

NEW DIRECTIONAL GROUND-FAULT ELEMENTS IMPROVE SENSITIVITY IN UNGROUNDED AND COMPENSATED NETWORKS

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ABSTRACT

This paper introduces two new directional elements for determining ground fault direction in ungrounded and compensated distribution networks. These elements only require information from the protected feeder and provide very high sensitivity. First, we review the basic characteristics of these distribution networks. Next we analyze the steady-state operation of a ungrounded and compensated system in the phase- and symmetrical-component domains under ground fault conditions and describe existing methods for detecting ground faults in these systems. We conclude by introducing new fault detection methods for compensated systems and show how those methods are implemented with modern relay technology.

INTRODUCTION

Ungrounded systems have no intentional ground. For a ground fault on these systems, the only path for ground current to flow is through the distributed line-to-ground capacitance of the surrounding system and of the two remaining un-faulted phases of the faulted circuit.

In resonant-grounded or compensated distribution networks the system is grounded through a variable impedance reactor, which compensates the system phase-to-ground capacitance. The reactor, known as the Petersen coil, permits adjustment of the inductance value to preserve the tuning condition of the system for different network topologies.

Because ground faults in ungrounded and compensated systems do not affect the phase-to-phase voltage triangle, it is then possible to continue operating either system in the faulted condition. The system must have a phase-to-phase insulation level and all loads must be connected phase-to-phase.

Resonant grounding provides self-extinction of the arc in overhead lines for about 80 percent of temporary ground faults [1]. Considering that about 80 percent of ground faults are temporary faults, we conclude that more than 60 percent of ground faults in overhead lines clear without breaker tripping. Ground faults represent more than 50 percent of all faults in overhead lines.

Ground relays for these systems require high relay sensitivity because the fault current is very low compared to solidly grounded systems. Most ground-fault detection methods use fundamental-frequency voltage and current components. The wattmetric method [2], [3] is a common directional element solution, but its sensitivity is limited to fault resistances no higher than a few kilohms. Other fundamental-frequency methods (such as the admittance method [4], [5]), provide increased sensitivity but require information about all feeders and/or the possibility of making control actions on the Petersen coil. There are also methods that use the steady-state harmonic content of current and voltage to detect ground faults [6], [7]. Another group of methods detects the fault-generated transient components of voltage and current [6], [8]. These methods have limited sensitivity, because high-resistance faults reduce the level of the steady-state harmonics and damp the transient components of voltage and current.

GROUNDING METHODS OF MEDIUM-VOLTAGE DISTRIBUTION NETWORKS

The main goals of system grounding are to minimize equipment voltage and thermal stresses, provide personnel safety, reduce communication system interference, and give assistance in rapid detection and elimination of ground faults.

With the exception of voltage stress, operating a system as ungrounded or resonant grounded restricts ground fault current magnitudes and achieves most of the goals listed above. The drawback of these grounding methods is that they also create fault detection (protection) sensitivity problems. We can create a system grounding that reduces voltage stress at the cost of large fault current magnitudes. However, in such a system the faulted circuit must be de-energized immediately to avoid thermal stress, communication channel interference, and human safety hazards. The disadvantage is that service must be interrupted even for temporary faults.

Ungrounded or Isolated Neutral

In an isolated neutral system (see Figure 1), the neutral has no intentional connection to ground: the system is connected to ground through the line-to-ground capacitances. Single line-to-ground faults shift the system neutral voltage but leave the phase-to-phase voltage triangle intact.

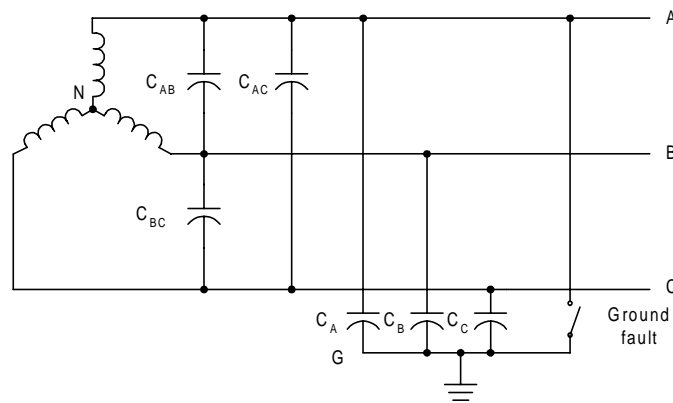


Figure 1 Isolated Neutral System Diagram

For these systems, two major ground fault current magnitude-limiting factors are the zero-sequence line-to-ground capacitance and fault resistance. Because the voltage triangle is relatively undisturbed these systems can remain operational during sustained, low-magnitude faults.

Self-extinction of ground faults in overhead-ungrounded lines is possible for low values of ground fault current. At higher magnitudes of fault current, faults are less likely to self-extinguish at the fault current natural zero-crossing because of the high transient recovery voltage. Later, we discuss how a resonant grounded system damps this recovery voltage rise, thereby increasing the likelihood of causing the ground fault to self-extinguish.

Zero-sequence [9], or three-phase voltage relays can detect ground faults in ungrounded systems. This method of fault detection is not selective and requires sequential disconnection or isolation of the feeders to determine the faulted feeder. A sensitive, directional ground varmetric element is the typical alternative to sequential disconnection [3]. These elements respond to the quadrature component of the dot product of the zero-sequence voltage and current. Later we

introduce a new directional element that uses the measured impedance as the measurand for differentiating forward and reverse ground faults.

Resonant Grounding

In this method of grounding, the system is grounded through a high-impedance reactor, ideally tuned to the overall system phase-to-ground capacitance (see Figure 2). The variable impedance reactor is called a Petersen coil after its inventor. It is also known as an arc-suppression coil or ground-fault neutralizer. The coil is typically connected to the neutral of the distribution transformer or a zigzag grounding transformer. Systems with this type of grounding are often referred to as resonant-grounded or compensated systems. When the system capacitance is matched by the inductance of the coil, the system is fully compensated or at 100 percent tuning. If the reactor inductance does not match the system capacitance, the system is off tuned. It can be over- or undercompensated, depending on the relationship between inductance and capacitance.

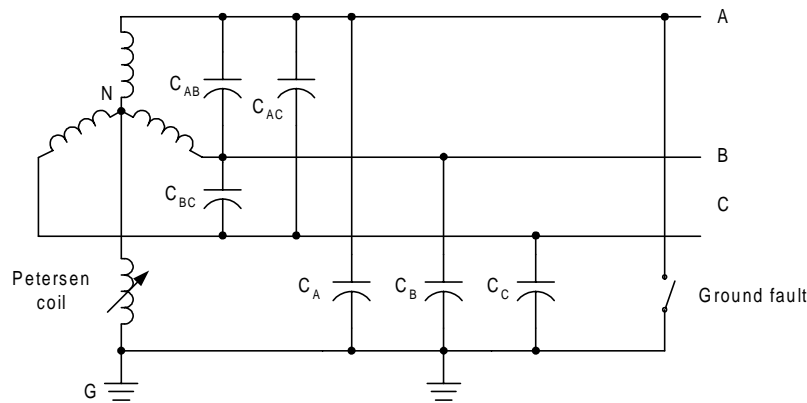


Figure 2 Compensated System

Older installations use a low-cost, fixed value reactor. In these systems the tuning condition (under- or overcompensated) changes with the configuration of the distribution network. Tap-changing reactors permit manual or automatic control of the tuning conditions. Modern installations include a moving-core (plunger) reactor equipped with a control system to provide almost 100 percent tuning for all system-operating conditions. These plunger systems also provide a smooth means of system tuning.

Resonant grounding a system can reduce the ground fault current to about 3 to 10 percent of that for an ungrounded system. For 100 percent tuning, the active coil losses, system harmonics, and system active leakage current determine the fault current magnitude [1]. Residual current compensation methods inject a current through the reactor to the system during the fault, reducing the fault current almost to zero [11].

