grounding system like an HRG system would be desirable for mission critical applications. However, besides the UPS issue mentioned above, the United States National Electrical Code (NEC) and the Canadian Electrical Code (CEC) place additional restrictions on when HRG systems can be used<sup>2</sup>. However, these restrictions tend to not apply to motor loads. In mission critical installations, larger motors are rarely connected line-to-neutral (one of the code prohibitions when using HRG). This means that mission critical sites could utilize HRG on the mechanical loads while using a solidly grounded system to power the ICT loads.

## Resonant Grounded

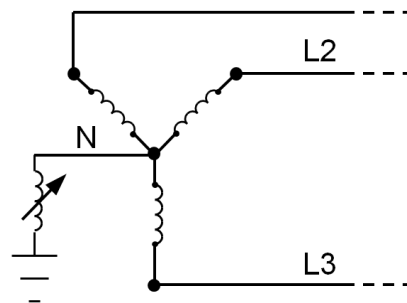
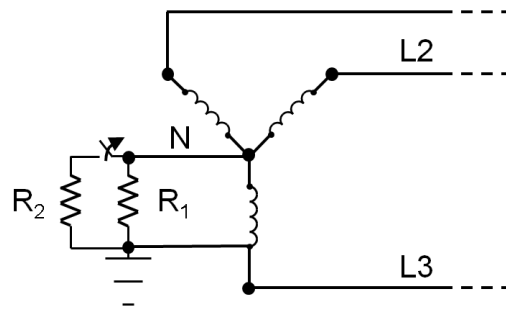


Figure 5: Resonant grounded system

A less common grounding scheme is known as resonant grounding. Resonant grounded systems are grounded through a variable inductance called a Peterson coil. The coil is in series with the effective line-to-ground capacitance of each phase conductor and is tuned to produce an impedance based on the series LC circuit. Since the Peterson coil is adjusted based on what is connected at the time, the disadvantage of this design is the Peterson coil would potentially need to be re-adjusted as different loads were switched on and off.

<sup>2</sup> These restrictions are discussed in Appendix B of this document.

## Hybrid High-Resistance Grounded



**Figure 6:** Hybrid high resistance grounded system

Hybrid-high resistance systems were developed for the special case of protecting generators from internal ground faults [5]. They operate as a low-resistance grounded system with a bypass device closed under normal conditions. When a fault is detected, the bypass device opens and ground current is forced through a second, higher resistance value resistor. This reduces the current and so reduces the likelihood of internal generator lamination damage.

**Table 1:** Overvoltage and Continuity Benefits of Grounding Options

	Protection against overvoltages	Operation During Fault	Ability to locate fault?
<b>Ungrounded</b>	No	Yes	Limited*
<b>Solidly grounded</b>	Yes	No	No
<b>Low-resistance grounded</b>	Yes	No	No
<b>High-resistance grounded</b>	Yes	Yes	Yes

\* Loads can be selectively switched off while simultaneously monitoring voltage line to ground. When the feeder with the ground is switched off, the line to ground voltage jumps to a higher value. However, this is very intrusive method of troubleshooting since it requires disconnecting loads.

As shown in Table 1, only the HRG system provides protection against overvoltages, while providing high service continuity and the ability to locate a fault – all attractive features for mission critical environments.

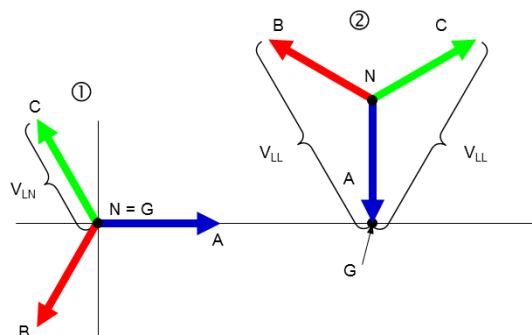
HRG systems, however, must be installed per article 250.36 of National Electrical Code which limits the use of HRG to only 3-phase installations where:

- No line-to-neutral loads are connected
- Ground detectors are installed

- Only qualified persons service the installation
- Where continuity of service is required

As mentioned earlier, this means that HRG systems cannot be used on 3-phase, 4-wire systems where line-to-neutral loads are connected. Since many commercial building distribution systems are 3-phase, 4-wire, loads are commonly connected between a line and neutral (e.g. 277 fluorescent lighting connected to a 480Y/277 3-phase, 4-wire system). In such a system, the NEC would prohibit using an HRG system.

