

Transient Overvoltages on Ungrounded Systems from Intermittent Ground Faults

Introduction

Many papers and standards [1][2][3][4][5][6] have discussed grounding of an electrical distribution system. Of course, an electrical distribution system may or may not include a reference to ground. In those instances allowed by the National Electrical Code, some designers view the opportunity to use an ungrounded system as a way of providing higher reliability than would a grounded system. The thinking is that since a ground would not create a fault, an ungrounded system would therefore provide higher system reliability.

What must be realized, however, is that even if no current carrying conductor is intentionally grounded, current still flows from any or all phase conductors to ground. This is done through phase to ground capacitance. While not enough current flows to cause damaging fault currents, it does provide enough current to create a unique overvoltage problem due to the particular way that intermittent ground faults operate on ungrounded systems.

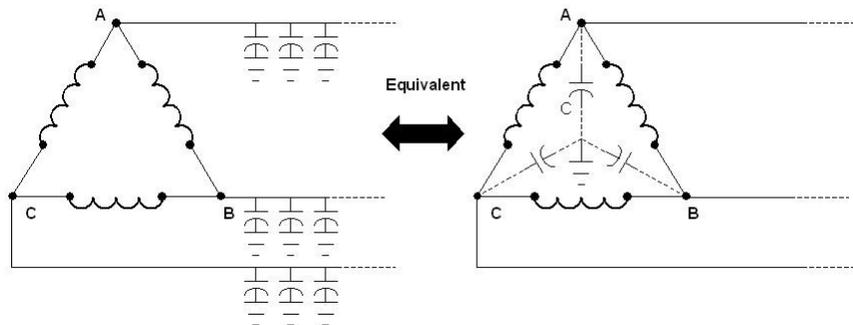


Figure 1: Distributed cable to ground capacitance can be drawn equivalently as a wye connected capacitor at the output terminals of the upstream transformer.

This capacitance becomes part of our circuit that already includes cable inductance and resistance. Therefore, we can draw this equivalent circuit as Figure 2 below.

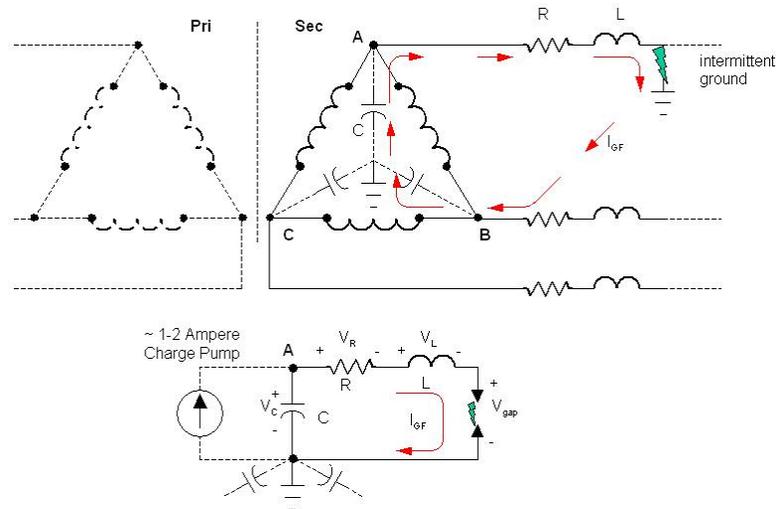


Figure 2: Upper diagram shows current path for a transformer feeding a single phase fault on an “ungrounded” system. Lower diagram shows the equivalent single phase schematic with the line-to-ground capacitor being charged from the adjacent conductors at the rate of about 1 to 2 amperes. The 1 to 2 amp “charging current” is typical for 480 V systems.

The amount of current flowing through this line-to-ground capacitance is called “charging current.” The magnitude of the charging current increases as you increase the capacitance, such as from longer cable distances between the source and the load or closer cable spacing, different cable insulation, and/or as you increase the system voltage. For 480 Vrms line-to-line systems, a typical value is around 1 to 2 amperes.