The arc self-extinction action depends not only on the fault current magnitude, but also on the transient recovery voltage rate after successful arc extinction at the current zero crossing. In compensated systems this voltage recovery time is much slower than in ungrounded systems.

Detecting high-impedance faults in compensated distribution circuits requires a device with a very sensitive residual current input to achieve high sensitivity. The wattmetric directional method (described later in this paper) is the most commonly used type of directional element. However, the ground fault resistive coverage of these elements is limited by the supervisory zero-sequence overvoltage element setting.

Utilities that trip the lines for permanent faults frequently detect the fault by measuring the zero-sequence voltage and then automatically change the system grounding condition. This switching operation is intended to enhance the sensitivity of the selective ground fault protection. The switching operation has an intentional delay of several seconds to allow the compensated system to extinguish the arc for temporary faults. The delay time is set by the thermal rating of the arc-suppression coil (ASC). In some systems [12] the practice is to by-pass the reactor with a single-pole breaker. Another alternative is to connect a resistor in parallel with the Petersen coil or to an auxiliary winding of the Petersen coil. A problem with these methods is that the connection of the resistor reduces the zero-sequence voltage without necessarily significantly increasing the zero-sequence fault current magnitude. The result is that the action taken to increase fault detection sensitivity can decrease the wattmetric ground directional element sensitivity.

UNGROUNDING DISTRIBUTION SYSTEM ANALYSIS

In this section we analyze the steady-state behavior of ungrounded systems in both the phase and the symmetrical component domains.

Three-Phase Analysis

Figure 3 shows a simplified representation of a three-phase ungrounded distribution system. The relay location defines the protected line. All the other distribution lines are lumped in an equivalent line representing the remainder of the distribution system. For simplification in our steady-state analysis, we assume ideal sources operating at nominal frequency, and no load, and disregard line series impedances (resistance and reactance). We justify disregarding load on the basis that all loads for these systems must be connected phase-to-phase and thereby do not generate any zero-sequence unbalance. These assumptions introduce no significant error in the results but greatly simplify the calculations.

In Figure 3, C_{AL} , C_{BL} , and C_{CL} represent the phase-to-ground capacitances of the protected line, and C_{AS} , C_{BS} , and C_{CS} are the phase-to-ground capacitances of the remaining network. We do not represent the phase-to-phase capacitances of the system in Figure 3 because they do not contribute to the residual current and are irrelevant to this analysis.

Using the circuit of Figure 3, we may write:

$$\vec{I}_{AL} + \vec{I}_{BL} + \vec{I}_{CL} + \vec{I}_{AS} + \vec{I}_{BS} + \vec{I}_{CS} = 0 \quad \text{Equation 1}$$

The relay element measures the residual current $3\vec{I}_{0L}$ of the protected line. From Equation 1:

$$3\vec{I}_{0L} = \vec{I}_{AL} + \vec{I}_{BL} + \vec{I}_{CL} = -(\vec{I}_{AS} + \vec{I}_{BS} + \vec{I}_{CS}) \quad \text{Equation 2}$$

We may represent the occurrence of a forward solid A-phase fault in the system of Figure 3 by closing Switch S_F . In this case the fault current I_F equals I_{AL} :

$$I_F = \vec{I}_{AL} = -(\vec{I}_{BL} + \vec{I}_{CL} + \vec{I}_{AS} + \vec{I}_{BS} + \vec{I}_{CS}) \quad \text{Equation 3}$$

From Equation 3, we see that the residual current measured by the relay is actually the residual current supplied by the remainder of the system. This also shows us that if the protected line were the only feeder connected to the bus, the residual current measured by the relay would equal zero (i.e., $3\vec{I}_0 = I_{AL} - (I_{BL} + I_{CL}) = 0$). For this switching configuration, detecting a ground fault is easily accomplished with a simple zero-sequence overvoltage element.

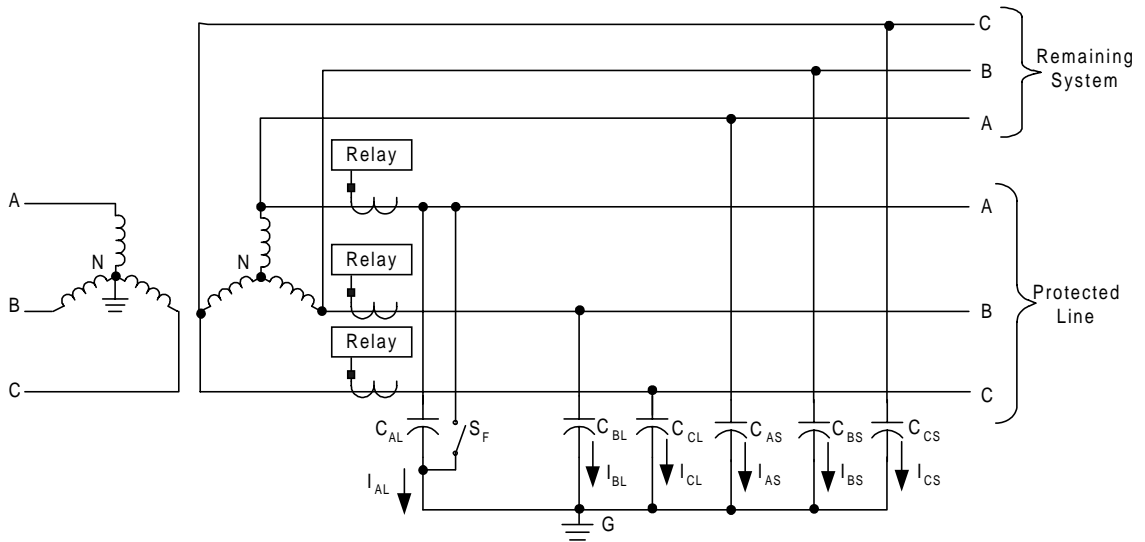


Figure 3 Three-Phase Simplified Representation of an Ungrounded Network

In a symmetrical unfaultered system the residual current for the protected line is zero ($3I_{OL} = 0$) and the system neutral N is at ground potential ($V_{NG} = 0$) (see Figure 4a). Natural system asymmetry produces some neutral current and shifts the system neutral from the ideal ground potential of $V_{NG} = 0$.

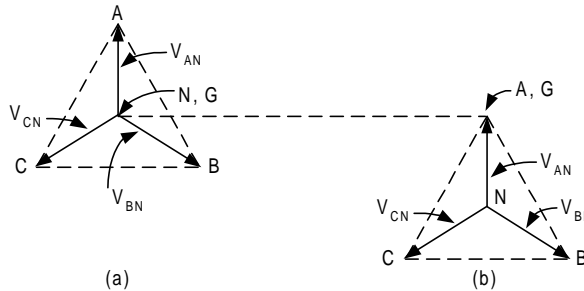


Figure 4 Voltage Phasor Diagrams for the System of Figure 3: (a) Unfaulted System. (b) Faulted System (Solid A-Phase Fault, $R_F=0$)

For a solid A-to-ground fault ($R_F = 0$) in the ideal lossless system, the faulted phase and ground potential are equal (see Figure 4b). The phase-to-ground voltage of the two remaining un-faulted phases equals the phase-to-phase voltage ($V_{BG} = V_{BA}$, $V_{CG} = V_{CA}$) and the neutral-to-ground voltage equals the negative of the source phase-to-neutral voltage corresponding to the faulted phase ($V_{NG} = -V_{AN}$).

Symmetrical Component Analysis

The phase-domain analysis provides an exact representation of the ungrounded system, which is valid even for asymmetrical systems. However, ground fault detection methods are typically based on zero-sequence quantities. It is then also important to outline a symmetrical-component-domain analysis of ungrounded systems operating in steady-state. If we consider that a ground directional relay relying on phase quantities would be supplied by high ratio phase current transformers (CTs), we immediately see that the need to size the phase CT ratio to sustain full load current automatically makes such a design less sensitive than that which can use a lower ratio core-flux summing CT.