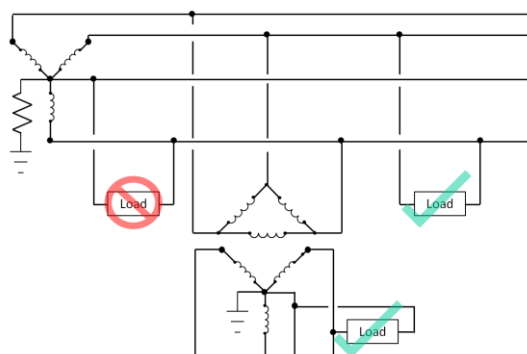
The principal reason for the prohibition is that during a ground fault, the neutral conductor in an HRG system is no longer at ground potential. The line-to-ground increases on the ungrounded phases to a value equal to the previous line-to-neutral voltage multiplied by  $\sqrt{3}$ . This can stress overvoltage protective devices in some cases.



**Figure 7** – Grounding a phase in HRG system causes line-to-ground voltage to increase by  $\sqrt{3}$

Likely the NEC code making panel didn't want to verify if the myriad of electrical devices that might possibly connect to the neutral conductor could tolerate a raised voltage, so the code makes a blanket prohibition of the use of line-to-neutral loads on HRG systems.

However, for 3-phase, 3-wire systems there are, by definition, no loads connected to neutral connection. In this case, HRG provides service continuity while simultaneously offering protection against transient overvoltages.



**Figure 8:** Acceptable and unacceptable single-phase loads on HRG system per NEC/CEC

## Installing HRG Systems

HRG can be installed either as part of a new installation or as a retrofit. HRG solutions can also be installed on systems fed by either wye or delta transformer secondaries.

Note that regardless of the type of connection, all HRG systems must have ground detectors per NEC 250.36. For this reason, manufacturers typically package the grounding resistor and detection systems into a single, easy-to-install package.

### Source Transformer: Delta Connected Secondary

Since a delta transformer winding has no neutral bushing, the recommended method of grounding a delta transformer is to first derive the neutral and then ground that derived neutral through a resistor.

Since the maximum amount of neutral current is limited by the resistor chosen, the size of the transformer used to derive that neutral must only be large enough to provide the maximum fault current (typically 5 or 10 A) at the rated line-to-neutral voltage (e.g. 277 V). The resistor is chosen to permit slightly more than system charging current to flow during a ground. Refer to [1] for a discussion of system charging current. For most low-voltage systems, system charging current will be no more than 1-2 amperes.