To understand how this current flows in an ungrounded system we show in Figure 2 an ungrounded winding of a transformer (in this case a delta winding) with a superimposed wye-connected capacitor representing the always-present phase to ground capacitance from the conductors. One side of each capacitor is connected to each of the “ungrounded” phases, with the other side of the capacitor grounded. The voltage developed across that capacitor is defined by Ohm’s Law as:

$$E = IZ = I(R + jX_C) = IR + jIX_C$$

Eq. 1

Where:

- E Voltage (Volts)
- I Current (Amperes)
- Z Impedance (Ohms)
- R Resistance (Ohms)
- j Imaginary operator ($\sqrt{-1}$, representing 90 phase shift for our complex/vector math equations)
- X_C Capacitive Reactance

We can likewise solve for unknown value of capacitive reactance using if we know the cable capacitance using Eq. 2 below:

$$X_C = \frac{1}{2\pi f C}$$

Eq. 2

Where:

X_C Capacitive reactance (ohms)

f Frequency (Hz)

C Capacitance (Farads)

Using this same equation and rearranging the variables allows us to solve for the cable capacitance if we know the magnitude of the charging current. Since we can measure this charging current as the current flowing out of the transformer even with all loads switched off, this is an easily available value.

Using this value and assuming we have a 480 Vrms (277 V_{L-G}), 60 Hz system with approximately 1 ampere of charging current flowing, the equivalent per-phase capacitance can be found by filling in the known values for Eq. 1 to solve for the impedance needed to limit a 277 V system to 1 amp and then using Eq. 2 to convert this impedance value (which is nearly all capacitive reactance) into C:

$$277 = 1R + j1X_C$$

Eq. 3

Due to the very high resistance of the insulation, we can assume the impedance of the line-to-ground capacitor is nearly all capacitive reactance ($R \gg X_C$), and simplify Eq. 3 to:

$$277 = j1X_C$$

Eq. 4

$$277 = j \frac{1}{2\pi f C} = j \frac{1}{377C}$$

Eq. 5

$$C = \frac{1}{277 \cdot 377} = 9.57 \mu F$$

Eq. 6

A capacitance of approximately 10 μ F on a 277 V system, then, will result in approximately 1 ampere of continuous (charging) current through that capacitance. As we trace the path of ground current shown in the schematic in the lower half of Figure 2, we use the Kirchhoff Voltage Law (KVL) to construct the equation of the voltage drops around the path of the ground fault.

$$V_C = V_R + V_L + V_{gap}$$

Eq. 7

Because current is flowing through the capacitor, by definition, the current through that capacitor will lead the voltage across that capacitor (V_C) by 90 degrees (because of the j operator as shown in the above equations). Said another way, when the current passes through a current zero point, the voltage across the capacitor will be at a peak.

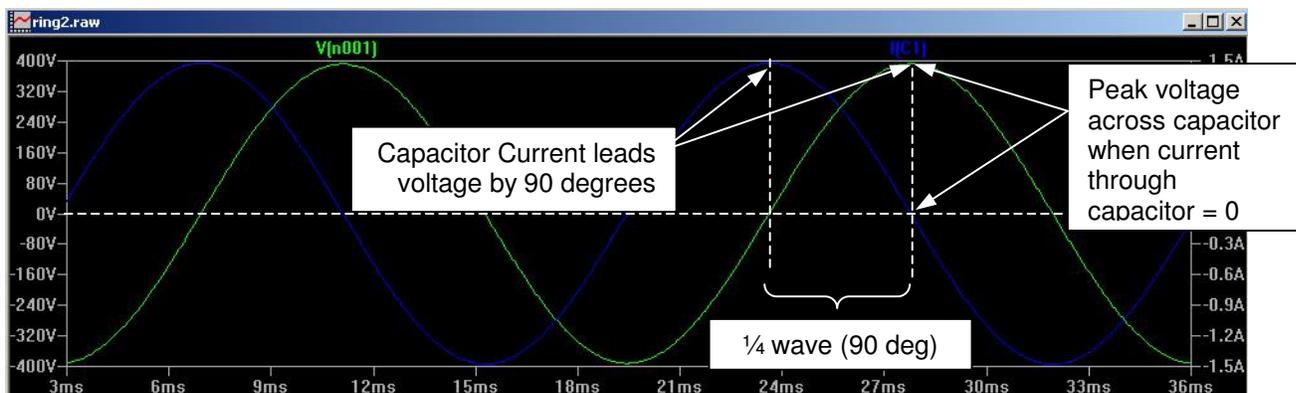


Figure 3: Current through phase to ground capacitance leads phase to ground voltage by 90 degrees

