

A Review of System Grounding Methods and Zero Sequence Current Sources

Gerald Johnson (Basler Electric), Mark Schroeder (Dominion VA Power)
and Gerald Dalke (Power System Relay Services)

Introduction

A large majority of three phase power system faults involves ground; therefore, a thorough knowledge of grounding methods and associated zero sequence current sources is essential to the effective protection of the power system. The particular method of system grounding selected will vary according to the resulting characteristics desired by the application. A grounding method can be used either to limit or entirely eliminate the level of ground fault current available so as to protect expensive equipment from damage under the most likely fault scenarios. Or, conversely, it can be used to ensure an adequate current level to aid in the prompt detection and isolation of fault conditions. The grounding method employed also may be used to reduce transient overvoltages, as well as to facilitate compliance with regulations affecting personnel safety. With retirements, new hires, reorganization, cross training, and so on, this subject, like many others, requires regular review to maintain the experience level of our protection engineers. The purpose of this paper is to provide a tutorial or “refresher” on grounding methods, sources of ground current, ground current flow in the power system, and how each impacts protective relaying.

A discussion of various ground sources, such as solidly grounded and impedance grounded generators, delta/wye ground transformers, and zig-zag transformers will be included, as well as a review of symmetrical components as related to grounding issues. Traditional response of protective relays to zero sequence current will be reviewed, including loss of zero sequence current sources while a ground fault is on the system, and methods for detecting the same. Zero sequence current traps used to balance a transformer differential scheme in the presence of an unaccounted for ground source are discussed, including mathematical alternatives used in modern protection products.

We begin with an analysis of power system grounding characteristics using the applicable zero sequence network modeling to address the effects of transformer and generator winding connection and neutral grounding method. The use of grounding transformers to alter the system grounding will be included in this discussion.

Special protection issues resulting from system grounding characteristics will include a discussion of the following:

- Coordination of Overcurrent Protective Relaying Under a Discontinuous Zero Sequence Network
- Preventing Operation of Transformer Differential Schemes Resulting from Zero Sequence Current Sources within the Zone
 - Traditional Zero Sequence Filtering External to the Relay
 - Zero Sequence Filtering Methods Internal to Digital Relay Packages

- Ground Fault Protection on Solidly Grounded Systems
- Ground Fault Protection on Impedance Grounded Systems
- Detecting Ground Faults in an Ungrounded System

The paper concludes with a detailed tabular comparison of things to consider before selecting a grounding system method.

Special acknowledgement is given to J. Lewis Blackburn's *Protective Relaying Principles and Applications* and is included with other references in the References at the end of this document and to the Electrical Transmission and Distribution reference book.

Analysis of Power System Grounding Characteristics by Consideration of the Zero Sequence Network Model

The analytical technique of Symmetrical Components provides a good understanding of power system grounding. Specifically, the sequence network interconnection representing the imbalance imposed by the Single-Phase-to-Ground (PG) fault is a useful tool for analyzing the effects of the various grounding methods (refer to Figure 1). The figure shows that each of the three possible sequence components of current is involved in representing the PG shunt imbalance. Each sequence network models the single phase, Thevenin equivalent path for each component of current from the system source(s) of generation to the fault location (on A-phase in this case). Provided none of the sequence networks is open to current flow, each of the sequence components of the total current, positive (I_1), negative (I_2), and zero (I_0) has equal magnitude and each is in-phase in the faulted A-phase. The corresponding balanced set of each component of the total fault current is indicated as a set of phasors in the diagram to the right of its respective sequence network. Summing the components of each phase current to obtain the actual phase current (e.g. $I_B = I_{B1} + I_{B2} + I_{B0}$) reveals that the total fault current in the unfaulted phases is zero. However, the total current in the faulted A-phase has a magnitude of three times the equal, per-phase magnitude of the three symmetrical component currents; that is, $3|I_1|$, $3|I_2|$, or $3|I_0|$. In terms of the applied voltage source in the positive sequence network (V_{PN}), and the total equivalent system impedance, the magnitude of each individual component current and the resulting total PG fault current (I_{PG}) are as follows:

$$|I_1| = |I_2| = |I_0| = \frac{V_{PN}}{(Z_1 + Z_2 + Z_0)} \quad (\text{Eq. 1})$$

$$I_{PG} = 3|I_0| = \frac{3V_{PN}}{(Z_1 + Z_2 + Z_0)} \quad (\text{Eq. 2})$$

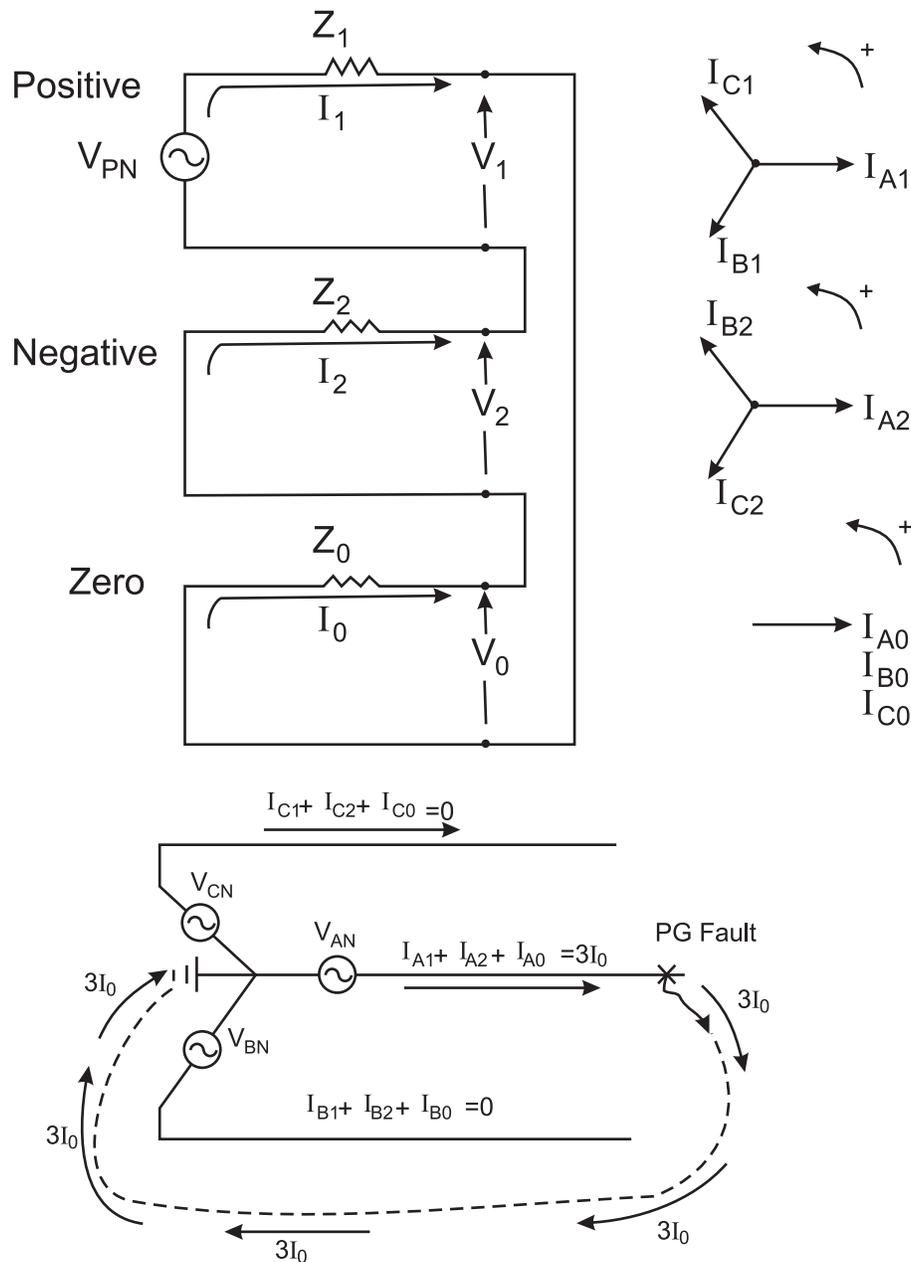


Figure 1. General Sequence Network Modeling for the PG Fault

Because the sum of the phase currents of both the positive and negative sequence component is zero, they exist only in the phase conductors of the system. Hence, only those impedance values in the phase paths are modeled in their respective sequence networks. With the exception of the reactance of the system generators within a few cycles after fault inception, the passive phase impedance values of the majority of the system elements (aerial lines, underground cables, and transformers) remain unchanged. For most system fault locations, these static impedance values predominate in determining the fault current magnitude. Unless analysis is being considered for a fault immediately at the

terminals of a particular generator, the transient changes in generator reactance after a fault is incident can be neglected. Thus, for most system faults being considered, the positive and negative sequence networks are identical, at least as far as their impedance values are concerned (i.e. $Z_1 = Z_2$), and Equation 2 becomes:

$$I_{PG} = \frac{3V_{PN}}{(2Z_1 + Z_0)} \quad (\text{Eq. 3})$$

Unlike the positive and negative sequence components, the Zero sequence phase currents are in-phase with one another. Instead of summing to zero at a neutral point, they are forced to flow together at three times their individual, equal magnitudes ($3I_0$); this, of course, is if a circuit path exists for them to flow. Thus, zero sequence is the only one of the three components that requires a complete circulation path; that is, it must include a “return” path back to the source. The individual zero sequence phase currents, therefore, not only encounter the impedance values in their respective phase paths (as do the positive and negative sequence components), but also in the portion of their circuit path where flow is shared with the other two phase currents, referred to as the “residual”. Impedance in the residual path may be comprised of any of the following: 1) resistive or reactive elements purposefully inserted between a neutral point and its earth connection, 2) the conductive plane of the earth in parallel with any aiding ground conductors, and 3) impedance (resistance) in a faulting medium. Because the zero sequence network models the circuit for only one of the component’s phase currents, only a third of the actual $3I_0$ current (causing voltage drops across impedance elements in the residual path) is accounted for. This situation results in all impedance in the residual portion of the circuit path being effectively modeled in the zero sequence network as three times their actual value:

$$Z_{EFFECTIVE} = \frac{V_{DROP}}{\left(\frac{1}{3} I_{FLOW}\right)} = 3Z_{ACTUAL} \quad (\text{Eq. 4})$$

Evident from the previous discussion is that the “grounding” characteristics for a three phase power system are a result of the state of a circuit path for allowing the zero sequence component of the current to return to the source (or sources) of the system. The state of this path is conveyed by the modeling within the zero sequence network.

Effects of Transformer Winding Connection and Neutral Grounding on System Grounding

All power transformers are, of course, designed to pass the intended positive sequence component of current. Under this assured ability, all power transformers, likewise, pass the “similar natured” negative sequence component. The zero sequence component of current, however, is an entirely different matter.

In order for a transformer to be able to “pass” zero sequence current, the component must be able to circulate in a “primary loop” on the source side of the transformer, which, in turn,

drives a “secondary loop” from the windings coupled with the primary loop windings. Each of these loops has zero sequence current circulating through both phase conductors and a return path on their respective sides of the transformer. The primary loop’s return path extends from the transformer’s primary windings back to the system source, while the secondary return path connects the point of imbalance back to the transformer’s secondary windings (see Figure 2). Any aspect of its connection that would effectively open either of these loops would result in a transformer not being able to pass zero sequence current.