The zero-sequence impedance of an ungrounded system has a very high magnitude. This high value permits us to ignore the positive- and negative-sequence impedances without significant loss of accuracy when evaluating single line-to-ground faults. Figure 5 shows an approximate zero-sequence representation of the forward ground fault in the system depicted in Figure 3 (Switch S_F closed). We assume that the system is symmetrical ($C_{AL} = C_{BL} = C_{CL} = C_L$, $C_{AS} = C_{BS} = C_{CS} = C_S$), and consider that the Thevenin voltage (pre-fault voltage at the fault point) is equal to the nominal (phase-to-neutral) system voltage, V_{nom} .

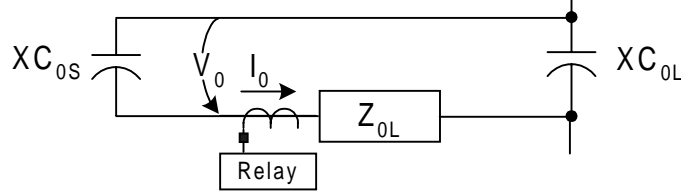


Figure 5 Zero-Sequence Network for the Forward Ground Fault in Figure 3 System

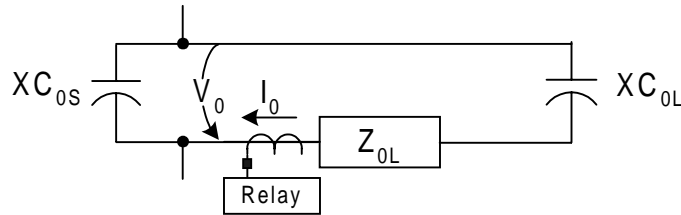
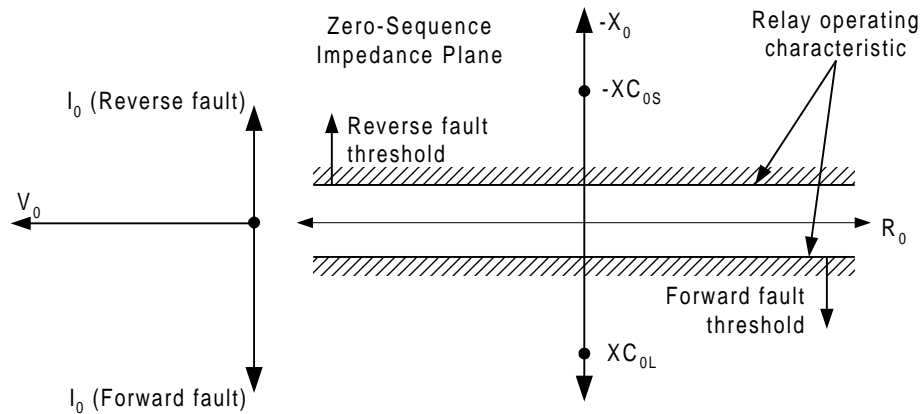


Figure 6 Zero-Sequence Network for the Reverse Ground Fault in Figure 3 System

Note that in Figure 5 the relay measures V_0 across and the current through XC_{0S} , where XC_{0S} is the zero-sequence impedance of the remaining system in Figure 3. Note that in Figure 6 the relay measures V_0 across and the current through the series combination of $(Z_{0L} + XC_{0L})$, where Z_{0L} is the zero-sequence line impedance and XC_{0L} is the distributed line-ground capacitance of the protected line. Thus, the relay measures $-XC_{0S}$ for forward faults and $(Z_{0L} + XC_{0L})$ for reverse faults.

Figure 7a shows the phasor diagram for forward and reverse faults in the system shown in Figure 3. Figure 7b shows a patent pending directional element characteristic for ungrounded systems. The function of a directional element is to determine forward and reverse conditions: i.e., differentiate $-XC_{0S}$ from XC_{0L} . This new element does this with two separately settable thresholds set between these two impedance values. If the measured impedance is above the forward threshold (and all of the supervisory conditionals are met), the fault is declared forward.



a. Zero-Seq. Phasors b. New Impedance-Plane Directional Element Characteristics

Figure 7 New Ground Directional Element Characteristics

System Unbalance Affects Sensitivity

CT inaccuracies could adversely affect directional element sensitivity. Similarly, if the line-ground capacitances are not equal, the system produces standing or un-faulted zero-sequence quantities. Typically these quantities are small but in a very large system, the cumulative effect of unequal capacitances can generate appreciable zero-sequence voltage. To preserve fault resistance sensitivity, a zero-sequence overvoltage element should not be used to supervise the directional element.

Let us review the effect of zero-sequence voltage supervision on ground relaying sensitivity. For this example, assume the end-of-line ground fault shown in Figure 8 delivers 5 mA of secondary current to the relay on a system where the nominal secondary line-neutral voltage is 66.4 V.

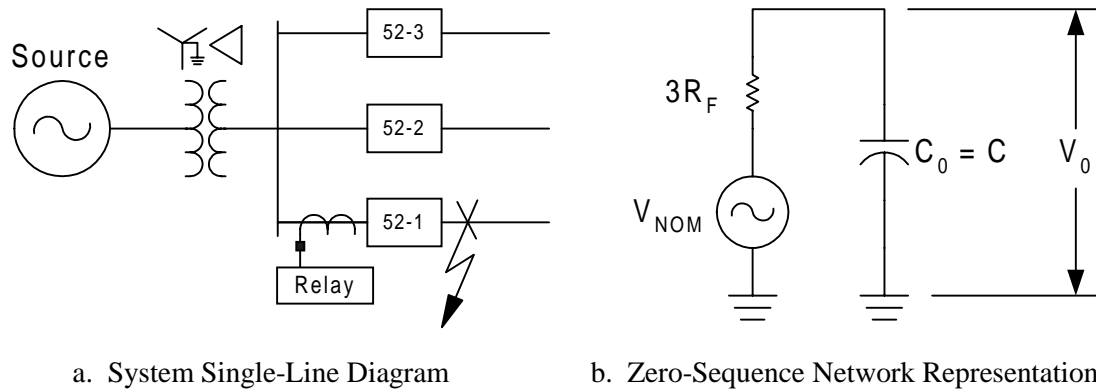


Figure 8 Zero-Sequence Overvoltage Sensitivity Example

From Figure 8b:

$$V_0 = I_0 \cdot \frac{1}{j\omega \cdot C} \quad \text{Equation 4}$$

$$C = \frac{I_0}{j\omega \cdot V_0} \quad \text{Equation 5}$$

Let us next set the minimum V_0 at 2 V for a starting place to calculate C in Equation 5 given a minimum I_0 of 5 mA. Doing this for a 60 Hz system, then $C = 6.63 \mu\text{F}$. Next let us evaluate another similar system but with Breaker 3 (52-3) closed to increase C . If this new system only produced 5 mA secondary and the capacitance equaled $13.26 \mu\text{F}$ then $|V_0| = 1 \text{ V}$ secondary. Given a $3V_0$ threshold of 6 V secondary, the relay using supervisory zero-sequence overvoltage would not operate due to an incorrect supervisory setting.

Looking again at Figure 8, we can calculate R_F as:

$$R_F = \frac{V_{\text{NOM}} - V_0}{3 \cdot I_0} \quad \text{Equation 6}$$

From Equation 6, raising the V_0 threshold decreases the numerator and thereby decreases the available fault resistance coverage (or sensitivity) for a given minimum magnitude of I_0 . An alternative to $3V_0$ security supervision is to require the ratio of residual current to positive-sequence current to exceed a minimum scalar threshold value. The benefit of this supervision is that the minimum sensitivity of each feeder relay is not dependent upon the total system unbalance.