This has a particular effect with intermittent grounds since the arc will always extinguish at a current zero. In this model, however, as the arc is extinguishing, the voltage across the capacitor, and therefore the air gap, is maximum. In Figure 4 below, we model an ungrounded (capacitively grounded) delta-connected power system connected through a single-phase fault to ground using a SPICE simulator [7]. In our model, we programmed a switch to open when the current flowing through it drops to a low value (nearly 0) to simulate how a real arcing ground fault would behave.

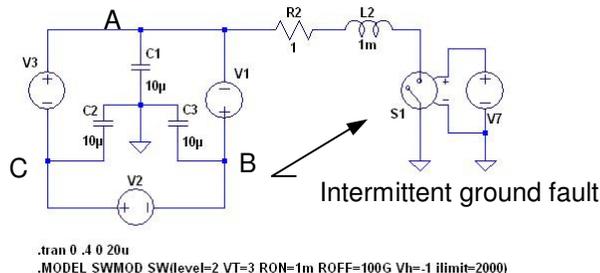


Figure 4: SPICE model of intermittent ground fault on an ungrounded with approximately 1 ampere of ground current.

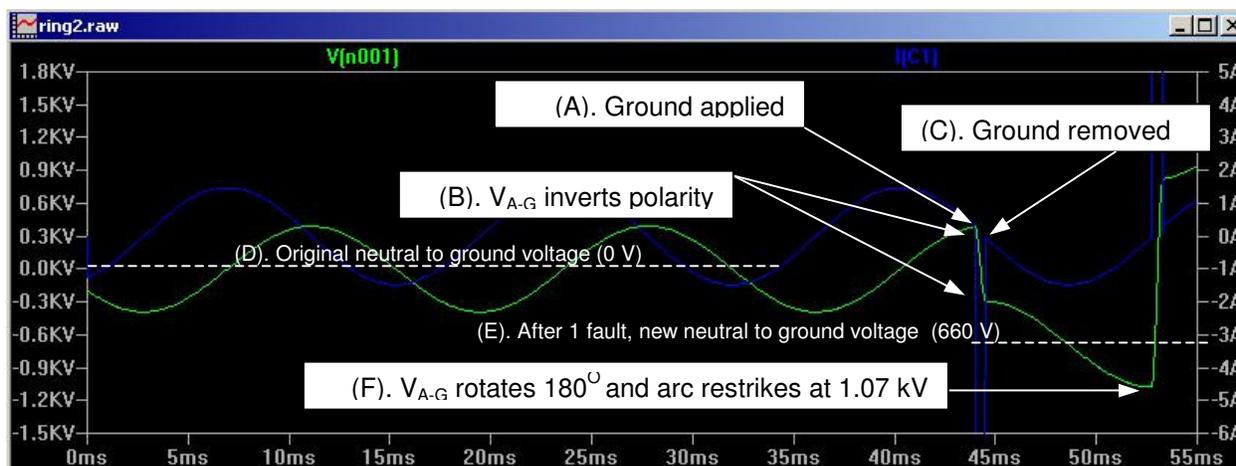


Figure 5: Voltage to ground on ungrounded system increases rapidly following intermittent ground fault

In our SPICE model, a phase to ground fault was applied at point (A) shown in Figure 5 above. This causes that phase's capacitor to discharge through circuit inductance, dropping to zero and then toward the opposite polarity (B) at a rate defined by the ringing (resonant) frequency established by the system inductance and capacitance. The line to ground capacitance discharges until current through that capacitor reaches zero at which point the arc extinguishes (C). Note that since this current leads the

voltage by 90 degrees, the current extinguishes at a voltage maximum. This is an important point. Again referring to Figure 5, our derived neutral point now shifts from approximately zero voltages at point (D) to approximately 660 V at point (E) as the peak line to ground voltage climbs to approximately 1.07 kV at point (F).