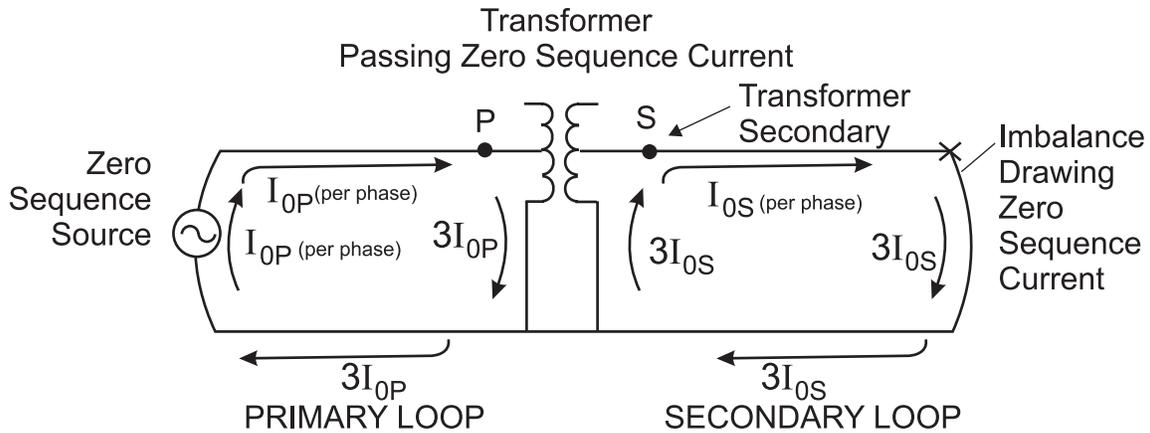


Figure 2. Primary and Secondary Zero Sequence Current Loops

Transformer Connections that Pass Zero Sequence Current

Any transformer that would not preclude the circulation of the coupled zero sequence current loops described above and shown in Figure 2 will pass zero sequence current; provided, of course, there is a source of it on one side of the transformer and an imbalance that draws it on the other. Figure 3a illustrates how a 2-winding Wye/Wye connected transformer with both neutrals solidly grounded would accomplish passing a zero sequence flow. In the zero sequence network, a transformer that passes would be modeled as an impedance directly connecting the transformer’s primary and secondary terminals. This impedance would be that experienced by current flowing through the coupled windings of the transformer, namely the “transformer” impedance. The single-phase view of an autotransformer, in Figure 3b, shows how this connection will support coupled loops of zero sequence current circulating on both sides of the transformer in a similar manner to the Grounded-Wye/Grounded-Wye connection (refer to Table 1).

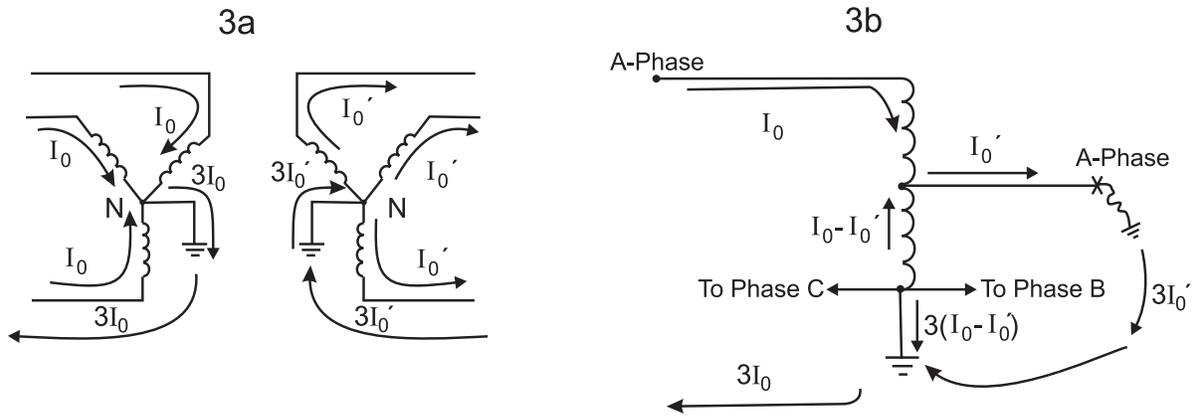


Figure 3. Two Transformer Connections that Pass Zero Sequence Current

Table 1. Transformer Connections and Zero Sequence Current

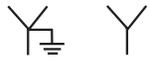
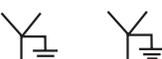
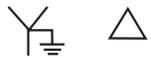
Transformation Primary ← (Pri.) Secondary (Sec.) →	Passes Zero Seq. Current?	Provides a Source for Zero Seq. Current?
	No	No
	No	No
	No	No
	Yes	No
	No	No
	No	Yes (to Sec. only)
	No	Yes (to Pri. only)
	No	No
	No	Yes (to Sec. only)
	Yes	Yes (to Pri. and Sec.)
	Yes	No
	Yes	Yes (to Pri. and Sec.)

Figure 4 shows the sequence network modeling for a bolted PG fault on a radial line extending from the secondary of a Grounded-Wye/Grounded-Wye transformer, with the transformer primary connected to a grounded-wye source. For this case, each of the three components of the fault current (positive, negative, and zero sequence) flows unobstructed from the system source to the fault. As described previously, the zero sequence current actually is circulating in the two coupled loops, one on the primary side and one on the secondary side of the transformer. The voltage and impedance values indicated in the figure are as follows:

V_{PN} : the applied phase to neutral system voltage (infinite source)

$Z_1(\text{sys})$, $Z_2(\text{sys})$, $Z_0(\text{sys})$: the equivalent positive, negative, and zero sequence source impedance values, respectively

Z_{TX} : the transformer impedance (since the return path for the transformer has negligible impedance, the positive, negative, and zero sequence impedance values for the transformer are all the same)

$Z_1(\text{line})$, $Z_2(\text{line})$, $Z_0(\text{line})$: the impedance values for the line between the transformer secondary terminals and the PG fault

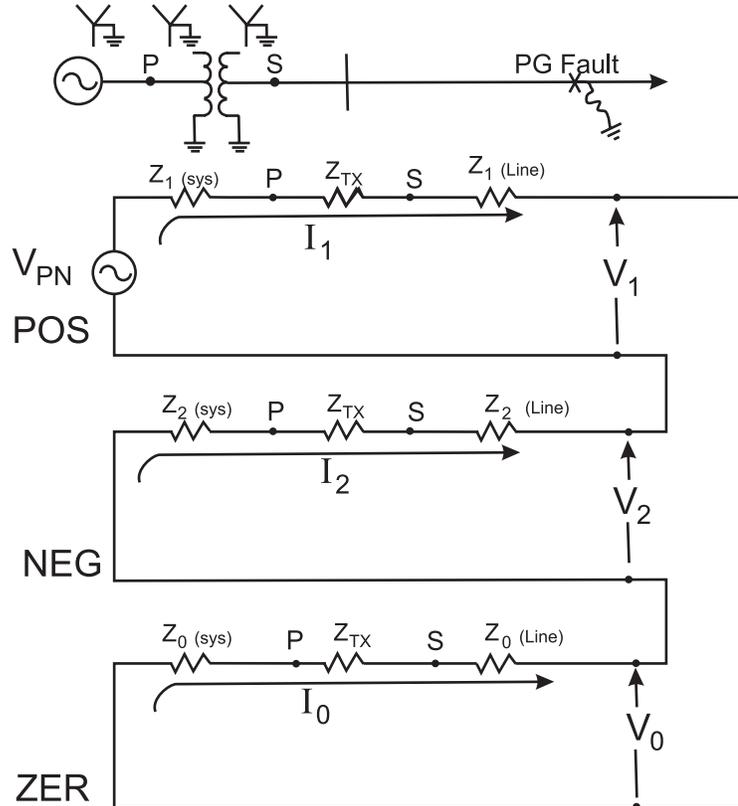


Figure 4. Sequence Network Model for Bolted PG Fault on a Grounded-Wye/Grounded-Wye Transformer Secondary

In terms of the applied voltage and system impedance values (shown above), the bolted (zero fault resistance) PG fault current magnitude would be determined as follows:

$$I_{\text{PG}} = \frac{3V_{\text{PN}}}{[2Z_1(\text{sys}) + Z_0(\text{sys}) + 3Z_{\text{TX}} + 2Z_1(\text{line}) + Z_0(\text{line})]} \quad (\text{Eq. 5})$$

A transformer that passes zero sequence current produces a secondary for which the grounding is an extension of that established at the transformer primary. In this example, the grounded wye source of the primary system provides the ground source for the transformer secondary.

Transformer Connections that Do Not Pass Zero Sequence Current

Removing the ground connection on the source side neutral of the Grounded-Wye/ Grounded-Wye transformer in the previous example will result in opening the zero sequence current circulation loop between the grounded-wye source and the transformer primary. Because zero sequence current would not be able to flow in the primary windings, it would, likewise, fail to flow in the coupled secondary windings, despite the winding neutral being grounded. In fact, removing the ground connection on either neutral will disrupt the flow of the primary and secondary coupled loops of current. Thus, under the state of one or both neutrals of a Wye/Wye transformer being ungrounded (floated), the transformation will not pass zero sequence current (refer to Table 1).

Like ungrounded wye windings, a set of delta connected transformer windings will fail to provide a path for zero sequence current to circulate between the transformer and the system to which the delta windings connect. Therefore, regardless of how the coupled windings are connected (delta, ungrounded wye, or grounded wye), delta connected windings on either the primary or secondary will not permit a passage of zero sequence current (refer to Table 1).

The failure of a transformer connection to pass zero sequence current is reflected in the zero sequence network by an open circuit between the primary and secondary terminals. An example incorporating such a transformer is shown in Figure 6. The sequence network modeling is given for a Delta/Delta transformer connecting a grounded-wye source on its primary to a radial line extending from the secondary with a bolted PG fault applied. As a result of the zero sequence network being open at the transformer, the zero sequence component of the total distributed shunt capacitive reactance of the system to the fault (X_{C0}) provides the only path for fault current (as opposed to $I_1 = I_2 = I_0 = 0$, and, thus, I_{PG} being absolutely zero). Systems such as this are referred to as “ungrounded”. They are ungrounded only in the sense that there is no intended physical connection between the system neutral and ground. Nonetheless, they are effectively grounded through the system’s zero sequence distributed capacitance as shown in Figure 6.

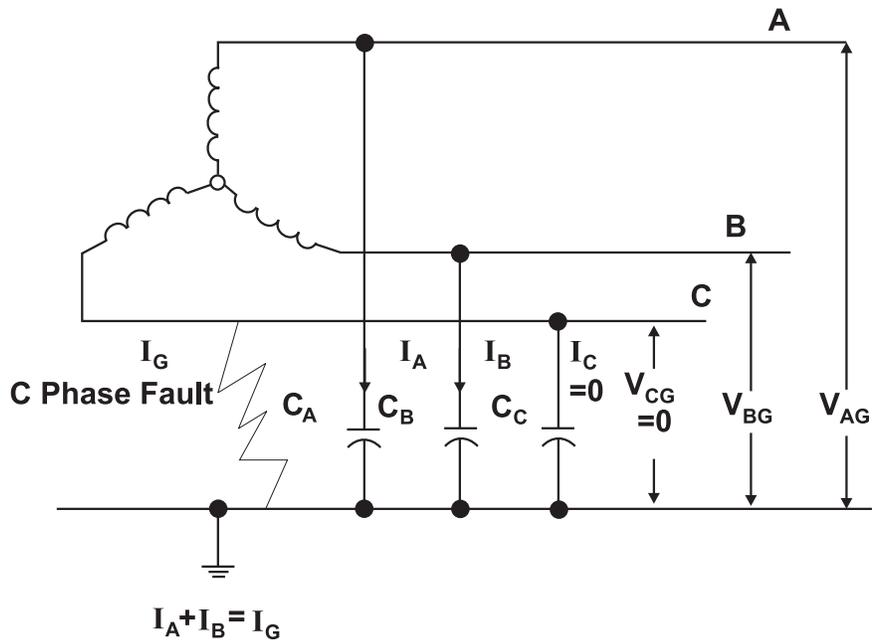


Figure 5. Ungrounded System Shown with a C-phase to Ground Fault Applied. Note Effective Grounding is provided by System Shunt Capacitance