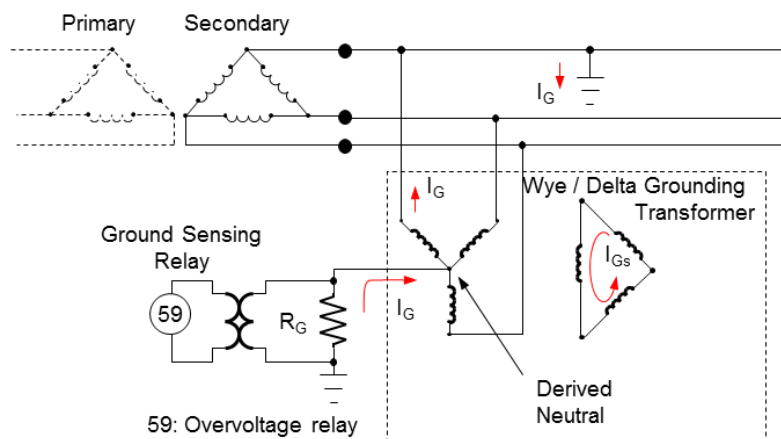
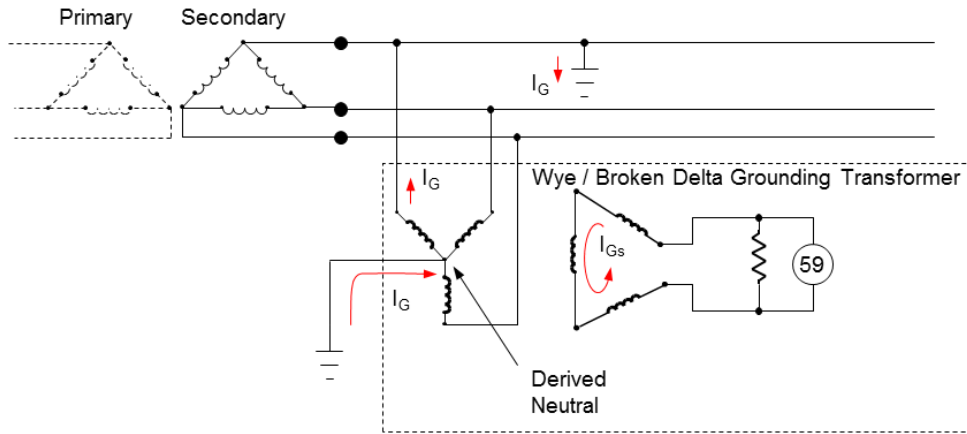
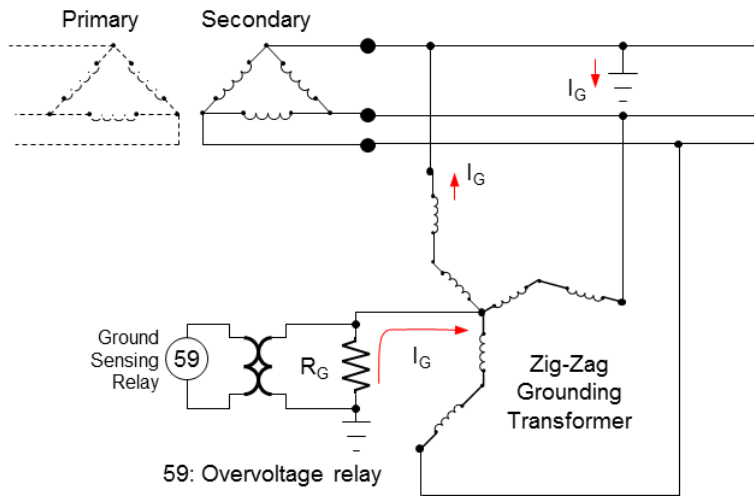


Figure 9: Derived neutral using a Wye-Delta transformer



**Figure 10:** Derived neutral using a Wye-Broken Delta transformer



**Figure 11:** Derived neutral using a Zig-Zag transformer

**Source Transformer: Wye Connected Secondary**

Since a neutral bushing exists on a wye secondary, adding HRG is as shown below in Figure 12.

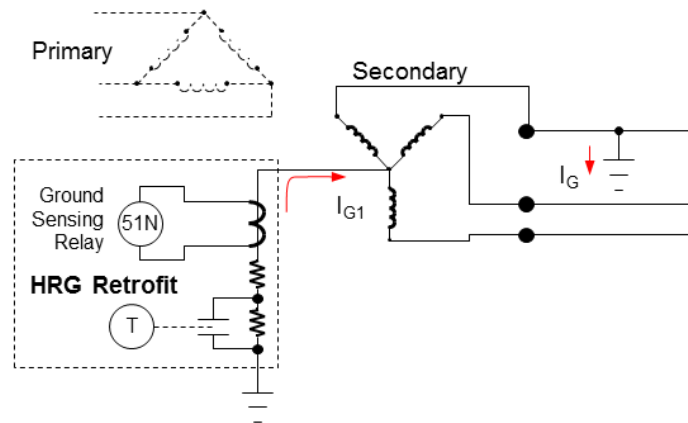


Figure 12: HRG with wye connected secondary

### Fault Location - Pulsing grounding

HRG systems, per the NEC, must include a method for detecting the presence of a ground fault. However, HRG systems can also be provided with an optional, but recommended feature that helps *locate* the fault. This method, called a pulsing ground system, is one of the key features that differentiate the HRG system from all other grounding systems.