Figure 6, below, summarizes the line-to-ground and peak voltages to ground for a repetitive (intermittent) restriking ground fault after two strikes (restrikes).

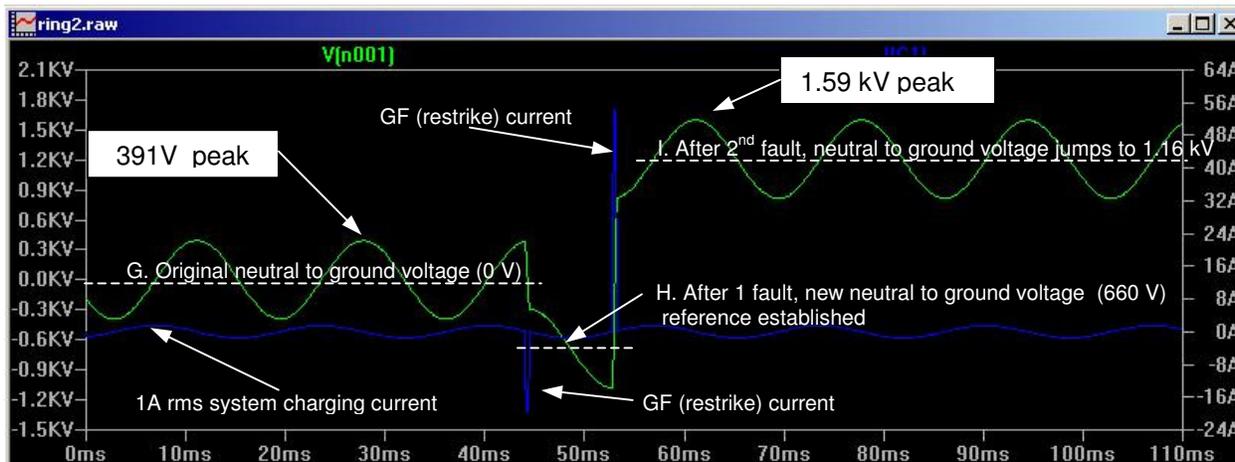


Figure 6: Following each line-to-ground restrike, the neutral to ground voltage jumps to an even higher voltage value. After only two line-to-ground strikes the neutral has shifted from 0 volts to 660V and then to 1.16 kV (I). As the phasor rotates around this new neutral reference, peak line-to-ground voltage reaches an even higher 1.59 kV possibly causing another restrike. Those subsequent restrikes can drive this voltage even higher. Typically this process continues until a permanent insulation failure occurs and the phase becomes solidly grounded.

Why does this voltage escalate so rapidly and to such high values? To answer this, we look at the equivalent phasor diagram shown on Figure 7 below. Referring to point ① on that diagram, we show a balanced phasor diagram on a normal system with no ground fault. In an A-B-C phasor rotation, the phasor diagram will be rotating counter-clockwise at the synchronous frequency (e.g. 60 times per second in our example).

If we were to ground the A-phase, our phasor diagram would appear as at point ②. This causes the neutral point to rise to a value equal to V_{L-N} . An arc forms as the system charging current previously flowing through the ground (approximately 1 A rms in this example shown in Figure 6) is now discharged through an air gap of this intermittent (vibrating) ground fault. The arc, by definition, must extinguish at the next current zero, since there will be zero current flowing at that point.

Note that since this current leads the voltage by 90 degrees, the voltage across the phase-to-ground capacitor is at a maximum when the arc extinguishes. Because the arc has extinguished, there is no longer a current to charge or discharge this capacitor and as a result, the phase to ground (i.e. capacitor) voltage remains at whatever value it was prior to the arc interruption. In our model, this establishes a new, now higher, neutral-to-ground reference point for the rotating phasor.