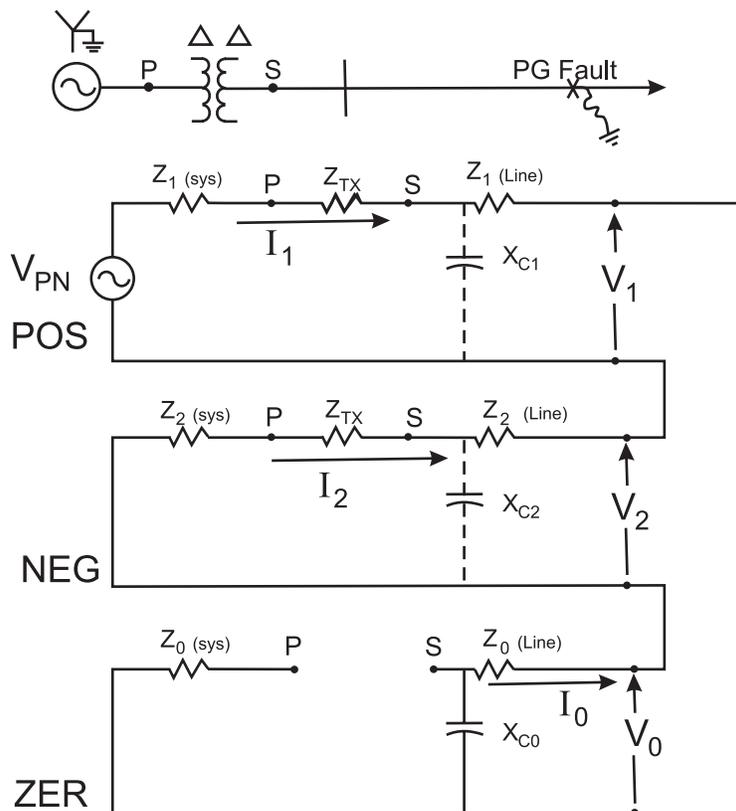


Figure 6. Sequence Network Model for a Bolted PG Fault on a Delta/Delta Transformer

The equal positive and negative sequence components of the total distributed shunt capacitive reactance (X_{C1} and X_{C2}), shown in Figure 6, are so large compared to the system impedances in parallel with them that they can be neglected. The other voltage and impedance values indicated in the figure are the same as those that were defined for Figure 4. In terms of the applied voltage and the system impedance values given, the bolted PG fault current magnitude would be determined as follows:

$$I_{PG} = \frac{3V_{PN}}{[2Z_1(\text{sys}) + 2Z_{TX} + 2Z_1(\text{line}) + Z_0(\text{line}) + X_{C0}]} \quad (\text{Eq. 6})$$

Because X_{C0} dwarfs the other system impedance values, the simplified Equation 7 gives a close approximation:

$$I_{PG} = \frac{3V_{PN}}{X_{C0}} \quad (\text{Eq. 7})$$

As a result, the PG fault current on an ungrounded system has a very small magnitude, much too small for overcurrent relaying to be used for detecting ground faults.

An ungrounded system having the same characteristics described above also results from a wye connected source generator with a floated neutral or from a delta connected generator.

Connections that Provide a Local Zero Sequence Current Source

Although a transformer having a set of grounded-wye windings coupled with a set of delta windings is just one of the many connections not passing zero sequence current, it does have the special characteristic of allowing a zero sequence circulation path on only one side of the transformation, as illustrated by Figure 7. While zero sequence current circulates in the system on the grounded-wye side, on the delta side it circulates only within the delta connected windings and not in their leads connecting to the system. For this connection, a “ground source” is said to be provided to the grounded-wye side of the transformer. In order for this so-called ground source to provide its zero sequence circulation, a “true generating source” (positive sequence) must be connected to the opposite side of the transformer (the delta side, in this case). In the zero sequence network, a transformer that “provides a source” for zero sequence current is modeled as an impedance connecting between the transformer’s grounded-wye terminals and the reference bus. Again, this impedance would be that experienced by current flowing through the coupled windings of the transformer, namely the “transformer” impedance.

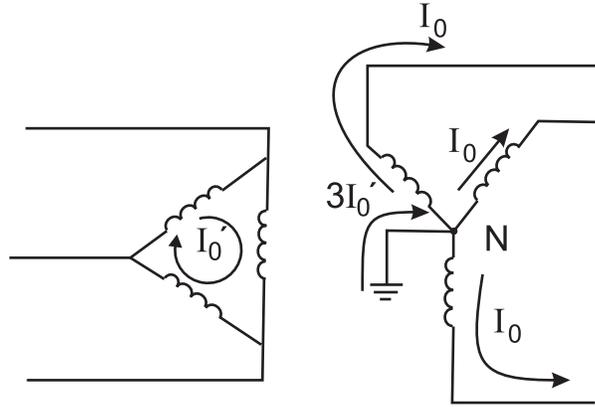


Figure 7. Delta/Grounded-Wye Transformer Connection Provides a Zero Sequence Current Circulation Path

Figure 8 shows the sequence network modeling for a bolted PG fault on a radial line extending from the secondary (grounded-wye side) of a Delta/Grounded-Wye transformer, with the transformer primary (delta side) connected to a grounded-wye source. The voltage and impedance values indicated in the figure are the same as those defined originally for Figure 4. In terms of the applied voltage and the system impedance values given, the bolted PG fault current magnitude would be determined as follows:

$$I_{PG} = \frac{3V_{PN}}{[2Z_1(\text{sys}) + 3Z_{TX} + 2Z_1(\text{line}) + Z_0(\text{line})]} \quad (\text{Eq. 8})$$

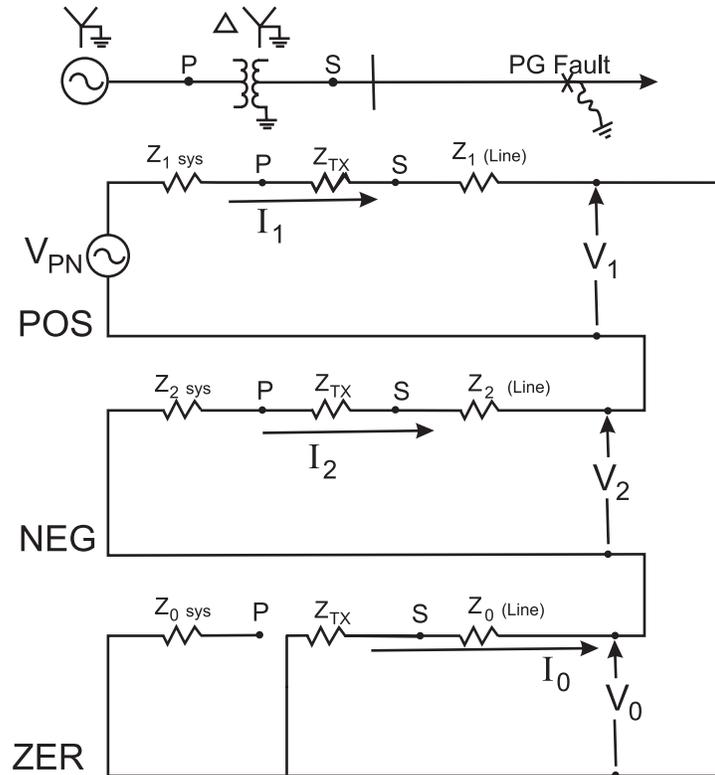


Figure 8. Sequence Network Model for a Bolted PG Fault on the Secondary of a Delta/ Grounded-Wye Transformer

There is an important difference to note about this result and that of the Grounded-Wye/ Grounded-Wye transformer of Figure 4. Unlike the previous case, the zero sequence network at the source side of the Delta/Grounded-Wye transformer is completely uninvolved in the secondary PG fault. In failing to pass zero sequence current yet provide a source for it at the grounded-wye side, the Delta/Grounded-Wye connection provides its own, separate grounded system on the secondary, effectively isolated from that of the primary.

The “ground source” described here for the Delta/Grounded-Wye, two winding transformer is, in fact, provided from a set of grounded-wye windings whenever they are coupled to a set of delta windings – regardless of whether or not the delta windings are connected for passing load. The delta connected windings can be a set of tertiary coupled windings not electrically connecting to anything. A review of Table 1 reveals a number of transformer connections for which the zero sequence (“ground”) source is provided. (These “Ground Sources” allow zero sequence current to circulate on a particular side of a transformation. Such circulations are independent of a transformer’s ability to pass zero sequence current from one side to another.)

Connections such as the Grounded-Wye/Grounded-Wye with Delta Tertiary three winding transformer and the Autotransformer with Delta Tertiary not only pass zero sequence current, but also provide a ground source to both the primary and secondary sides. Figure 9 shows how the simultaneous “passing” and “providing” zero sequence behavior of these two connections is represented in the zero sequence network by the equivalent “T-model”.

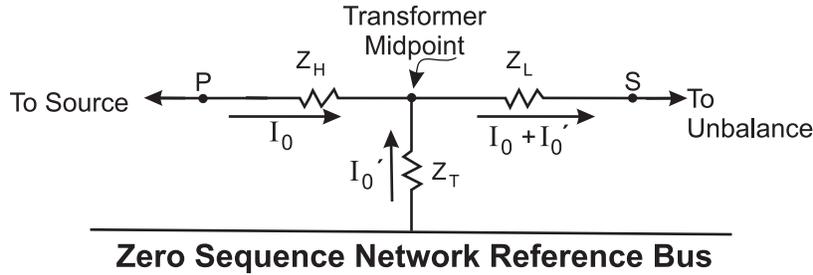


Figure 9. Equivalent Zero Sequence Network “T” Model for Transformations that Pass and Provide a Source of Zero Sequence Current

Use of Grounding Transformers for Creating a Grounded System

Certain transformers, due to their winding connections, are used solely for the purpose of establishing a grounded system; such transformers are referred to as Grounding Banks. They are employed in situations where a grounded system is desired and the source transformer or generator would, otherwise, yield an ungrounded system.

Grounded-Wye/Delta Grounding Banks

The previous discussion of local ground sources elaborated on the characteristic of the delta coupled with grounded-wye transformer connection as providing a path for zero sequence current circulation on the grounded-wye side. For this reason, Grounded-Wye/Delta connected power banks often are used as grounding banks. Figure 10 shows the sequence network modeling for a bolted PG fault on a radial line supplied from the secondary (delta side) of a Grounded-Wye/Delta source transformer, with a smaller, unloaded Grounded-Wye/Delta transformer, connected at the secondary terminals of the main transformer, serving as a grounding bank. In this diagram, Z_{GB} refers to the grounding bank impedance, while Z_{TX} , as in the previous figures, is the impedance of the main transformer. The voltage and impedance values indicated in the figure are, otherwise, the same as those defined originally for Figure 4. In terms of the applied voltage and the system impedance values given, the bolted PG fault current magnitude would be determined as follows:

$$I_{PG} = \frac{3V_{PN}}{[2Z_1(\text{sys}) + 2Z_{TX} + Z_{GB} + 2Z_1(\text{line}) + Z_0(\text{line})]} \quad (\text{Eq. 9})$$

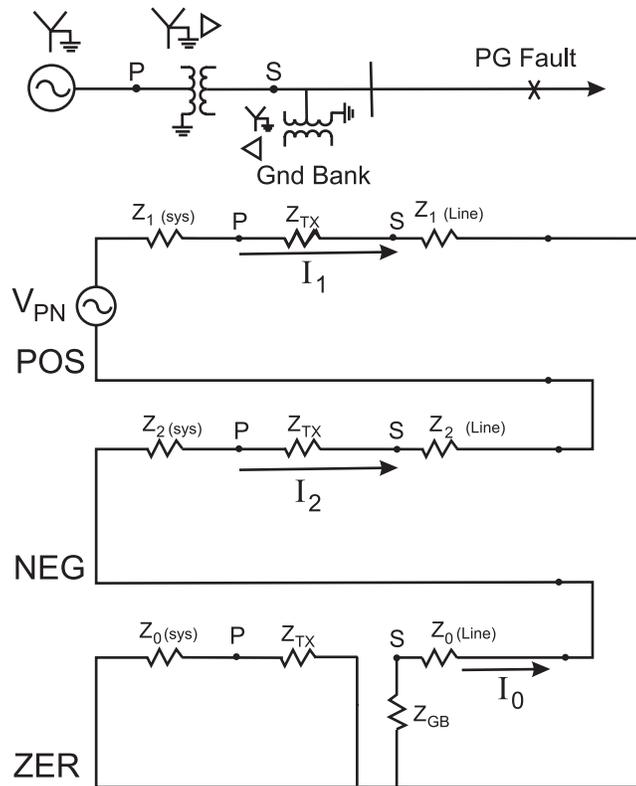


Figure 10. Sequence Network Model for a Bolted PG Fault on the Secondary of a Grounded-Wye/Delta Transformer with a Ground Bank connected to the Secondary System

Providing a much more substantial path for the fault current than the system distributed shunt capacitance of the ungrounded system presented in Figure 6, the grounding bank effectively provides solid grounding for the secondary system. Note how the ground bank impedance contributes to the resulting available ground fault levels. The total current ($3I_0$) contributed to secondary system ground faults can be monitored from a ground bank neutral current transformer (CT), or residually from a set of CTs monitoring the ground bank leads.