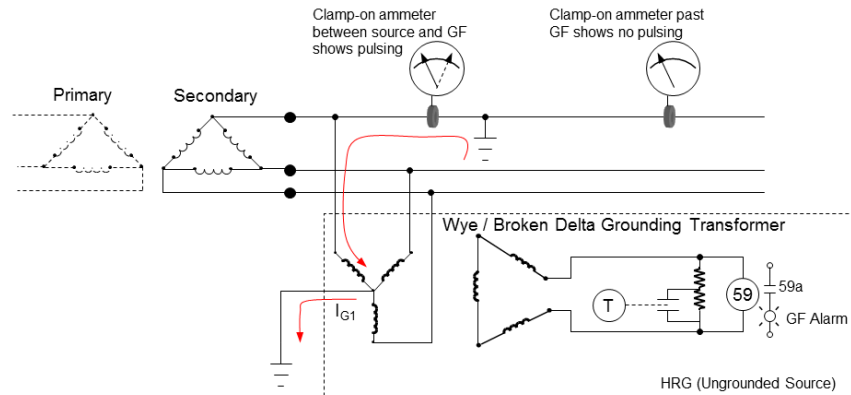
A pulsing ground system works as follows:

1. Once a fault is detected, an alarm is triggered (i.e. contact closure to PLC, DCS, BMS, horn, light)
2. Operator switches HRG system into “pulse” mode to begin fault locating process.
  - a. HRG activates timer which selectively shorts out part of the grounding resistor
  - b. Ground current increases to roughly twice original value (e.g. 5 A → 10 A)
  - c. After 1-2 seconds HRG timer times out and the resistor bypass is removed
  - d. Ground current then decreases (e.g. 10 A → 5 A)
  - e. Process repeats to “a.” until operator locates fault (step 3) and switches system out of pulse mode
3. Operator places a clamp-on ammeter over all current carrying conductors (even if enclosed in conduit) starting from the source out to each load
  - a. If the ammeter is clamped between the source and the fault, the pulsing will be visible
  - b. If the ammeter is clamped on a feeder without a ground fault, not pulsing will be visible

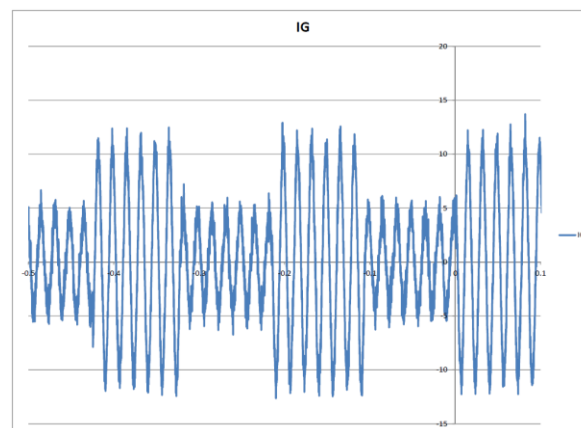
A clamp-on ammeter with a sufficiently large current transformer (CT) window diameter to fit over any conduit can be used to detect this pulsing current. In the case of a ground fault, the current flowing through the conductors will not sum to zero. This difference will be displayed on the meter.

Since the current is very low (~5 A), the pulsing system makes the ground current more visible against ordinary background current that might be displayed due to position of the CT relative to other current carrying conductors.

The “heartbeat” pulse stands out from other noise signals that might be present.