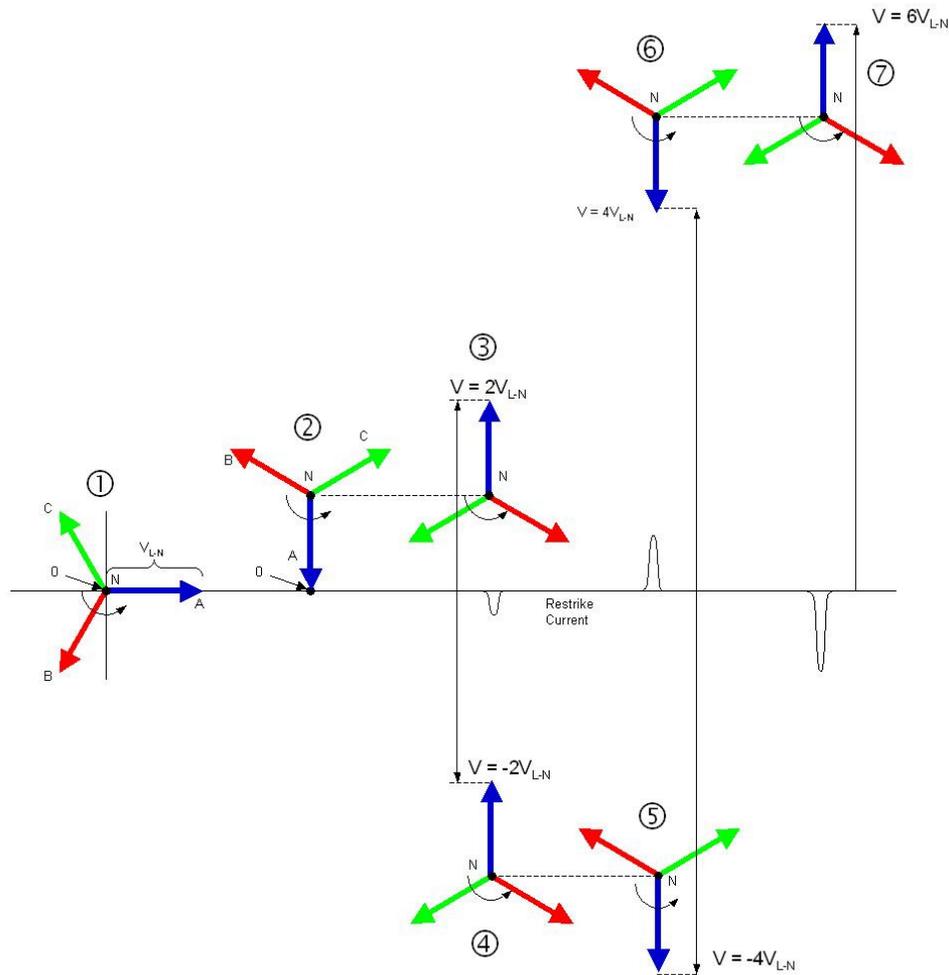


Figure 7: Intermittent arcing faults on ungrounded systems can result in very high voltages being developed phase to ground.

Since that phasor will continue to rotate counterclockwise around this newly established neutral reference voltage-to-ground value, in one-half cycle of time the A-phase phasor will have spun 180° away from the point when it was grounded as shown at point ③. At this point the A-phase voltage line-to-ground is now *twice* the first line to ground voltage.

If this is sufficiently high to arc again, the A-phase is rapidly pulled to ground again and some restrike current flows. This change in current flows through the series RLC circuit as shown in the lower half of Figure 2 and in the SPICE model shown in Figure 4. The voltage induced across the system inductance will have an opposite polarity to the source voltage and will drop to a value equal to the negative of the previous phase-to-ground voltage (as shown in ④), changing from a +2 times line-to-ground volts to a -2 times line-to-ground volt value as shown in the transition from point ③ to ④.

Note that while the peak phase voltage simply changes sign, the resultant neutral point shifts to yet an even higher voltage relative to ground, in this case 3 times the initial V_{L-N} . This is due to the relative phase position to ground prior to the arc, versus the inverted phasor position after the arc. From this new, higher neutral reference the phasor continues to spin. 180 degrees later at position ⑤ the phase-to-ground voltage has now risen to a value 4 times the initial phase-to-ground voltage. This could result in yet another restrike and a corresponding increase in voltage across the phase to ground system capacitance.