Zig-Zag Grounding Banks

Figure 11 shows the unusual core configuration of the single set of grounded-wye connected windings that comprises the so-called “Zig-Zag” grounding bank. Each phase winding is divided into two parts; those sections drawn in parallel on the diagram are coupled on the same core leg. The inner section of each winding shares a core leg with the outer winding section of one of the adjacent phases, as shown. All winding sections are wound so as to have the opposite polarity of the winding section with which it is coupled. With this winding / core arrangement, the positive sequence impedance of the bank is very high (equal to the magnetizing impedance) and can essentially be treated as an open circuit, while the zero sequence impedance is equivalent to the leakage reactance. This situation results in the Zig-Zag grounded-wye windings having the same

external effect with respect to zero sequence current circulation as a “regular” set of grounded-wye windings coupled with a set of delta connected windings. As with the Grounded-Wye/Delta bank, the total current ($3I_0$) contributed to the secondary system ground faults can be monitored from a neutral CT, or residually from a set of CTs monitoring the ground bank leads.

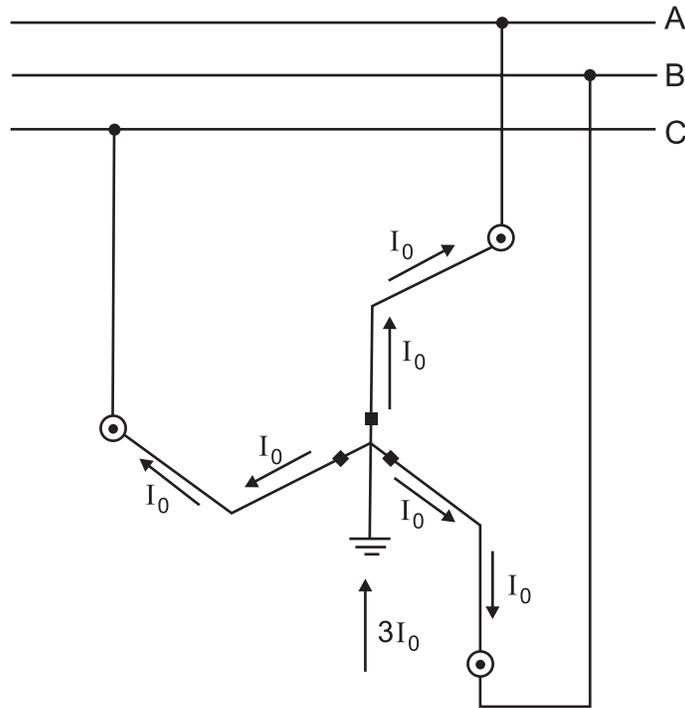


Figure 11. “Zig-Zag” Grounding Bank

Unlike the Grounded-Wye/Delta ground bank, the Zig-Zag ground bank has no power passing capability, and, as such, is designed solely for the purpose of providing a ground source. Because it is much more economical to build, the Zig-Zag bank is the most commonly applied design for grounding bank purposes. In general, Grounded-Wye/Delta power banks are only used for grounding purposes when a spare is available, or if there is a desire to also supply a load from the delta winding.

Inserting Impedance between the Ground and the Neutrals of Wye Connected Transformer and Generator Windings

“Impedance” grounding entails the insertion of either a reactor or a resistor between the neutral and ground of a grounded-wye connected generator, or the grounded-wye winding of a power or grounding transformer. These neutral elements are intended to limit the magnitude of ground fault current to some value lower than what the solidly grounded neutral levels would be, yet greater than the generally miniscule levels drawn for the ungrounded system (discussed previously). Figure 12 shows the sequence network

modeling for a bolted PG fault at the terminals of a wye-connected generator with an impedance inserted between the generator neutral and ground. Since the neutral impedance is in a residual portion of the zero sequence current circulation path, its impedance value is modeled as three times its actual value. In general, this neutral impedance value is much larger than the corresponding generator values. For this reason, the terminal PG fault current magnitude is, in essence, determined by the neutral impedance value used:

$$I_{PG} = \frac{3V_{PN}}{3Z_N} = \frac{V_{PN}}{Z_N} \quad (\text{Eq. 10})$$

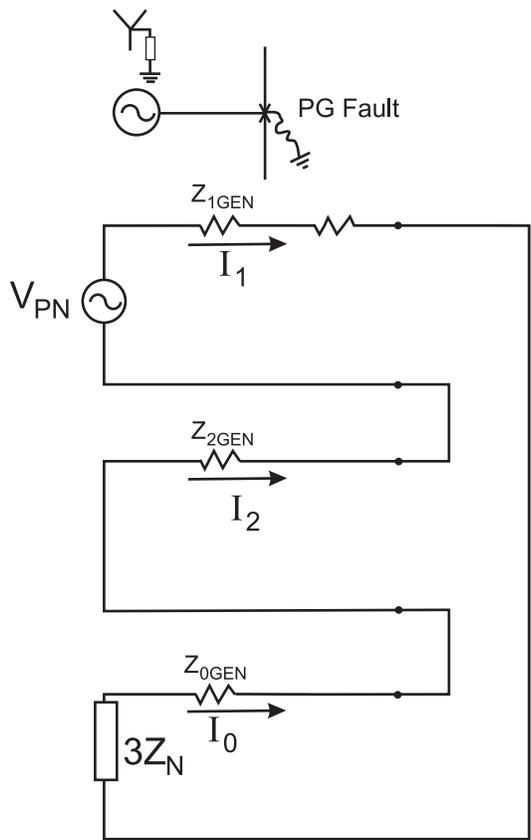


Figure 12. Sequence Network Model for a Bolted PG Fault at the terminals of an Impedance Grounded Generator

High Impedance Grounding

Normally, high impedance grounding is employed for the neutrals of grounded-wye generators, for the main purpose of keeping the current levels for ground faults on the machine leads and windings down to very low levels (generally to between 5 and 10 A primary for a bolted PG fault at the terminals). The central goal in achieving this is to prevent the machine’s iron from being damaged by arcing conditions under the high fault energies that otherwise would be available for the most likely PG fault.

Under the presence of a large neutral reactance, however, high voltage transients can result when low current, arcing ground faults, are cleared. This, coupled with the fact that the neutral reactor BIL capability generally is superior to that of the generator, results in insulation failures being quite likely to occur in the generator windings. For this reason, high resistance grounding for generators generally is preferred over high reactance grounding.

With a wye connected generator typically feeding the delta side of a Delta/Grounded-wye step-up transformer, high resistance grounding for the generator windings is normally achieved with a “neutral” transformer and resistor. Under this configuration, the generator itself is grounded through a high resistance, while the generator-transformer combination provides a solidly grounded wye source to the system. The grounding resistor is connected to the low voltage side (120 or 240V) of a distribution-sized neutral transformer, with the higher voltage side (conservatively rated for the generator PP voltage) connected between the neutral and ground. With the neutral transformer reflecting the resistance on the secondary by the square of the high to low voltage turns ratio to the primary (neutral side), a smaller resistor with a lower voltage rating can be used. This arrangement has the benefit of being much less costly than a resistor rated to be connected directly in the neutral. The lower voltage resistor also permits overvoltage relaying to readily sense generator winding and leads ground faults by monitoring the proportional neutral shift voltage appearing across the resistor. The resistor value is selected so that its kW loss for a bolted PG fault at the generator terminals is greater than or equal to the charging kVA of the generator’s low voltage system. Such a resistor size will generally limit the bolted PG fault at the generator terminals to between 5 and 10A primary, thereby keeping the machine’s iron from incurring significant damage. In addition, undesirable oscillations tend to be dampened quickly, and the peak transient overvoltage is limited to 250% of the normal PG voltage, or less.

Low Impedance Grounding

Faults that involve ground are far more likely to occur than any other type of fault. Although generally true for any part of a power system, ground faults are known to occur “with regularity” in motor loads. For this reason, some form of “low impedance” grounding is usually desirable for industrial type loads where large motors predominate. With the wye-connected windings of a source transformer supplying the load (usually a Delta/Grounded-wye transformer), low impedance grounding is accomplished by connecting either a resistor or reactor between the neutral of the wye windings and ground. The impedance value selected should yield a fault current low enough to greatly limit the damaging energy available, yet high enough so that overcurrent protection can be employed to allow a faulted area to be selectively isolated. Depending on the application, or in some cases, simply owner’s preference, PG fault currents are limited to within a selected value. Typical values range from 100 to 2500A.

Voltage Characteristics of Grounded versus Ungrounded Power Systems

Up to this point, the sequence network models for PG faults have been used to show the affect that various grounding methods have on the circulation path and magnitude of the ground fault current. Here, the same models will be considered to gain an understanding of the corresponding voltage conditions present on the system under the application of a PG fault.

Grounded Systems

Consider, as Case 1, the “general” grounded system with a bolted PG fault on A-phase, represented by Figure 1. Assume that there is no significant impedance in any part of the return path for the zero sequence component of the current, so that: $Z_1 = Z_2 = Z_0$. Under this situation, a third of the applied V_{PN} will be dropped across the impedance of each sequence network. As a result, the positive sequence voltage at the fault (V_1) will be 66.6% of V_{PN} :

$$V_1 = V_{PN} - (Z_1 I_1) \quad (\text{Eq. 11})$$

Meanwhile, the negative and zero sequence voltages at the fault (V_2 and V_0 , respectively) will each have a magnitude of 33.3% of V_{PN} (or half the magnitude of V_1), and, in the faulted phase, will each be 180 degrees out of phase with V_1 :

$$V_2 = -(Z_2 I_2) = V_0 = -(Z_0 I_0) \quad (\text{Eq. 12})$$

The sequence component phasors for the voltages at the fault location (for Case 1) are indicated in Figure 13. Their resultants, the actual phase voltages at the fault, are shown in comparison to the normal balanced voltage conditions, at the bottom of the figure. While V_{AG} collapses to zero at the fault, the voltages between phase and ground on the unfaulted phases remain unaltered from their normal magnitude and angles. Also at the fault, the point of the system neutral, maintained at the center of the collapsed voltage triangle, is shifted away from ground by 33.3% of the normal PN voltage magnitude, which corresponds exactly to the V_0 magnitude ($V_{NG} = |V_0|$). The voltage conditions at system points located up-line from the fault have V_{AG} increasing, in continuum, from zero at the fault back to the normal PN magnitude at the infinite source (as V_{NG} drops from 33.3% of the normal PN magnitude at the fault back to zero at the source).