**Figure 13:** Clamp on ammeter can be used to detect location of a fault.



**Figure 14** – Power Xpert snapshot of ground current waveform “heartbeat” after HRG “pulsing” is activated.

For more information on pulsing ground detection systems, refer to references [6] and [7].

### Multiple Sources / Multiple Grounds

As discussed earlier, the NEC/CEC requires a ground fault detection system on all HRG systems. Multiple sources (especially those that can be paralleled, such as M-T-M systems) and systems with multiple ground sources complicate ground fault sensing [11].

Eaton’s Consulting Application Guide<sup>3</sup> (CAG) describes various schemes for detecting the location of ground faults in systems with multiple sources. Those sources may or may not be grounded.

However, one type of system requiring extra scrutiny is a system with multiple sources, each separately grounded and each paralleled to another. For such a system a DGFS is recommended.

### Differential Ground Fault System (DGFS)

A DGFS (see [11]) system uses signals from multiple sensors and connects those sensors in a differential or bridge scheme. The purpose of the differential connection is to measure the difference of current flowing into or out of a zone and only trip when the fault exists within that zone.

<sup>3</sup> Figures 1.4-8 and 1.4-9

## References

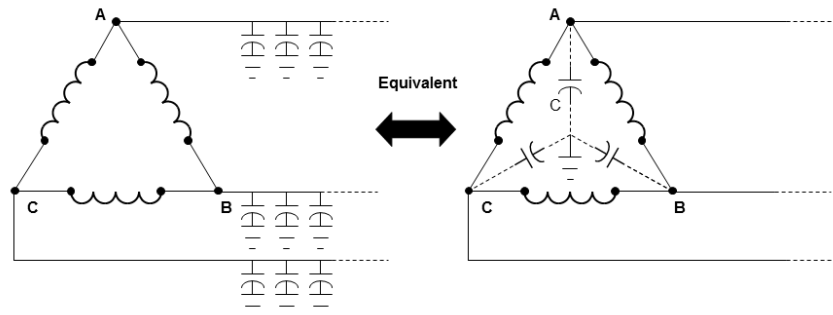
- [1] IEEE STANDARD 142-2007 - *IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems* (Green Book)
- [2] IEEE STANDARD 1100-2005 - *IEEE Recommended Practice for Powering and Grounding Electronic Equipment* (Emerald Book)
- [3] D. Shipp, F. Angelini, "Characteristics of different power system neutral grounding techniques: Fact & Fiction," 1988 IEEE IAS National Meeting
- [4] D.G. Loucks, "Transient Overvoltages on Ungrounded Systems from Intermittent Ground Faults", [http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ia08700001\\_e.pdf](http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ia08700001_e.pdf)
- [5] D. Shipp, et.al, "Switching Transient Analysis and Specifications For Practical Hybrid High Resistance Grounded Generator Applications", 2009 IEEE IAS Pulp & Paper Industry Conference, Birmingham, AL., [http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ct\\_237872.pdf](http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ct_237872.pdf)
- [6] Eaton High Resistance Grounding Overview, [http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/br01905001\\_e.pdf](http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/br01905001_e.pdf)
- [7] Eaton Resistance Grounding Systems, [http://www.eaton.com/Electrical/Consultants/ConsultingApplicationGuide/idcplg?IdcService=GET\\_FILE&RevisionSelectionMethod=LatestReleased&Rendition=Primary&dDocName=TB02203002E](http://www.eaton.com/Electrical/Consultants/ConsultingApplicationGuide/idcplg?IdcService=GET_FILE&RevisionSelectionMethod=LatestReleased&Rendition=Primary&dDocName=TB02203002E)
- [8] "Fault Characteristics in Electrical Equipment," [http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/tp08700001\\_e.pdf](http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/tp08700001_e.pdf)
- [9] IEEE STANDARD 493-1997 – *IEEE Power Systems Reliability* (Gold Book)
- [10] D.G. Loucks, "3-Pole and 4-Pole Transfer Switch Switching Characteristics", Eaton , [http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ia08700002\\_e.pdf](http://www.eaton.com/ecm/groups/public/@pub/@electrical/documents/content/ia08700002_e.pdf)
- [11] "Ground Fault Isolation with Loads Fed from Separately Derived Grounded Sources", Eaton, <http://pps2.com/go/dgfs/>