This process repeats (⑥ and ⑦, etc.) until some device fails, typically a lower BIL (Basic Impulse Level) device such as a control power transformer, a motor starter coil, a motor winding or a dry-type transformer. At that point, the failure is permanently shorting that phase to ground and the overvoltages cease. However, before this happens, there may be multiple, simultaneous failures of electrical and electronic devices as those devices are exposed to line to ground voltages many multiples of their design rating.

Note that we have included copies of the SPICE models used in this analysis and have included a link to a free version (for home or commercial use) of SPICE so you can run the models yourself [7].

If you have an ungrounded system, there are several things you can do to properly ground it.

Solutions

Grounded Transformer Systems

Systems can be grounded using a variety of methods including solidly grounded, resistance grounded or derived neutral grounded systems. Typically the first two solutions require that a neutral bushing be available, whereas the last solution does not require a neutral.

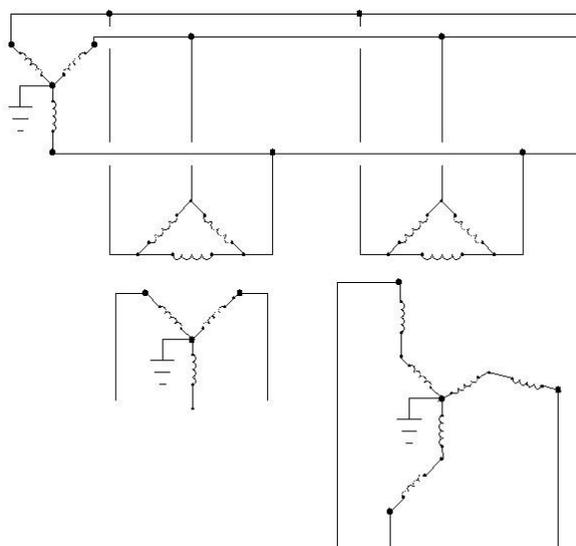


Figure 8: Grounding the secondary neutral winding of a delta-wye or delta-zigzag (Harmonic Mitigating) transformer are two commonly used methods of providing a ground reference.

For systems that have delta windings on their secondaries, or where there is no neutral is available, it is generally not desirable to ground a phase conductor (e.g. corner-grounded delta)

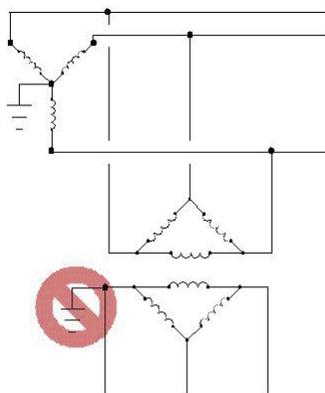


Figure 9: Generally not considered good practice to corner ground a delta transformer.

While some people like to save money and purchase 2-pole switching devices on systems where a phase conductor is grounded, any time you ground a phase conductor you are intentionally bonding a live phase conductor to the equipment enclosure. This can be a safety hazard should the ground on that enclosure be disconnected.

Also, the interrupting rating of some molded case circuit breakers must be derated when applied in a system with an intentionally grounded phase conductor, such as in a corner-grounded delta system. The interrupting rating may need to be derated because you may be interrupting all the fault current across a single pole at full line-to-line voltage. Contrast this with breakers protecting systems with grounded neutrals. In such systems, full voltage will always be interrupted across two poles. For faults where current only flows through one pole, the voltage across the pole will only be line-to-neutral or 57.7% of the line-to-line voltage.

A better way of grounding an ungrounded system that has no neutral bushing is to first derive a neutral using a set of small add-on transformers, then ground that derived neutral through a high resistance. We discuss methods of doing that next.

Grounded Derived Neutral Systems

The most common methods of deriving a neutral on ungrounded systems include using wye/delta, wye/broken-delta, zig-zag connected grounding transformers.