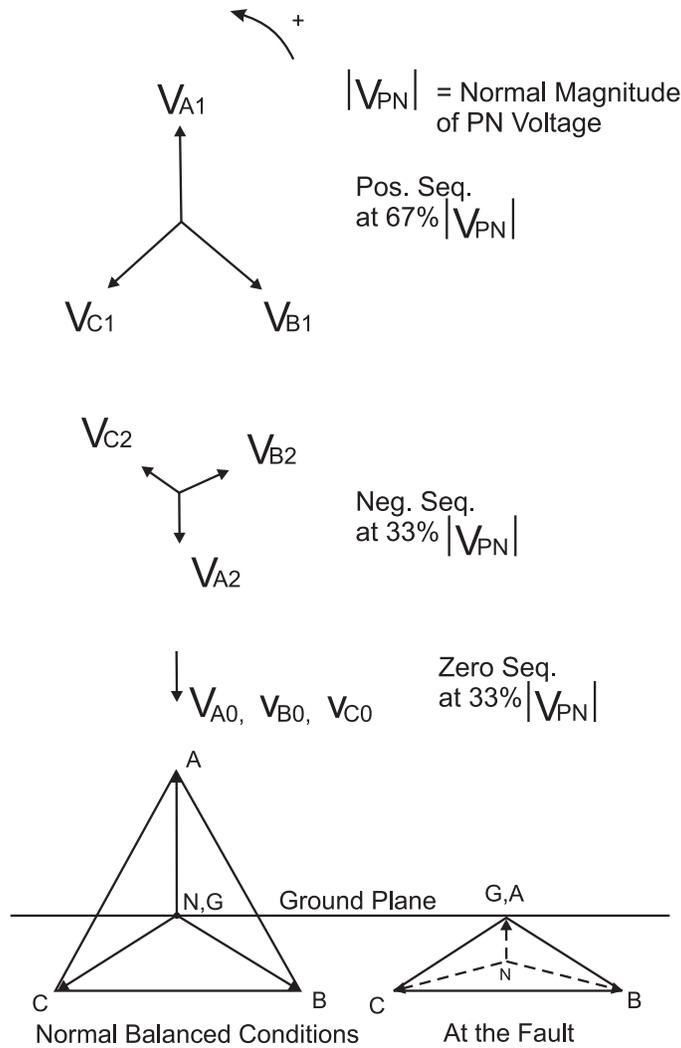


Figure 13. Case 1: Sequence Component Voltages and Resulting Voltage Profile for a Bolted PG Fault with $Z_1 = Z_2 = Z_0$

The situation described by Case 1 exists only if the impedance in the zero sequence return path can be neglected. In reality, the equivalent impedance in the zero sequence network will be greater than those of the equal positive and negative sequence values. This is due to: 1) impedance in the return circuit paths through the earth's conductor, 2) unintentional impedance between neutral and ground, and/or by 3) the insertion of purposeful impedance (via a reactor or resistor) in between neutral and ground. In addition, if the return path impedance is highly resistive, the zero sequence impedance angle also can differ significantly.

Still referring to Figure 1, consider the Case 2 grounded system, where $Z_0 = 2Z_1 = 2Z_2$ (for simplicity, assume that the Z_0 angle is approximately the same as for Z_1 and Z_2). Now, a quarter of the applied V_{PN} will be dropped across the impedance of the positive and negative sequence networks, with half appearing across the zero sequence. As compared

to Case 1, the positive sequence voltage at the fault (V_1) will rise to 75% of the normal V_{PN} magnitude; V_2 will fall to 25% of the normal V_{PN} magnitude, while V_0 rises to 50% of it. The sequence component phasors for the voltages at the fault location are indicated in Figure 14. As in Case 1, their resultants, the actual phase voltages at the fault, are shown in comparison to the normal balanced voltage conditions, at the bottom of the figure. With the 0 degree reference considered to be straight down on the diagram and 90 degrees to the right, the resultant B-phase voltage at the fault, in per unit of normal V_{PN} , is given by the following:

$$V_B = 0.50\angle 0^\circ + 0.25\angle 120^\circ + 0.75\angle 60^\circ = 1.15\angle 49^\circ \quad (\text{Eq. 13})$$

(By a similar derivation, V_C would be the “mirror image” of the V_B phasor, at 49° to the left of center.)

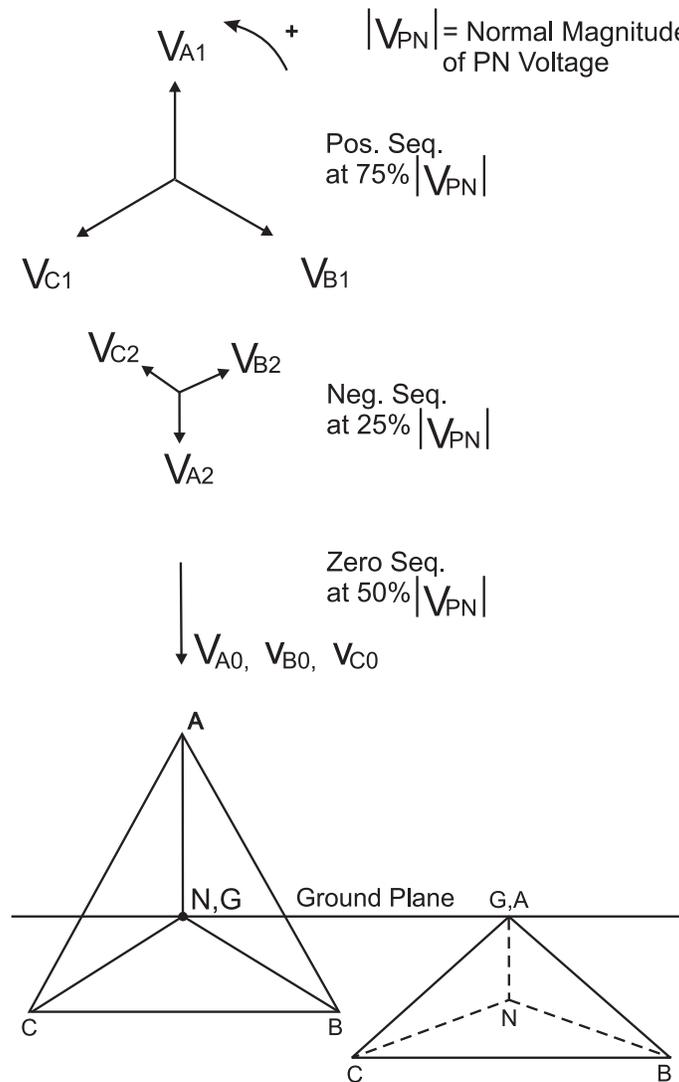


Figure 14. Case 2: Sequence Component Voltages and Resulting Voltage Profile for a Bolted PG Fault with $Z_0 = 2Z_1 = 2Z_2$

Again, V_{AG} collapses to zero at the fault; however, for this case, the voltages between phase and ground on the unfaulted phases increase to a magnitude that is 15% above the normal V_{PN} magnitude while the angle between V_B and V_C closes-in from the 120° found in Case 1 to 98° . The point of the system neutral, again maintained at the center of the collapsed voltage triangle, is shifted away from ground by 50% of the normal V_{PN} magnitude or equal to the V_0 magnitude ($V_{NG} = |V_0|$).

If the magnitude of the equivalent Z_0 between source and fault is increased further in relation to that of Z_1 and Z_2 , the trend noted between Cases 1 and 2 continues. The neutral shift voltage (V_{NG}), as well as the voltages on the unfaulted phases, continues to increase in magnitude. As the magnitude of Z_0 approaches infinity, the situation approaches that of the ungrounded case, to be discussed next.

Ungrounded Systems

For Case 3, an ungrounded system will be considered. Refer to Figure 6, which shows the sequence network modeling for a bolted PG fault on the ungrounded system formed on the secondary of the Delta / Delta transformer, supplied on the primary by a grounded-wye source. Recall that, since the zero sequence network is open at the transformer, the zero sequence component of the total distributed shunt capacitive reactance of the system to the fault (X_{C0}) provides the only path for any fault current to flow. Due to its magnitude being so large compared to any other impedance in the loop of the series connected sequence networks, almost all of the applied V_{PN} is dropped across X_{C0} . The limit approached by this situation is indeed an open circuit between the transformer secondary terminal and the zero sequence reference bus. Under this arrangement there would be zero fault current with 100% of V_{PN} appearing all along the “effective terminals” extending from the source in the positive sequence network to the open circuit in the zero sequence network.

Under the limiting case described above, both V_1 and V_0 at the fault will be 100% of the normal V_{PN} magnitude, but V_2 will be zero. The sequence component phasors for the voltages at the fault location are shown in Figure 15. As in previous cases, their resultants, the actual phase voltages at the fault, are shown in comparison to the normal balanced voltage conditions, at the bottom of the figure. With the 0 degree reference considered to be straight down on the diagram and 90 degrees to the right, the resultant B-phase voltage at the fault as per unit of the normal V_{PN} magnitude is given by the following:

$$V_B = 1.00\angle 0^\circ + 1.00\angle 60^\circ = 1.73\angle 30^\circ \quad (\text{Eq. 14})$$

(By a similar derivation, V_C would be the “mirror image” of the V_B phasor, at 30° to the left of center.)

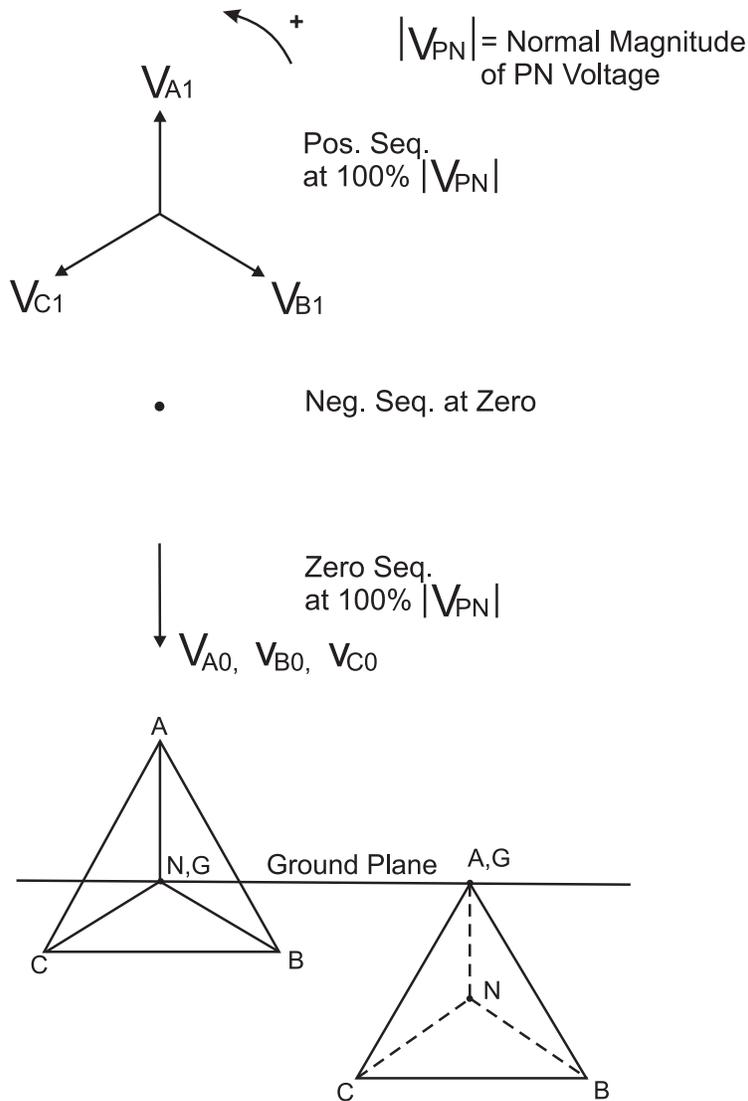


Figure 15. Case 3: Sequence Component Voltages and Resulting Voltage Profile for a Bolted PG Fault on an Ungrounded System

As for the previous cases, V_{AG} collapses to zero at the fault; however, for the ungrounded case, the voltages between phase and ground on the unfaulted phases increase to a magnitude of $\sqrt{3}$ times the normal V_{PN} magnitude which happens to be full, normal, PP voltage magnitude. Additionally, the angle between V_B and V_C closes-in to 60° , as they become aligned with system voltages V_{AB} and V_{AC} . Also for this case, the point of the system neutral, maintained at the center of the voltage triangle, is shifted away from ground by 100% of the normal V_{PN} magnitude ($V_{NG} = |V_o|$). This resulting situation is referred to as a “full neutral shift”. It is important to note about this fault case, that since there is always negligible voltage drop in the ungrounded system between the point at which the source voltage connects and any location the PG fault might be applied, the voltage profile at the fault will essentially exist at all points on the ungrounded system.