NEW UNGROUNDED DIRECTIONAL ELEMENT PERFORMANCE

To demonstrate the performance of this new ground directional element for ungrounded systems we modeled a distribution power system using EMTP (Electromagnetics Transients Program). Figure 9 shows the simulated system and the placement of an A-ground fault with $R_F = 10 \text{ k}\Omega$. All of the seven feeders are overhead lines with differing lengths.

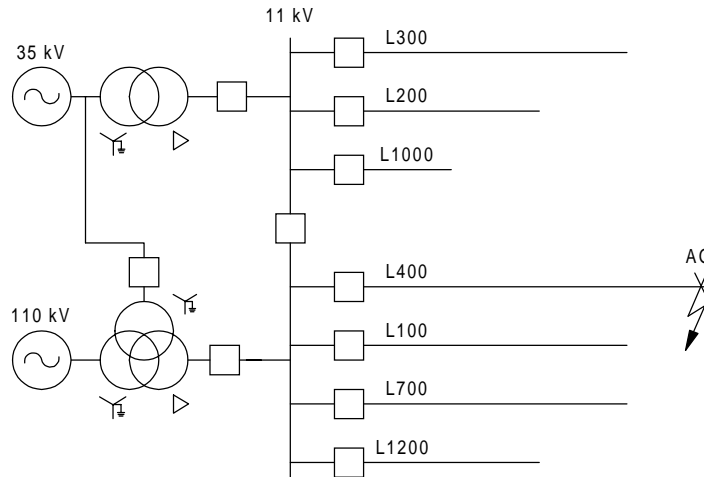


Figure 9 Ungrounded System Single-Line Diagram

Figure 10 shows the zero-sequence voltage and current presented to the relay on Feeder L400: fault inception is at cycle 18. From the upper plot ($V_0 = 1.5 \text{ v}$) notice that the high R_F restricted the available $3V_0$ to only 4.5 V secondary.

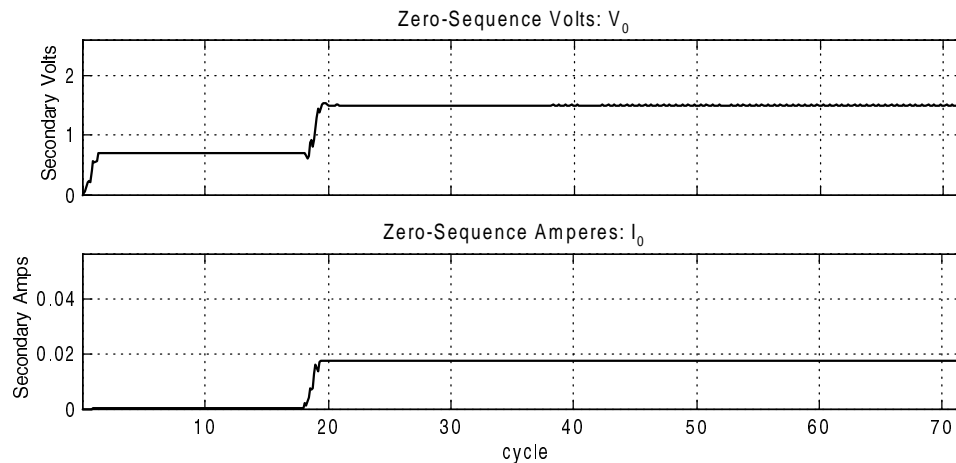


Figure 10 Line L400 Zero-Sequential Voltage and Current for End-of-Line AG Fault, $R_F = 10 \text{ k}\Omega$

Figure 11 shows the new directional element calculation results for this fault (the results prior to fault inception are erroneous because there is no pre-fault zero-sequence current). Note that the forward directional decision is very stable after the current magnitude rises above the minimum threshold of 5 mA (indicated by the thicker line in the plot).

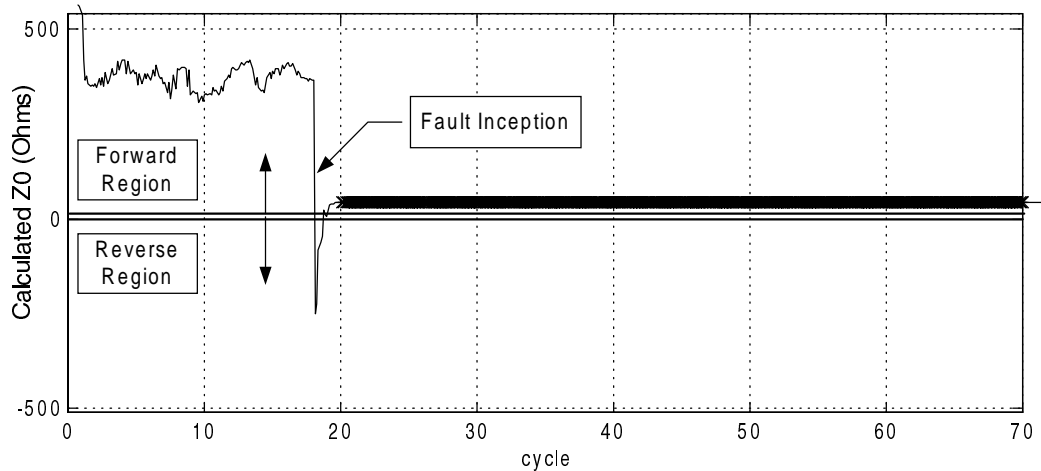


Figure 11 Line L400 Relay New Ungrounded System Directional Element Calculates Forward Direction Independent of Fault Resistance (R_F)

COMPENSATED DISTRIBUTION SYSTEM ANALYSIS

Operation analysis of compensated distribution networks is important for identifying the available alternatives for ground fault detection in these systems. In this section we analyze the steady-state behavior of compensated systems both in the phase and in the symmetrical component domains. We also summarize the harmonic content and the transient behavior of these systems.

Three-Phase Analysis

Figure 12 shows a simplified representation of a three-phase compensated distribution system in which all the feeders appear in a single circuit. Again, for simplification in our steady-state analysis, we assume ideal sources operating at nominal frequency, and no load, and disregard line series impedances (resistance and reactance).

We represent the Petersen coil in Figure 12 as a parallel combination of an inductance (L_N) and a resistance (R_N). This configuration is the equivalent parallel circuit of the coil (the coil inductance and resistance are actually in series). This same combination may also represent the equivalent circuit for the case in which we connect a resistor in parallel with the Petersen coil or to an auxiliary winding of the coil. In Figure 12, C_A , C_B , and C_C represent the phase-to-ground capacitances of the network. Resistances R_A , R_B , and R_C represent the phase-to-ground leakage resistances. Both the capacitance and leakage resistance values could be different for the different phases (especially for overhead lines), which means that the system may be asymmetrical. Typical values of the phase-to-ground leakage resistances are in the order of ten to 20 times the phase-to-ground capacitive reactances [2]. We do not represent the phase-to-phase capacitances of the system in Figure 12 because they do not contribute to the residual current and are irrelevant to this analysis.

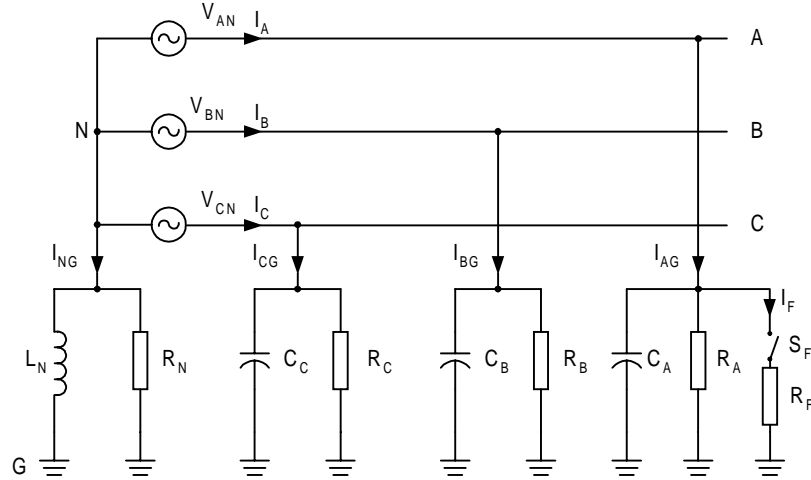


Figure 12 Three-Phase Simplified Representation of a Resonant Grounded Network

We may represent the occurrence of an A-phase fault in the system of Figure 12 by closing Switch S_F . R_F represents the fault resistance. For solid faults $R_F = 0$.