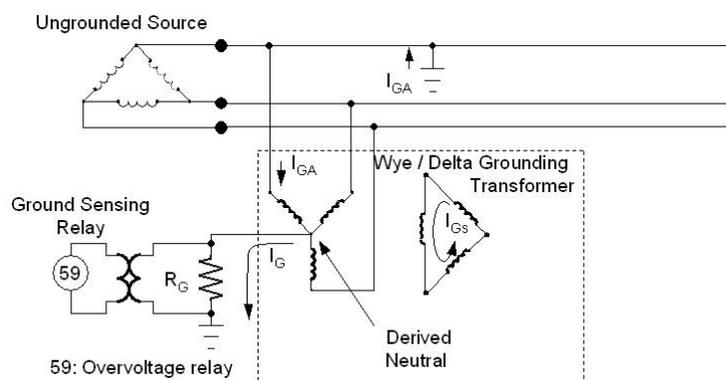


Figure 10: Wye/delta grounding transformer with high resistance grounding resistor and alarm

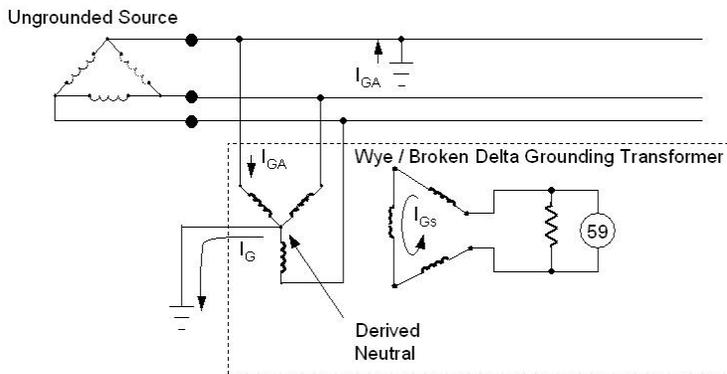


Figure 11: Wye/broken-delta with resistor inserted into broken delta

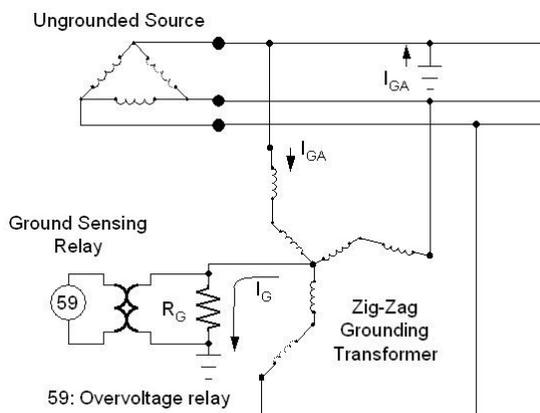


Figure 12: Zig-Zag grounding transformer with high resistance grounded derived neutral

Regardless of the method used to derive and ground the neutral, it is wise to include the additional “pulsing” circuitry to help locate a fault within a system.

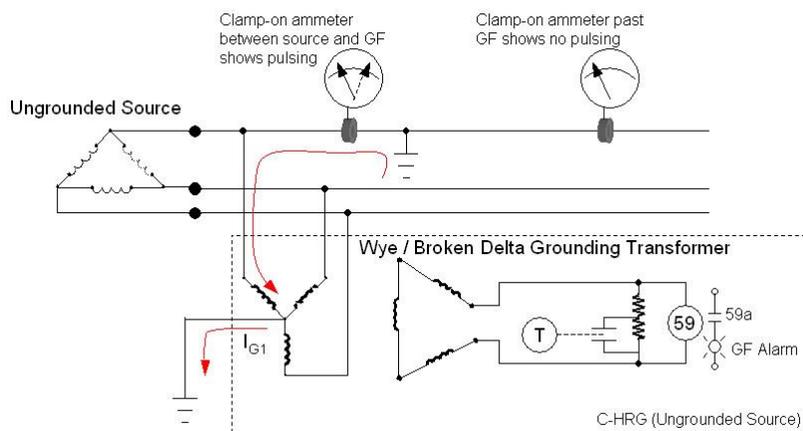


Figure 13: Pulsing High Resistance Grounding System

Note that a pulsing system can be added to conventional neutral-grounded transformer systems too.