## Appendix A – Ungrounded Systems

While a complete study of grounding [1][2][3] is beyond the scope of this document, proper grounding can be summarized in the following “rules-of-thumb”:

1. No loads should be connected to ungrounded sources
2. The type of ground (solid, low-resistance, high-resistance, resonant or hybrid) varies with the type of system needs

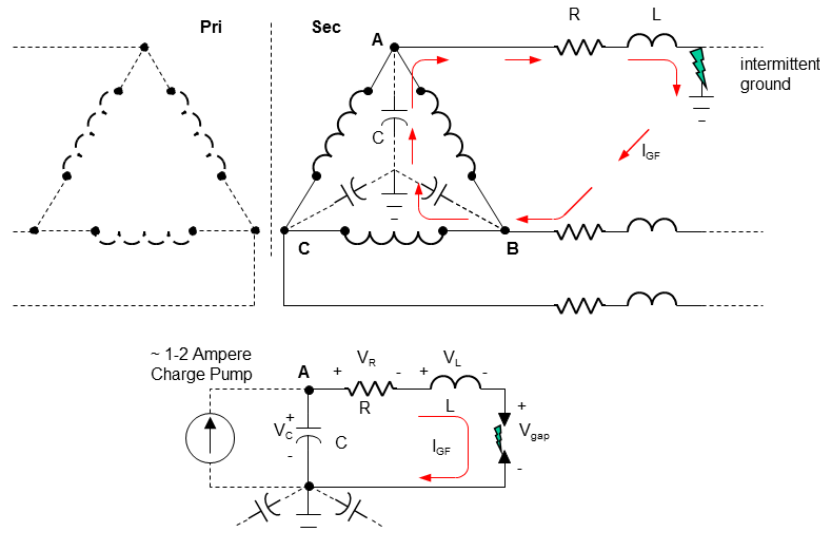
While the term “ungrounded” is used, at least as early as the 1950’s power systems engineers have recognized that there is no such thing as an ungrounded alternating current source. Even sources with no intentional ground connection are actually grounded through system line-to-ground capacitance.



**Figure 15:** Naturally occurring line-to-ground capacitance in "ungrounded" system

The problem with such a system is that while the voltage across this line-to-ground capacitance can be *nominally* line-to-line voltage divided by 1.732, in actual systems it may not. The problem is that since these capacitors are unknown, this voltage is unknown, and as such, can (and frequently is) much higher than expected.

To understand why, an analysis of the equivalent circuit of a single-phase reveals that these capacitors are charged by the line-to-line voltage and they can be discharged by a single-phase ground fault. When that capacitor is discharged, the current flows through a series LC circuit. An equivalent circuit is shown below.



**Figure 16:** Intermittent ground fault creates a series LC system that can produce substantial overvoltages

If the additional criterion is added that this ground fault is intermittent, the current flowing through the system inductance is interrupted. Since the voltage across an inductor is proportional to the rate of change of current flow, the voltage generated across this inductance can be arbitrarily large. Using Kirchhoff equations, notice that this voltage is able to “charge” the line-to-ground capacitance. Therefore, since this inductance value can be high, the resulting line-to-neutral voltage levels can be very high [4].

For these and other reasons, ungrounded systems are rarely used today.

## Appendix B – NFPA 70 (National Electrical Code) HRG Restrictions

Article 250.36 of the NEC places restrictions on when HRG systems can be implemented. In particular, high resistance grounding cannot be used on systems unless the following conditions are met:

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

Without a ground fault, ①, the neutral-to-ground voltage is essentially zero.

When a ground fault occurs, ②, the neutral to ground voltage rises to equal the nominal line-to-neutral voltage.