Special Protection Issues that Result from System Grounding Characteristics

Protective Relaying Concerns Under a Discontinuous Zero Sequence Network

The ability of a transformer's connection either to allow or inhibit the flow of zero sequence current was discussed earlier in this paper. Discontinuities introduced by transformers that do not pass zero sequence current obviously can have a significant impact on protective schemes that rely on the monitoring of zero sequence current.

Consider the system presented in Figure 4. Here, the Grounded-Wye/Grounded-Wye transformer connection results in a zero sequence network that is "continuous" between the grounded-wye source of the system and the transformer secondary. For ground faults on the secondary (as modeled in this example), a zero sequence detecting ("ground") overcurrent function monitoring at the transformer primary sees the same flow of current as a ground function on the secondary, monitoring up-line of the fault. Although the levels of current seen by the two functions will, of course, differ according to the turns ratio between the transformer's primary and secondary windings, there will be a need to ensure proper time coordination between them. That is, the fault clearing operation of the secondary overcurrent function should be completed sooner than a corresponding operation of the primary function, with adequate margin, for every possible fault scenario within the detection range of the two.

An example of a discontinuous zero sequence network was given in Figure 6. In this secondary ground fault situation, the Delta/Delta transformer opens the zero sequence network and yields an ungrounded secondary system. As previously was seen, the level of zero sequence current flowing on the secondary was quite small, being determined, essentially, by the zero sequence distributed shunt capacitance of the system. If the primary system is at a higher voltage, the corresponding current flow there would be smaller yet, by the transformer turns ratio. Although ground overcurrent relaying could be applied on the grounded wye primary system, any protective coverage would extend only as far as the transformer primary windings. For ground faults on the secondary, the current levels are too low for any primary overcurrent function to detect, and too low for any ground overcurrent protection to be applied on the secondary. If a transformer differential scheme were applied on the Delta/Delta transformer, a similar situation arises. Although ground faults could be detected in the primary windings and leads, it is likely that there would be insufficient sensitivity to detect ground faults in the secondary side of the zone coverage.

Figure 8 provided another example where the zero sequence network is discontinuous. Although the Delta/Grounded-Wye transformer opens the zero sequence network, this situation differs from the Figure 6 example in that a ground source, independent of that provided by the primary system's grounded-wye source, is provided by way of the transformer's delta / grounded-wye connection. Unlike the case of the ungrounded secondary, full zero sequence current circulation is permitted on the secondary, and a hierarchy of coordinating overcurrent ground functions, therefore, can be applied with no special problems. Ground overcurrent protection, likewise, can be applied at the primary;

however, since the zero sequence network is open to the secondary, their protective coverage, as for the Figure 6 example, extends only as far as the transformer primary windings. Thus, there is no need to coordinate the primary and secondary ground detecting functions.

Unlike the case of the Figure 6 example, the substantial, independent ground source introduced on the secondary of the Figure 8 Delta/Grounded-Wye transformer will permit a transformer differential scheme to detect ground faults on the secondary windings and leads, in addition to the primary. A detrimental side effect, however, does arise with the ground source being effectively provided from within the transformer differential zone. For ground faults external to the zone, on the secondary side, the differential will (effectively) detect the zero sequence component currents flowing out through the secondary phase CTs. Yet, because the zero sequence current only appears inside the delta connected windings of the primary and not in the primary leads, current detected as leaving the zone is never detected as entering it. Unless extra measures are taken, such a scenario will be seen as an internal fault, and a misoperation will occur. Solutions to this particular problem are addressed in the following section.

The Grounded-Wye/Delta source transformer, with the Grounded-Wye/Delta grounding transformer connected at the main secondary terminals, covered in Figure 10, also presents a discontinuous zero sequence network. With respect to the application of ground overcurrent protection and transformer differential protection, the concerns are similar to those considered for the Figure 8 example just discussed. In this configuration, however, a local ground source is presented to both the primary and secondary sides of the main transformer/grounding bank combination. Not only would a transformer differential scheme that wraps the transformer combination be subject to misoperation for external ground faults on either side of the zone, phase and ground overcurrent functions on the primary also can misoperate due to the zero sequence current contributed from the transformer for ground faults up-line of the transformer.

Preventing Operation of Transformer Differential Schemes Resulting from Zero Sequence Current Sources within the Zone

A ground source (delta/grounded wye transformer winding or zigzag grounding bank) within the zone of protection can result in differential current being measured during ground imbalances. The most common example of this is when the zone of protection is around a delta/grounded wye transformer. If a ground fault or neutral imbalance occurs on the power system external to the wye side of the zone of protection, zero-sequence current will flow through the grounded neutral and out on each phase. On the delta side, however, it will circulate only inside the delta winding and will not be detected on the transformer leads. The resulting differential current can cause the relay to misoperate.

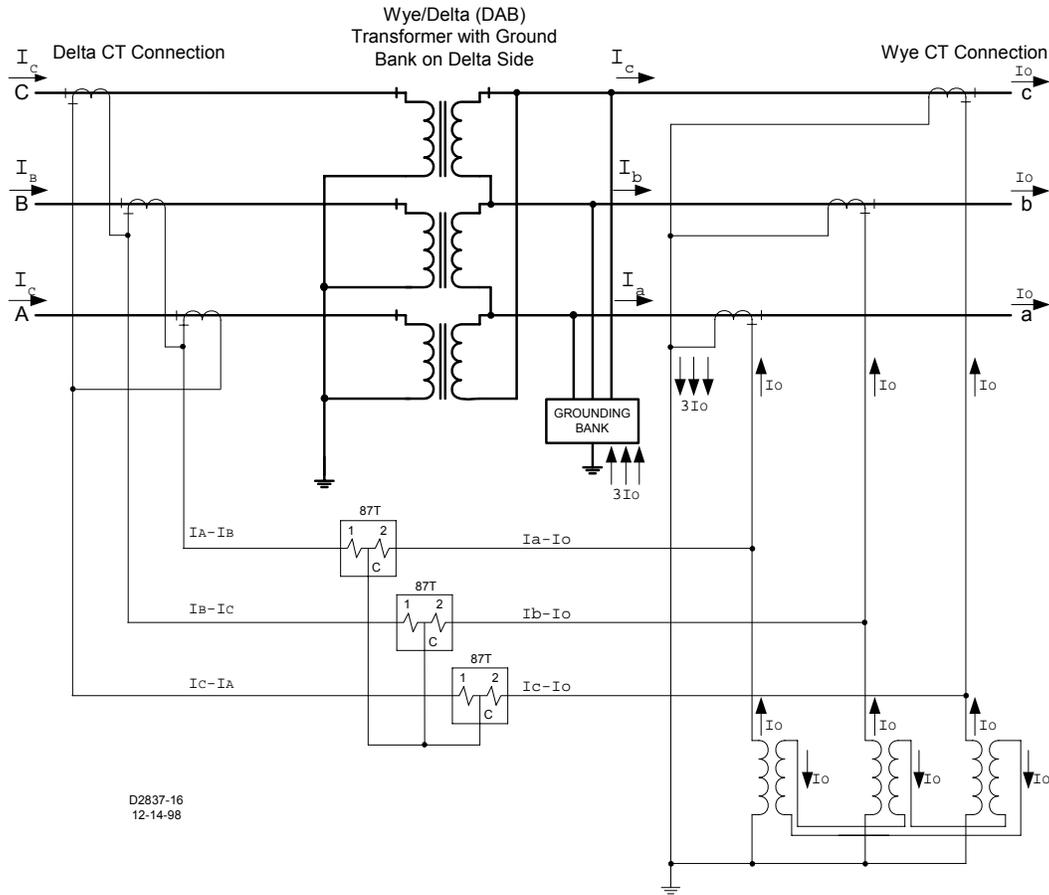
There are two traditional solutions to this problem; each of which physically prevents the zero-sequence component phase currents from getting to the differential protection. The first is to use delta connected CTs on the grounded-wye side of the zone of protection. The

second is removing the zero-sequence components from the currents, using a “zero-sequence trap”.

A major goal of transformer differential protection is to compensate for all magnitude and angle differences between the primary and secondary currents being compared. As such, their difference will reflect as closely as possible the true ampere-turns entering and leaving the zone. For instance, if the CTs monitoring the leads of delta-connected transformer windings are connected in wye, and those monitoring the leads of wye-connected windings are connected in delta so that they mimic (match) the transformer’s delta connection (Delta A-B or Delta A-C), the 30° phase shift introduced by Delta / Wye transformer connections for positive and negative sequence current flow will be compensated. As an additional benefit, delta connected CTs monitoring transformer wye windings that are grounded, will succeed in blocking the zero-sequence phase currents from flowing to the differential protection. Any zero sequence current detected will circulate only within the CT delta connection (in the form of I_0). This is in the same manner as it circulates in the delta windings of the power transformer when zero sequence current is circulating on the grounded-wye coupled windings (refer to Figure 7).

Most modern numeric relays can be programmed to provide the proper phase shift compensation, as well as block zero-sequence currents as appropriate. This can be achieved even if no external means of accomplishing these is being provided (as was the case for the traditional measures described above). That is, all CT sets providing current to the differential protection can be connected in wye. By the same token, they also can be programmed to accommodate any traditional, external measure that might, nonetheless, be applied,

The second traditional solution of inserting a zero-sequence trap is used in applications where there is a grounding bank within the zone of protection that is not predicted by the transformer connection information contained in the CT circuit setup parameters. In the example shown in Figure 16, traditional compensation measures would require that delta connected CTs be applied to the grounded wye winding. With traditional wye connected CTs on the delta side of the transformer zone, the grounding bank within the delta side is subject to causing the differential protection to misoperate for external ground faults. Figure 16 shows how this situation would be handled with a traditional differential relaying scheme.



D2837-16
12-14-98

Figure 16. Traditional Zero-Sequence Trap for Application with Ground Banks

This application can be greatly simplified with modern numeric relays. The user can connect all CTs in wye and specify that the delta transformer winding has a ground source. The relay will apply delta compensation to the wye winding to obtain phase shift and zero-sequence compensation for that current input. For the delta winding with ground source, it will numerically remove the zero-sequence components from that current input just as traditionally would be done with a zero-sequence trap. The parameters specifying CT connection, transformer connection, and ground source for each current circuit determine the angle and zero-sequence compensation used on each current input.

Ground Fault Protection on Solidly Grounded Systems

Solidly or effectively grounded systems are defined as any system for which both of the following inequalities (the “grounding ratios”) are true for any ground fault occurring in the system:

$$\left(\frac{X_0}{X_1} \leq 3.0 \right) \text{ and } \left(\frac{R_0}{X_1} \leq 1.0 \right)$$

where the variables represent the equivalent system impedance parameters for a particular fault location:

X_1 = the equivalent system positive sequence reactance

X_0 = the equivalent system zero sequence reactance

R_0 = the equivalent system zero sequence resistance

Solidly grounded systems equate to no substantial impedance existing between the system neutral and ground. If the grounding ratios are maintained to within the values specified above, the PG voltage on the unfaulted phases for a bolted PG fault will not rise to more than 80% of the normal PP magnitude. Ground fault current magnitudes available on such systems are comparable to, or even greater than, those for 3-phase faults (considering no fault resistance), and vary significantly with fault location. In addition, ground fault currents will vary considerably depending on the power system configuration, location of the fault, and fault resistance, which may be considerable depending on the type of contact (tree limb, wind, downed conductor, etc.).