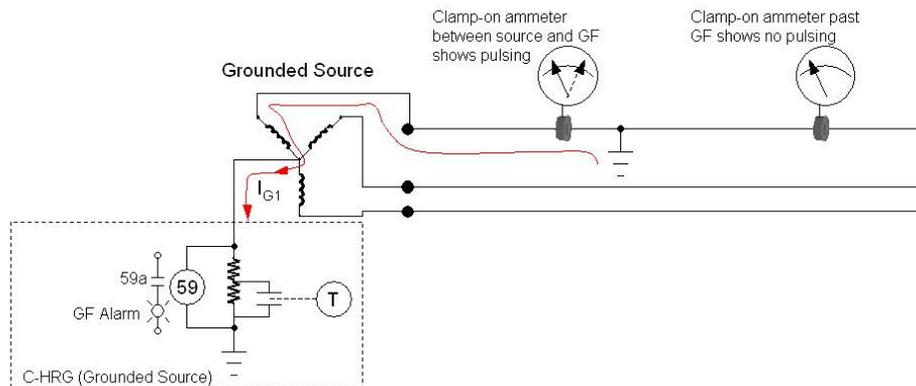


Figure 14: Add-on pulsing ground detection system

To locate a ground fault using a pulsing ground system, the system is placed into “pulse mode” and a clamp-on ammeter is placed around conduit containing the suspected faulted conductors. The ammeter will display a characteristic “pulse” of current as the timer selectively shorts, then reopens, then shorts again a part of the grounding resistor. The ground current jumps from the nominal value (typically 5 amperes) to some multiple of that value (e.g. 10 amperes). This higher current still is not high enough to cause damage, but is high enough to be detected on a clamp-on ammeter.

The operator places the clamp-on ammeter around the conduit feeding one or a group of loads and looks for the characteristic “pulse” or jump of the ammeter value in tempo with the timing set in the high resistance ground unit (typically switching each few seconds). As the operator moves the ammeter further from the source and towards the load, the pulsing may stop. Once the clamp-on ammeter is no longer located between the source and the point of the ground, the pulsing stops. By comparing where the pulsing is detected with where it is not detected, the location of the ground fault can be isolated.

Summary

Ungrounded systems, while offering a measure of protection against high current ground faults, allow transient overvoltages to form during intermittent ground faults. These overvoltages *do not* form if the distribution system is grounded and a current is allowed to flow through that ground fault at some value greater than system charging current. This value of current is set by the value of the neutral-to-ground resistor. For typical 480V systems ($277 V_{L-G}$), that resistor is usually sized to allow 5 amperes or 55.4 ohms to flow through a fault. A resistor for such a system would need to be sized to carry 1385 watts continuously.

Refer to the bibliography [8] for information on various retrofit solutions from Eaton that are available to derive a neutral on an ungrounded system. These systems also provide a high-resistance ground through that derived neutral and include a pulsing ground system to permit easier troubleshooting of the ground fault location.

Bibliography

- [1] IEEE STD 141-1993 (Red Book)
- [2] IEEE STD 142-2007 (Green Book)
- [3] IEEE STD 1100-2005 (Emerald Book)
- [4] D. Shipp, F. Angelini, "Characteristics of different power system neutral grounding techniques: fact & fiction," 1988 IEEE IAS National Meeting
- [5] R.B. West, "Grounding for Emergency and Standby Power Systems," *IEEE Industrial and Commercial Power Systems Conference*, 1978
- [6] D. Beeman, "Industrial Power Systems Handbook," 1955
- [7] A free version of a SPICE modeling tool (including a free schematic capture program) can be downloaded from Linear Technologies web site:
<http://www.linear.com/designtools/software/ltspice.jsp>
Once this program (LTSPICE) is installed, you may download the models used in this paper from:
<http://pps2.com/files/xfer/spice/?d=LTSPICE-Models/Ungrounded-Systems>
- [8] Eaton offers both low and medium voltage high resistance grounding solutions:
<http://www.eaton.com/EatonCom/Markets/Electrical/Products/Switchgear/HighResistancePulseGroundingSystems/index.htm>