To discuss the basic principles of resonant grounding [13] we can disregard all active losses in the equivalent circuit of Figure 12 ($R_N = R_A = R_B = R_C \rightarrow \infty$). Using the circuit of Figure 12, we can calculate the current through the system grounding I_{NG} using the phase currents as as:

$$\vec{I}_{NG} + \vec{I}_{AG} + \vec{I}_{BG} + \vec{I}_{CG} = 0 \quad \text{Equation 7}$$

$$\vec{I}_{NG} = -(\vec{I}_{AG} + \vec{I}_{BG} + \vec{I}_{CG}) \quad \text{Equation 8}$$

In a symmetrical unfaultered system the neutral current is zero ($I_{NG} = 0$) and the system neutral N is at ground potential ($V_{NG} = 0$), similar to that of the ungrounded system voltage phasor diagram shown in Figure 4(a). Natural system asymmetry produces some neutral current and shifts the system neutral from the ideal ground potential of $V_{NG} = 0$. For a solid A-to-ground fault ($R_F = 0$) in the ideal lossless system, the faulted phase and ground potential are equal. The phase-to-ground voltage of the two remaining un-faulted phases equals the phase-to-phase voltage ($V_{BG} = V_{BA}$, $V_{CG} = V_{CA}$) and the neutral-ground voltage equals the negative of the source phase-to-neutral voltage corresponding to the faulted phase ($V_{NG} = -V_{AN}$).

For the solid fault in Figure 12, calculate the total fault current, I_F :

$$\vec{I}_F = \vec{I}_{AG} = -\vec{I}_{NG} - (\vec{I}_{BG} + \vec{I}_{CG}) \quad \text{Equation 9}$$

Note that I_{NG} is 180° out-of-phase with respect to $(I_{BG} + I_{CG})$ in the ideal lossless system. By selecting the appropriate Petersen coil inductance, we can theoretically reduce the fault current to zero. This is the tuning or compensation condition, in which the system is in parallel resonance:

$$|\vec{I}_{NG}| = |\vec{I}_{BG} + \vec{I}_{CG}| \quad \text{Equation 10}$$

For an off-tuned system (i.e., not 100 percent tuned), the two possible operating conditions are:

$$|\vec{I}_{NG}| > |\vec{I}_{BG} + \vec{I}_{CG}| \quad (\text{overcompensated system}) \quad \text{Equation 11}$$

$$|\vec{I}_{NG}| < |\vec{I}_{BG} + \vec{I}_{CG}| \quad (\text{undercompensated system}) \quad \text{Equation 12}$$

In a system with losses, the 100 percent tuning condition does not result in a zero-ampere fault condition. For these systems the coil and system active losses, and the amount of R_F determine the ground fault current magnitude.

If $R_F \neq 0$, the current through the fault is only a portion of the faulted phase current (i.e., $I_F \neq I_{AG}$ for an A-phase fault). We can represent the fault inception as a change in the faulted phase admittance [13], [14]. In this case the magnitude of the neutral voltage shift as a result of the fault is less than the source phase-to-neutral voltage ($V_{NG} < V_{AN}$).

The normalized neutral-to-ground voltage [11], [13] for the system of Figure 12 is given by:

$$\frac{\vec{V}_{NG}}{V_{nom}} = -\frac{\vec{Y}_A + a^2\vec{Y}_B + a\vec{Y}_C}{\vec{Y}_N + \vec{Y}_A + \vec{Y}_B + \vec{Y}_C} \quad \text{Equation 13}$$

Where V_{nom} is the nominal system voltage, $a = 1 \angle 120^\circ$, $a^2 = 1 \angle -120^\circ$, and

$$\vec{Y}_A = G_A + jB_A = \frac{1}{R_A} + j\omega C_A \quad (\text{A-phase-to-ground admittance}) \quad \text{Equation 14}$$

$$\vec{Y}_N = G_N + jB_N = \frac{1}{R_N} + \frac{1}{j\omega L_N} \quad (\text{Neutral admittance}) \quad \text{Equation 15}$$

$$R_N = \frac{R^2 + \omega^2 L^2}{R} \quad \text{Equation 16}$$

$$L_N = \frac{R^2 + \omega^2 L^2}{\omega^2 L} \quad \text{Equation 17}$$

where R and L are the Petersen coil resistance and inductance, respectively.

For the faulted system (Switch S_F of Figure 12 closed), all parameters remain unchanged except the A-Phase admittance (Y_A). We represent Y_A for the faulted system as:

$$\vec{Y}_A = \frac{1}{R_F} + \frac{1}{R_A} + j\omega C_A \quad \text{Equation 18}$$

As a result, the fault changes both the magnitude and phase of the neutral-ground voltage V_N . However, the phase changes are not a clear indicator of the fault, and the magnitude changes could be very small or even negative for high-resistance faults. As a result, faults can enhance system balance instead of perturbing it. This represents a limit to the sensitivity of the fault detection based on the magnitude of the neutral-to-ground voltage. The variation of this voltage (incremental neutral-to-ground voltage) is a better indicator of the fault. The value of this voltage is free from the pre-fault normal system unbalance; however, the voltage could be affected by system switching operations (connection or disconnection of distribution lines), by tap-changing operations, or by resistor insertion in the Petersen coil [13].

Symmetrical Component Analysis

The phase-domain analysis provides an exact representation of the compensated system, which is valid even for asymmetrical systems. However, ground fault detection methods are typically based on zero-sequence quantities. So, it is also important to outline a symmetrical-component-domain analysis of compensated systems operating in steady-state.

The zero-sequence impedance of a compensated system has a very high magnitude. This high value permits us to ignore the positive- and negative-sequence impedances without significant loss of accuracy when evaluating single line-to-ground faults. Thus, we represent the ground fault by connecting an equivalent Thevenin source in series with a resistance at the point of fault

in the zero-sequence network. Figure 13 shows an approximate zero-sequence representation of a ground fault in the system depicted in Figure 12. We assume that the system is symmetrical ($C_A = C_B = C_C = C$), disregard the leakage resistances ($R_A = R_B = R_C \rightarrow \infty$), and consider that the Thevenin voltage (pre-fault voltage at the fault point) is equal to the nominal (phase-to-neutral) system voltage, V_{nom} .

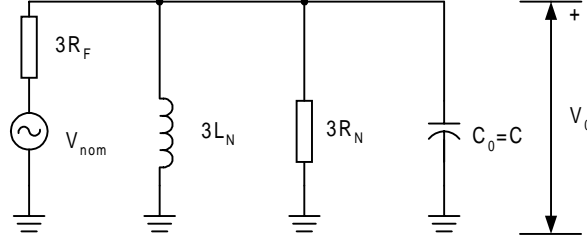


Figure 13 Zero-Sequence Representation of a Ground Fault in Figure 12 System

From Figure 13 we obtain:

$$\frac{\vec{V}_0}{V_{nom}} = \frac{1}{1 + \frac{R_F}{R_N} + j3R_F \left(\omega C - \frac{1}{3\omega L_N} \right)} \quad \text{Equation 19}$$

For ground faults the system zero-sequence voltage equals the neutral-to-ground voltage [10]. Then, Equation 19 is the zero-sequence version of Equation 13 for a symmetrical system if we disregard leakage resistances.