Based on the substantial level of ground fault current available in solidly grounded systems, modern ground overcurrent, directional ground overcurrent, ground distance, relaying systems all can be used for providing excellent high speed protection and zone selectivity. High impedance ground faults, however, do pose challenges for reliable detection and clearing of these faults.

For example calculations associated with a solidly grounded system, refer to Section 7 of J. Lewis Blackburn's Protective Relaying Principles and Applications. [2]

Ground Fault Protection in an Impedance Grounded System

Impedance grounded systems are designed to limit primary ground fault current to levels that prevent damage to primary equipment. Depending on the method used, secondary ground fault current may be reduced below the capability of overcurrent detecting protection systems. In these cases, protection similar to that used for ungrounded systems, or others, may be employed.

Impedance grounded systems are categorized as High Impedance grounding and Low Impedance grounding. Several types of impedance grounding systems are in use today, primarily consisting the following:

- High Z Resistor Grounded Systems
- High Z Resonant Grounded Systems
- Low Z reactor Grounded Systems
- Low Z resistor Grounded Systems

High Z resonant grounding is used extensively in the countries of northern and central Europe, but it is only used in a few places in the U.S. such as in New England for

generator grounding (see References for paper references). High resistance grounding, however, is widely used for generator and industrial applications throughout the U.S.

High resistance grounding typically incorporates the use of a distribution transformer and a secondary resistor. This arrangement normally is used for unit generator applications and industrial power systems with a single power transformer supply as shown in Figure 17. For this grounding method, a neutral voltage relay (59N) is applied to measure the voltage drop across the secondary resistor. In some cases, there is enough current flow in the secondary resistor circuit that a 51N overcurrent relay can also be applied in a backup role.

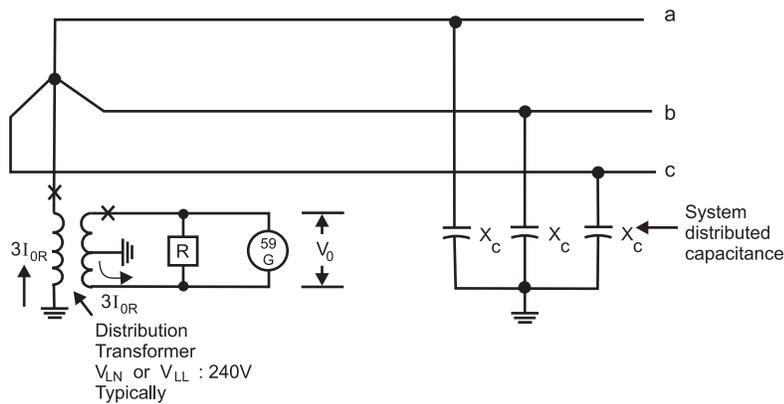


Figure 17. High-resistance Grounding with Resistor in the Neutral

For example calculations associated with high resistance grounding of a unit generator system as shown in Figure 17, refer to Section 7 of J. Lewis Blackburn's Protective Relaying Principles and Applications. [2]

For systems with several power sources or multiple generators, the best high impedance grounding approach includes the grounding resistor across the broken delta point of line to ground connected distribution transformers as shown in Figure 18. The wye-connected primary must be grounded solidly with the current limiting resistor connected across the broken delta connected secondary windings. Note that this arrangement will also be used in the next section on protecting ungrounded systems.

Remember, this type of grounding system produces $\sqrt{3}$ x P-N voltage across the two unfaulted transformers for a bolted PG fault. Therefore, it is good practice to use P-P rated transformers for the protection application.

For example calculations for the system shown in Figure 18, refer to Section 7 of J. Lewis Blackburn's Protective Relaying Principles and Applications. [2]

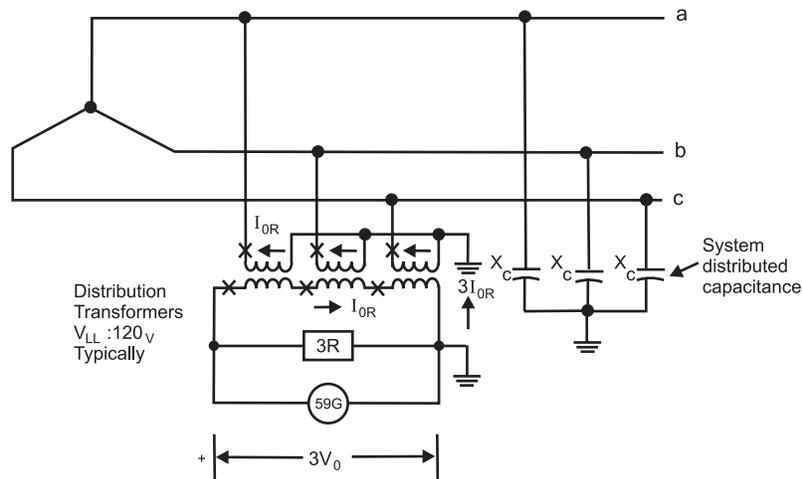


Figure 18. High-resistance Grounding with Resistor across Distribution Transformer Secondaries

Low-impedance grounding methods have the advantage of limiting fault current as well as allowing for selective protection based on magnitude differences in the fault current, i.e. selective protection with overcurrent relays. Such magnitude differences result from predictable differences in impedance between the source and the point of fault. Although there is enough ground fault current availability for overcurrent protection selectivity, bolted faults involving multiple phases (phase faults) tend to draw substantially higher fault current levels. Due to the significant difference in magnitude between ground faults and phase faults, typical for these systems, separate overcurrent protection schemes for phase and ground faults generally need to be applied. Low impedance grounding typically is implemented with a reactor or resistor installed in the system neutral (Figure 19). Several generator units that are connected to a common bus also may be grounded in this manner.

In a typical distribution substation or source station to an industrial facility, Low impedance grounding may be installed in the neutral of the delta-wye power transformer. Several generator units that are connected to a common bus also may be grounded in this manner.

For example calculations low Z grounded with a reactor and a resistor, refer to Section 7 of J. Lewis Blackburn's Protective Relaying Principles and Applications. [2]

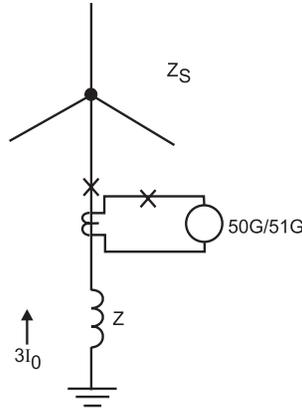


Figure 19. Low-impedance Grounding

Detecting Ground Faults in an Ungrounded System

Phase to ground faults on an ungrounded system cause a shift in the normal voltage triangle. Referring to the phasor diagrams in Figure 20, during normal operation with no ground fault or line to ground current:

$$\begin{aligned}
 V_{NG} &= 0 && \text{(Eq. 15)} \\
 V_{AG} &= V_{AN} + V_{NG} = 1\angle 0 + 0 \\
 V_{BG} &= V_{BN} + V_{NG} = 1\angle -120 + 0 \\
 V_{CG} &= V_{CN} + V_{NG} = 1\angle 120 + 0
 \end{aligned}$$

However, during a ground fault, virtually all of the faulted phase's voltage is impressed upon the neutral impedance. For a phase A to ground fault, $V_{AN}=0$, and the voltage across the neutral resistor is essentially the negative of the Phase A to neutral voltage.

Mathematically:

$$V_{AG} = 0 = V_{AN} + V_{NG} \quad \text{(Eq. 16)}$$

which means:

$$V_{NG} = -V_{AN} = 1\angle 180 \quad \text{(Eq. 17)}$$

which, therefore, means:

$$\begin{aligned}
 V_{BG} &= 1\angle -120 + 1\angle 180 = 1.732\angle -150 \\
 V_{CG} &= 1\angle 120 + 1\angle 180 = 1.732\angle 150
 \end{aligned} \quad \text{(Eq. 18)}$$

Since a broken delta sums the 3 phase voltages,

$$\begin{aligned}
 V_{BrokenDelta} &= V_{AG} + V_{BG} + V_{CG} && \text{(Eq. 19)} \\
 &= 0 + 1.732\angle -150 + 1.732\angle 150 = 3\angle 180
 \end{aligned}$$

From this line of reasoning, one should be able to see that the worst case steady state fundamental frequency voltage seen at the broken delta will be:

$$V_{\text{Broken Delta}} = 3 * \frac{V_{\text{SYS,LG,NORMAL}}}{\text{VTR}} \angle (V_{\text{Unfaulted Phase Angle}} + 180) \quad (\text{Eq. 20})$$

The VTR in the above equation is best thought of in terms of the *winding turns ratio*, rather than voltage ratios. This is highlighted because the question of whether one should use V_{LL} or V_{LN} to calculate VTR is avoided if one thinks in terms of winding turns ratio.

For an example, if normal system voltage was 13.8kV_{LL} and 7.97kV_{LG}, and a VTR of 115 were used, for a phase A fault, the worst case broken delta voltage would be:

$$V_{\text{Broken Delta, Phase A Fault}} = 3 * \frac{7970}{115} \angle (0 - 180) \quad (\text{Eq. 21})$$

With a VTR of 115, the normal secondary voltage during unfaulted conditions on each leg of the delta will be:

$$V_{\text{LL, Delta Sec, Normal}} = \frac{V_{\text{VT Primary}}}{\text{VTR}} = \frac{7970}{115} = 69.3\text{V} \quad (\text{Eq. 22})$$

During a fault, secondary voltage on the two unfaulted phases rises to 120V (=13800/115). Note that 69.3 * 3 = 207.9V, which agrees with the earlier calculations for the maximum broken delta voltage during the fault. If the ground fault impedance is high or the source ground impedance is low, the voltage that will arise during a ground fault will be something less than 3 per unit. The calculation of what will occur can be analyzed using a set of simultaneous equations. The circuit in Figure 20 is analyzed in a Mathcad™ (Revision 7) document, "59N_R#.MCD" found in the "Downloads" section of the Basler Electric web site, www.basler.com.