Figure 14a shows a single-line diagram of a compensated radial distribution system in which the relay location defines the protected line. All of the other distribution lines are lumped in an equivalent impedance representing the remainder of the distribution system.

Figure 14b is an approximate zero-sequence representation of the system. C_{0L} and R_{0L} are the protected line zero-sequence capacitance and leakage resistance, respectively. C_{0S} and R_{0S} are the corresponding values for the remainder of the system. In this case $C_0 = C_{0L} + C_{0S}$ and $1/R_0 = 1/R_{0L} + 1/R_{0S}$, where C_0 and R_0 are the system zero-sequence capacitance and leakage resistance, respectively.

Again, we represent the fault by connecting an equivalent Thevenin source in series with a resistance. In Figure 14b we close Switch S_F to represent a ground fault on the protected line (forward fault direction from the perspective of the relay) and close Switch S_R to represent a ground fault elsewhere in the system (reverse direction fault).

We may also approximately represent system unbalance by connecting an equivalent Thevenin source in series with an impedance in the zero-sequence network. In Figure 15a, Z_{LU} represents the unbalance of the protected line and Z_{SU} is the unbalance impedance corresponding to the rest of the system. At the relay side the unbalance includes the primary system neutral asymmetry and the additional unbalance introduced by the current transformers.

In the typical residual connection of the relay to three phase current transformers, CTs, the measurable zero-sequence current is corrupted by CT errors; the CT phase-angle error is particularly influential in this case. The Holmgreen connection of the CTs is a residual connection of the relay to phase CTs that are specially matched to reduce the residual current measurement error.

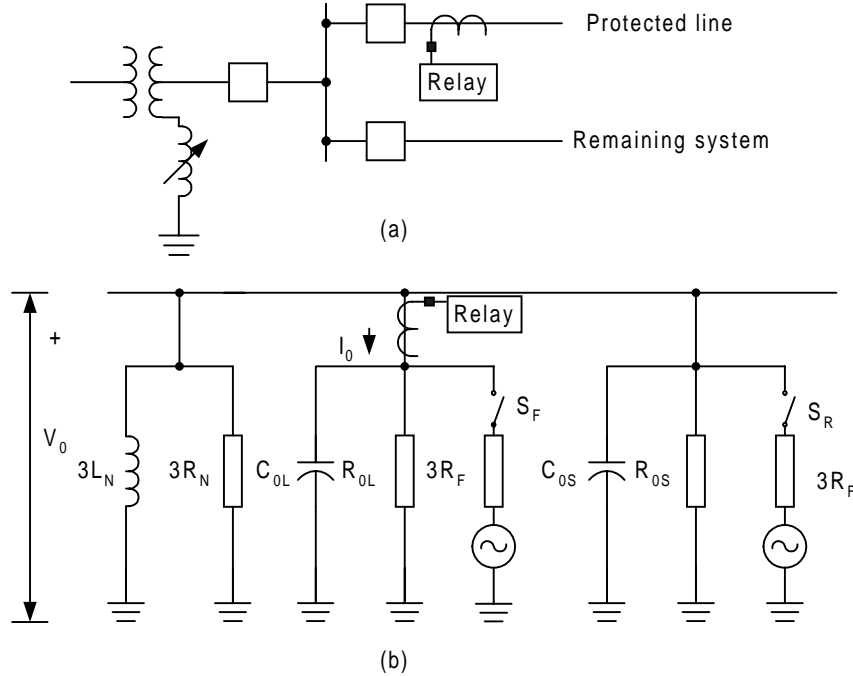


Figure 14 Compensated Distribution System. (a) Single-Line Diagram. (b) System Zero-Sequence Network

By far the best solution is the flux-summation or window-type CT (because it transforms the zero-sequence current directly and therefore does not include the cumulative error of the phase CTs). In addition, the CT ratio may be as low as 10:1, thus providing a significant increase in secondary current delivered to the protective relay. (Hence, increasing the zero-sequence current means more sensitivity for ground faults.)

It is possible to determine the unbalance impedances Z_{LU} and Z_{SU} or their corresponding admittances Y_{LU} and Y_{SU} . The admittance method for sensitive ground fault detection in compensated distribution circuits [4] requires the protective instruments to calculate these admittance values for the pre-fault system for use as a reference. The same calculation is also the reference for a residual current compensation method in resonant systems [11]. To calculate the unbalance admittances, you must have system information for two different tuning conditions. Typically, this means the protective instrument must control the Petersen coil. An obvious restriction to this requirement is that the protective instrument must be located within the substation, unless we include fast and secure external communications in the protection scheme.

A new approach to this problem is to exclude the effect of the unbalance from the zero-sequence network by using incremental (or delta) quantities [15]. The advantages of this method are that it does not require Petersen coil control and it uses information from the protected line. Thus, the new type of protective relay can be located elsewhere in the system without the need for dedicated communications channels. The incremental zero-sequence voltage (ΔV_0) and current (ΔI_0) are:

$$\Delta \vec{V}_0 = \vec{V}_{0, \text{FAULT}} - \vec{V}_{0, \text{PRE-FAULT}} \quad \text{Equation 20}$$

$$\Delta \vec{I}_0 = \vec{I}_{0, \text{FAULT}} - \vec{I}_{0, \text{PRE-FAULT}} \quad \text{Equation 21}$$

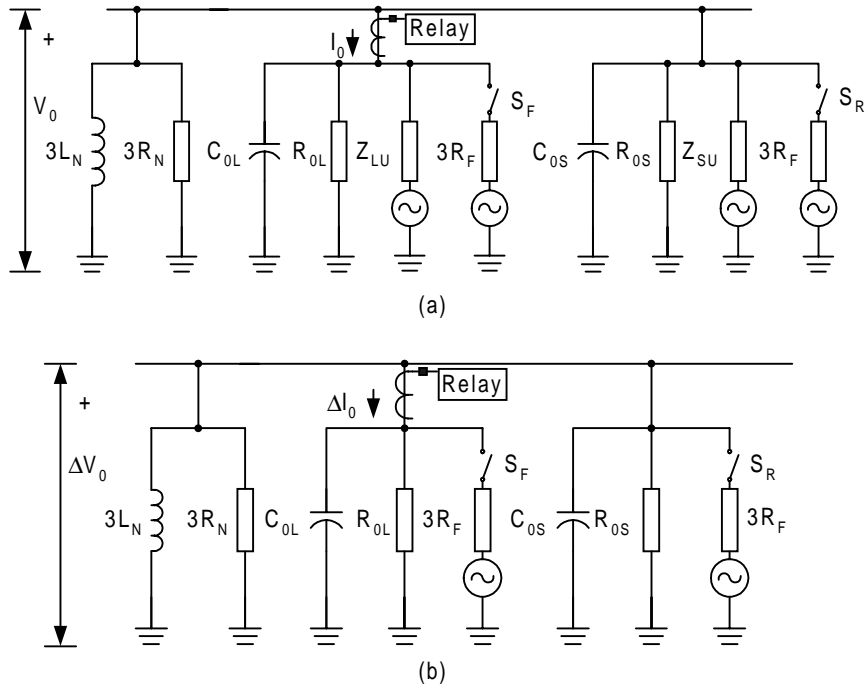


Figure 15 Zero-Sequence Network for the System of Figure 14a Considering System Unbalance. (a) Total Quantities. (b) Incremental Quantities

Figure 15b depicts the zero-sequence system network for incremental quantities. Note that it only shows those components necessary for calculating fault quantities. The results are independent from the natural system asymmetry and from CT errors. The latter feature permits a relay with this new means of ground fault detection to be used with conventional CTs. While the incremental quantities do reduce the zero-sequence current measurement error, this method cannot overcome the problem of extremely low zero-sequence current being presented to the relay because of the large ratios used for the phase CTs.