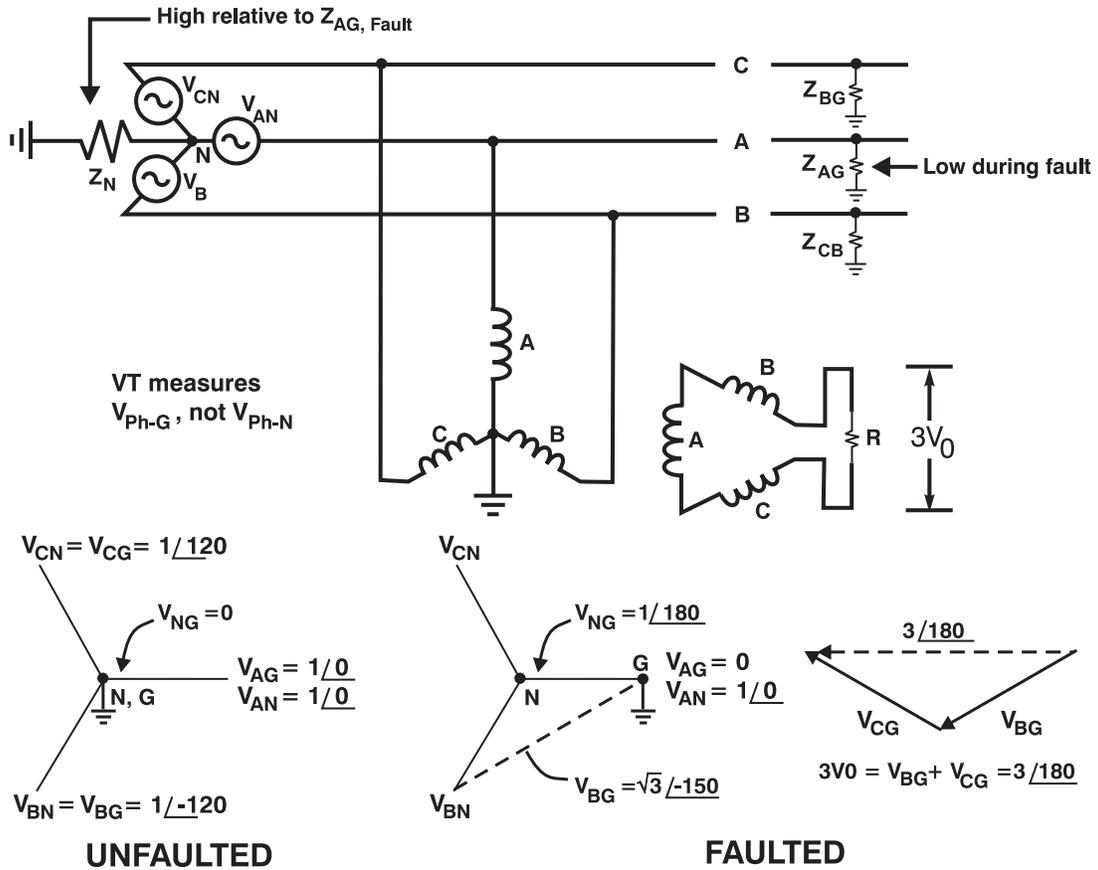


Figure 20. Phasor Diagrams during a Line-to-ground Fault

It is important to note that, during a ground fault, two of the VTs must withstand and reproduce full line-line voltage. It would be an error to use a VT rated only for line-ground voltage. For instance, in the wye-broken delta system described above, the normal system voltage is $13.8\text{kV}_{\text{LL}}$ and $7.97\text{kV}_{\text{LG}}$, and secondary voltage is 69.3 under normal operating conditions but rising to 120V during a fault. The VT in this case needs to be rated for $13.8\text{kV}/120\text{V}$.

Things to Consider before Selecting a Grounding System Method

After considerable review of system grounding methods and zero sequence current sources, one might suspect this assortment of methods was developed to keep protective relay engineers employed, but we all know how that worked out. One might also consider that the genesis of the phrase “The Art and Science of Protective Relaying” may have sprung forth late one night from a weary protection engineer pondering the variety of options available for grounding a 3-phase power system. Of course, the overall objective is to select a grounding method that establishes a balance point among all the opposing advantages and disadvantages of the available grounding options. Table 2 from the

Electrical Transmission and Distribution Reference Book still provides the most efficient and concise comparison of considerations and is included as Appendix A of this document.

Conclusion

As stated in the introduction, the purpose of this paper is to provide a tutorial or “refresher” on grounding methods, sources of ground current, ground current flow in the power system, and how each impacts protective relaying. With retirements, new hires, reorganization, cross training, and so on, this subject, like many others, requires regular review to maintain the experience level of our protection engineers and we trust that the authors accomplished this task.

References

1. Schroeder, Mark S. 2008; Author and Instructor. “Dominion VA Power- Circuit Calculations Engineering Development Program”.
2. Blackburn, J. Lewis. 1998. “Protective Relaying, Principles and Applications.” Second Edition, Copyright 1998 by Marcel Dekker, Inc.; Section 7 “System-Grounding Methods”.
3. Westinghouse Electric Corporation, Copyright 1950. “Electrical Transmission and Distribution Reference Book” Fourth Edition, by Central Station Engineers of the Westinghouse Electric Corporation East Pittsburgh, Pennsylvania; Chapter 19 “Grounding of Power System Neutrals”; Original author S. B. Griscom.
4. Westinghouse Electric Corporation, Copyright 1976. “Applied Protective Relaying” Section 11, System Grounding and Protective Relaying – J. L. Blackburn and J. V. Kresser.
5. IEEE C37.230-2007, “Guide for Protective Relay Applications to Distribution Lines”.
6. Beltz, Robert; Peacock, Ian; Vilcheck, William. 2001. “Application Considerations for High Resistance Ground Retrofits in Pulp and Paper Mills”. IEEE Industry Applications Magazine; March/April 2001 Issue.
7. “Ground Fault Protection on Ungrounded and High Resistance Grounded Systems”. Date NA. Application Guide; i-GARD; Mississauga, Ontario Canada
8. Gulachenski, E.M.; Courville, E.W. 1984. “30 Years of Experience with Resonant Neutral Grounding of Unit-Connected Generators”; IEEE Transactions on Power Apparatus and Systems; Issue 9, Sept 1984.

9. Gross, Eric T. B.; Gulachenski, Edward M "Experience of the New England System with Generator Protection by resonant Neutral Grounding", IEEE Transactions on Power Apparatus and Systems; Issue 4, July 1973.
10. Gross, E.T.B., Atherton, E.W., "Application of resonant grounding in power systems in the United States", *AIEE Transactions*, vol. 70, part 1, pp. 389-397, 1951.
11. A Mathcad™ file (59N_R1.MCD). Set of simultaneous equations used for analysis of Figure 20, Phasor Diagrams during a Line-to-ground Fault. Available in the "Downloads" section Basler web site: www.basler.com. Note: You must have the Mathcad software installed to utilize this file.
12. *Transformer Protection Application Guide*, Basler Electric Company, Highland, Illinois, 2007, pp. 4-5.
13. *BE1-CDS220 Instruction Manual for Current Differential System, Revision B*, Basler Electric Company, Highland, Illinois, 2006, pp. 1-12 and 1-13.

Biographies

Jerry Johnson is Principal Applications Engineer for Basler Electric Company and is based in Richmond, Virginia. Prior to joining Basler in 1999, Jerry spent 29 years in the System Protection organization of Dominion VA Power, including 12 years as Director of the System Protection Engineering. Jerry is a graduate of Virginia Commonwealth University and is a registered professional engineer in the State of Virginia. He is a senior member of IEEE, a member of the Power System Relaying Committee, a member of IEEE SCC21 Standards Coordinating Committee, and a member of the Texas A&M and Georgia Tech Planning Committees.

Mark Schroeder has been employed by Dominion Virginia Power for the last 30 years. At the present, he is a Level III Engineer in the System Protection Calculations Group of Electric Transmission & Distribution, where has charge of the standards, methods, and training. Mark is a graduate of Virginia Tech and is a registered professional engineer in the State of Virginia. He is a member of IEEE, and is an active participant in the Power System Relaying Committee.

Gerald Dalke is a semi-retired power system protection consultant living in Edmond Oklahoma. Gerald spent 33 years in system protection and control with OG&E, retiring in July 1994. After ten years with Basler Electric as a Senior Application Engineer he retired in October 2005. At the present time he is consulting for C. H. Guernsey & Company of Oklahoma City. Gerald is a graduate of Oklahoma State University and a registered professional engineer in Oklahoma. He is a Senior Member of IEEE and the Industrial Application Society. He is also an active member of the Texas A&M Protective Relay Conference Planning Committee.

Appendix A.

Table 2. Grounding of Power System Neutrals ^[3]

		A	B	C	D	E
		Ungrounded	Effectively Grounded	Reactance Grounded	Resistance Grounded	Resonant Grounded
1	Apparatus Insulation	Fully Insulated	Lowest	Partially Graded	Partially Graded	Partially Graded
2	Fault to Ground Current	Usually Low	Maximum value rarely higher than three-phase short circuit current	Cannot satisfactorily be reduced below one-half or one-third of values for solid grounding	Low	Negligible except when Petersen coil is short circuited for relay purposes, when it may compare with solidly-grounded systems
3	Safety from voltage gradient considerations	Usually good, but not fully dependable because of possibility of simultaneous fault on another phase	Gives greatest gradients, but not usually a problem where continuous ground wires are used.	Slightly better than effective grounding.	Better than effective or reactance grounded.	Least gradient normally, but may approach effective grounding values when necessary to shunt ground fault neutralizer to isolate faulty circuit by relaying.
4	Stability	Usually unimportant	Lower than with other methods, but can be made satisfactory by use of high speed relays and circuit breakers	Improved over solid grounding, particularly if used at receiving end of system	Improved over effective grounding, particularly if used at sending end of system	Is eliminated from consideration during single line-to-ground faults unless neutralizer is short circuited to isolate fault by relays
5	Relaying	Difficult	Satisfactory	Satisfactory	Satisfactory	Requires special provisions, but can be made satisfactory
6	Arcing Grounds	Likely	Unlikely	Possible if reactance is excessive	Unlikely	Unlikely
7	Localizing Faults	Effect of fault transmitted as excess voltage on sound phases to all parts of conductively connected network	Effect of faults localized to system or part of system where they occur	Effect of faults localized to system or part of system where they occur, unless reactance is quite high	Effect of faults transmitted as excess voltage on sound phases to all parts of conductively connected network	Effect of faults transmitted as excess voltage on sound phases to all parts of conductively connected network
8	Double faults	Likely	Unlikely	Unlikely, unless reactance is quite high and insulation weak	Unlikely, unless resistance is quite high and insulation weak	Seem to be more likely, but conclusive information not available
9	Lightning Protection	Ungrounded neutral service arresters must be applied at sacrifice in cost and efficiency	Highest efficiency and lowest cost	If reactance is very high, arresters for ungrounded neutral service must be applied at sacrifice to cost and efficiency	Arresters for ungrounded, neutral service usually must be applied at sacrifice in cost and efficiency	Ungrounded neutral service arresters must be applied at sacrifice in cost and efficiency

Table 2. Grounding of Power System Neutrals, Continued

10	Inductive Coordination	Will usually be low except in cases of double faults or electrostatic induction with neutral displaced, but duration may be great	Will be greatest in magnitude due to higher fault currents, but can be quickly cleared particularly with high speed breakers	Will be reduced from solidly grounded values	Will be reduced from solidly grounded values	Will be low in magnitude except in cases of double faults or series resonance at harmonic frequencies, but duration may be great
11	Radio Influence	May be quite high during faults or when neutral is displaced	Minimum	Greater than for solidly grounded, when faults occur	Greater than for solidly grounded, when faults occur	May be high during faults
12	Line Availability	Will inherently clear themselves if total length of interconnected line is low and require isolation from system in increasing percentages as length becomes greater	Must be isolated for each fault	Must be isolated for each fault	Must be isolated for each fault	Need not be isolated, but will inherently clear itself in about 60 to 80 percent of faults
13	Adaptability to Interconnection	Cannot be interconnected unless interconnecting system is ungrounded or isolating transformers are used	Satisfactory indefinitely with reactance-grounded systems	Satisfactory indefinitely with solidly-grounded systems	Satisfactory with solidly- or reactance-grounded systems with proper attention to relaying	Cannot be interconnected unless interconnected system is resonant grounded or isolating transformers are used. Requires coordination between interconnected systems in neutralizer settings
14	Circuit breakers	Interrupting capacity determined by three-phase fault conditions	Same interrupting capacity as required for three-phase short circuit will practically always be satisfactory	Interrupting capacity determined by three-phase fault conditions	Interrupting capacity determined by three-phase fault conditions	Interrupting capacity determined by three-phase fault conditions
15	Operating procedure	Ordinarily simple, but possibility of double faults introduces complication in times of trouble	Simple	Simple	Simple	Taps on neutralizers must be changed when major system switching is performed, and difficulty may arise in interconnected systems. Difficult to tell where faults are located.
16	Total cost	High, unless conditions are such that arc tends to extinguish itself, when transmission circuits may be eliminated, reducing total cost	Lowest	Intermediate	Intermediate	Highest, unless the arc suppressing characteristic is relied on to eliminate transmission circuits when it may be lowest for the particular type of service



Highland, Illinois USA
Tel: +1 618.654.2341
Fax: +1 618.654.2351
email: info@basler.com

Suzhou, P.R. China
Tel: +86 512.8227.2888
Fax: +86 512.8227.2887
email: chinainfo@basler.com