Ground Faults in Compensated Distribution Networks

The self-extinction mechanism for arcing ground faults in cable lines is not as effective as in overhead lines because cable insulation breakdown is generally definitive. Even if the arc self-extinguishes during the current zero-crossings, the damaged insulation fails again when the instantaneous phase-to-ground voltage reaches a level higher than the damaged dielectric withstand level. The result is a restriking fault. Restriking ground faults produce repetitive overvoltages in the un-faulted phases that can eventually lead to these phases faulting to create a cross-country fault. Given the low probability of self-clearing, many utilities trip (without reclosing) cable distribution lines when the protection detects a ground fault. Another solution is to introduce residual current compensation in the Petersen coil control system [11]. This system reduces the ground fault current to zero, thus reducing the restriking mechanism. It is then possible to operate the system with a faulted cable.

In summary, the basic types of ground faults in compensated distribution networks are self-clearing faults, restriking faults, and sustained faults. Restriking faults are self-clearing faults that become repetitive as a result of permanent insulation breakdown. Sustained faults include all permanent faults and some temporary faults not cleared by the arc-extinction mechanism of resonant grounding.

GROUND FAULT DETECTION METHODS FOR COMPENSATED DISTRIBUTION NETWORKS

Ground fault detection methods for compensated distribution networks may be classified according to the components of the relay input signals that they use to detect the fault. For this discussion, we grouped the methods into the following four classifications:

1. Fundamental frequency
2. Harmonic based
3. Transient-components based
4. Other

Methods included in the first two groups use information corresponding to the steady-state of the faulted distribution network; some of these methods also require steady-state pre-fault information. Group 3 methods use information on the transient process generated by the fault. Group 4 includes methods that basically use steady-state information, but require control actions on the Petersen coil (current injection or temporary detuning).

In this section we describe the different fundamental-frequency ground fault detection methods in compensated systems.

These methods generally use the fundamental-frequency components of the zero-sequence voltage and/or current as relay input information. However, some methods also require information on the fundamental-frequency components of the phase-to-ground voltages.

Voltage Detection

Ground faults in compensated systems reduce the line-ground voltage of the faulted phase and shift the system neutral, increasing the system zero-sequence voltage in most cases. Both the zero-sequence voltage and the phase-to-ground voltages have been used as indicators of ground faults [2], [9]. However, for high-resistance faults the voltage change could be very small. Some researchers have proposed [13] using the incremental zero-sequence voltage in order to increase the detection sensitivity. Even this method may fail for high-resistance faults, because in some cases the ground fault balances the system and reduces the zero-sequence voltage [5].

Another problem is that the zero-sequence voltage has almost the same value in the entire distribution network. The voltage drops caused by the zero-sequence currents circulating through the zero-sequence impedances of the lines and transformers are very small as compared to the voltage drops across the phase-to-ground system impedances. In other words, voltage-based ground fault detection methods are not selective. They detect the ground fault, but do not determine the faulted element. It is then necessary to manually disconnect and reclose every feeder of the substation to locate the fault. These short service interruptions represent a power quality problem. For this reason, voltage detection is typically used as a starting function of selective ground fault detection methods in compensated distribution networks.

Wattmetric Method

Selective ground-fault detection methods require current information. Zero-sequence directional relays are a classical solution [2], [3], [9]. For ungrounded networks the relay responds to the quadrature (imaginary) component of the dot product of the zero-sequence voltage and current (varmetric relay) [3], [9]. For compensated networks the relay uses the in-phase (real) component of that dot product (wattmetric relay) [2], [3].

We may analyze these fault-detection methods, referring to the system depicted in Figure 15a. Figure 15b shows the approximate zero-sequence representation for the balanced version of the system.

For a forward fault (Switch S_F closed and Switch S_R open in Figure 15b) the relay zero-sequence current, \bar{I}_0 , is:

$$\bar{I}_0 = -\bar{V}_0 \left[\left(\frac{1}{R_{0S}} + \frac{1}{3R_N} \right) + j \left(\omega C_{0S} - \frac{1}{3\omega L_N} \right) \right] \quad (\text{Forward fault}) \quad \text{Equation 22}$$

For a reverse fault (Switch S_F open and Switch S_R closed in Figure 15b) the relay current is:

$$\bar{I}_0 = \bar{V}_0 \left(\frac{1}{R_{0L}} + j\omega C_{0L} \right) \quad (\text{Reverse fault}) \quad \text{Equation 23}$$

In ungrounded systems ($R_N = L_N \rightarrow \infty$) Equation 23 does not change. For ungrounded systems Equation 22 takes the form:

$$\bar{I}_0 = -\bar{V}_0 \left(\frac{1}{R_{0S}} + j\omega C_{0S} \right) \quad (\text{Forward fault}) \quad \text{Equation 24}$$

In compensated networks the direction of the quadrature component of I_0 may change for forward faults depending on the system tuning conditions (see Equation 22). This direction depends on the values of the equivalent zero-sequence capacitance of the unfaulted lines, C_{0S} , and the zero-sequence parallel-equivalent inductance of the Petersen coil, $3L_N$. Figure 16 shows the phasor diagram for ground faults in compensated networks. For reverse faults I_0 exhibits the same behavior as in ungrounded systems. For forward faults the angular position of I_0 with respect to V_0 may vary widely. The quadrature component of I_0 is negative (as in ungrounded systems) in an undercompensated (undertuned) network, and it is positive in an overcompensated network. On the other hand, the sign of the in-phase (active) component of I_0 is always positive for reverse faults and negative for forward faults. We may use a wattmetric directional relay having the following output quantity (* = complex conjugate):

$$W = \text{Re} \left[\bar{V}_0 \cdot \bar{I}_0^* \right] = V_0 I_0 \cos \phi_0 \quad \text{Equation 25}$$

We may compare W with positive and negative thresholds ($+\epsilon$ and $-\epsilon$). Then $W < -\epsilon$ indicates a forward fault and $W > \epsilon$ indicates a reverse fault. The wattmetric relay operating characteristic is also represented in Figure 16.

Figure 17 depicts a simplified logic diagram for a wattmetric element. The active component of I_0 is very low during ground faults, so the relay should be very sensitive (ϵ should be very small). To avoid relay misoperations during normal system conditions, it is necessary to add a starting function responding to the magnitude of V_0 . Then wattmetric relay sensitivity is determined by the V_0 element sensitivity. The threshold V_0 value should be greater than the value of V_0 for normal system unbalances. A typical setting is 20 percent of the nominal system voltage.

The wattmetric method has been in use for many years in compensated systems. It is simple, secure, and dependable for low-resistance ground faults. However, the requirement of V_0 detection limits the sensitivity of the wattmetric method for high-resistance faults. Another drawback is that the method is very sensitive to CT accuracy problems. In the typical residual connection of the relay to three CTs, CT angle errors may produce a change in the sign of the

element output, W . Careful calibration of the CTs is a possible solution, but flux-summation CTs are strongly recommended for wattmetric relays.

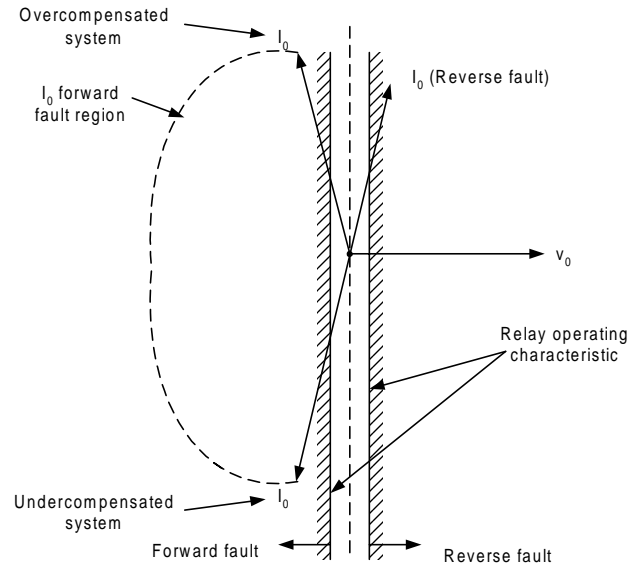


Figure 16 Typical Phasor Diagram for Ground Faults and Relay Operating Characteristics in a Compensated Network (Wattmetric Relay)

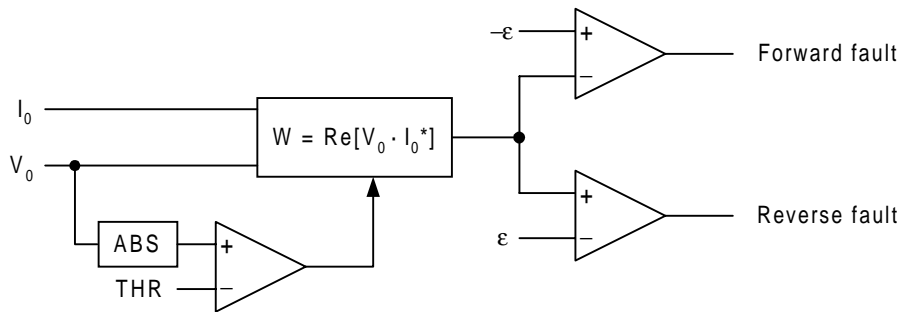


Figure 17 Simplified Logic Diagram of a Wattmetric Relay Element

Some utilities use zero-sequence voltage relays to detect ground faults in compensated systems and automatically connect a resistor in parallel with the Petersen coil or to an auxiliary winding of the coil. For high-resistance faults, connecting the resistor reduces the zero-sequence voltage without necessarily increasing the zero-sequence fault current; the output of the wattmetric element actually decreases. The other limitation of this method is reduced sensitivity resulting from the use of the zero-sequence voltage for fault detection.

Phase Comparison of Zero-Sequence Currents

During normal operating conditions of a distribution network the phase shift between the zero-sequence currents of all feeders is small. For a ground fault the zero-sequence current of the faulted feeder shifts its phase angle with respect to the currents of the remaining feeders. We may use this fact to detect the faulted feeder. This method [17] calculates the phase differences between the zero-sequence currents of all pairs of feeders and forms a matrix with these values. For a healthy system all matrix elements are near zero. For a ground fault we see an increase in the values of all matrix elements involving the faulted feeder. A simple searching process determines the faulted feeder.

This method requires a difficult-to-set angle threshold to discriminate between the phase-shifts caused by normal system unbalance and those created by ground faults. It requires information from all feeders.

NEW FAULT DETECTION METHODS FOR COMPENSATED DISTRIBUTION NETWORKS

Fundamental-frequency components of current and voltage provide the most reliable and significant information for detecting high-resistance faults in compensated distribution networks. The harmonic content of the ground-fault current is small and variable, especially for high-resistance faults. The transient components of current and voltage are severely damped for high-resistance faults. Methods that need some type of control on the Petersen coil or current injection provide high sensitivity, but require costly equipment.

All known fundamental-frequency methods that provide high sensitivity require information on all feeders and/or some sort of control on the Petersen coil or current injection. For example, the admittance method and the method based on the phase comparison of the zero-sequence currents require information from all feeders. The admittance method also needs control on the Petersen coil or current injection. The wattmetric method is a good solution for low-resistance faults, but has sensitivity limitations in detecting high-resistance faults.

We may provide high-resistance coverage by measuring the zero-sequence conductance or the zero-sequence resistance in the protected feeder. These new methods use only information from the feeder and do not require control on the Petersen coil or current injection. The methods are suitable for stand-alone, high-sensitivity devices that can be located at any point of a distribution network. A typical application is in the control unit of an automatic recloser.

Traditional Conductance Method

Next we use the distribution network depicted in Figure 15a to outline the conductance method. First we disregard the system unbalance. Figure 15b shows the zero-sequence network for the balanced system. Equations 26 and 27 describe the zero-sequence relay current, I_0 , for forward and reverse faults. We reproduce these equations here for convenience:

$$\bar{I}_0 = -\bar{V}_0 \left[\left(\frac{1}{R_{OS}} + \frac{1}{3R_N} \right) + j \left(\omega C_{OS} - \frac{1}{3\omega L_N} \right) \right] \quad (\text{Forward fault}) \quad \text{Equation 26}$$

$$\bar{I}_0 = \bar{V}_0 \left(\frac{1}{R_{OL}} + j\omega C_{OL} \right) \quad (\text{Reverse fault}) \quad \text{Equation 27}$$

We may then use Equations 28 and 29 to calculate the apparent zero-sequence admittance, Y_0 , measured by the relay for forward and reverse faults:

$$\bar{Y}_0 = \frac{\bar{I}_0}{\bar{V}_0} = - \left[\left(\frac{1}{R_{OS}} + \frac{1}{3R_N} \right) + j \left(\omega C_{OS} - \frac{1}{3\omega L_N} \right) \right] \quad \text{Equation 28}$$

$$\bar{Y}_0 = \frac{\bar{I}_0}{\bar{V}_0} = \frac{1}{R_{OL}} + j\omega C_{OL} \quad (\text{Reverse fault}) \quad \text{Equation 29}$$

Taking the real part from Equations 28 and 29, we can determine the conductance, G_0 , measured by the relay for both faults:

$$G_0 = \operatorname{Re} \left[\frac{\bar{I}_0}{\bar{V}_0} \right] = - \left(\frac{1}{R_{OS}} + \frac{1}{3R_N} \right) = -(G_{OS} + G_{ON}) \quad (\text{Forward fault}) \quad \text{Equation 30}$$

$$G_0 = \operatorname{Re} \left[\frac{\bar{I}_0}{\bar{V}_0} \right] = \frac{1}{R_{OL}} = G_{OL} \quad (\text{Reverse fault}) \quad \text{Equation 31}$$

where $G_{OL}=1/R_{OL}$ is the zero-sequence leakage conductance of the protected feeder, $G_{OS}=1/R_{OS}$ is the equivalent zero-sequence leakage resistance of the remaining feeders, and $G_{ON}=1/3R_N$ is the zero-sequence conductance corresponding to the parallel equivalent of the Petersen coil.

We may use a conductance element responding to the real part of the I_0/V_0 ratio to detect ground faults. The element compares the measured conductance, G_0 , with positive, ϵ , and negative, $-\epsilon$, thresholds. Then $G_0 < -\epsilon$ indicates a forward fault, and $G_0 > \epsilon$ indicates a reverse fault. For forward faults (see Equation 30) the conductance element measures the equivalent inductance behind the relay. This includes the conductance of the remaining feeders and that of the parallel equivalent of the Petersen coil. For reverse faults the conductance element measures the conductance of the protected feeder.

The conductance method is inherently directional. It responds to the sign of the real part of the measured admittance. This is an advantage compared to the admittance method, which responds to the magnitude of the admittance and does not use valuable phase information.

The conductance method responds to the current/voltage ratio. Its output is relatively independent of the magnitudes of the zero-sequence current and voltage. This is an advantage compared to the wattmetric method, which fails to detect high-resistance faults caused by low values of both V_0 and I_0 . Recall that the wattmetric element is a product-type element and the conductance element is a ratio-type element.

Incremental Conductance Method

The traditional conductance method described above works well in balanced systems and for low CT errors (using flux-summation CTs, for example). System and CT unbalances introduce errors in the measured conductance and thereby limits sensitivity. A solution to this problem is the incremental conductance method. We use the incremental zero-sequence current, ΔI_0 , and voltage, ΔV_0 , to calculate an incremental zero-sequence conductance, ΔG_0 :

$$\Delta G_0 = \operatorname{Re} \left[\frac{\Delta \bar{I}_0}{\Delta \bar{V}_0} \right] \quad \text{Equation 32}$$

Figure 15b shows the zero-sequence network of the Figure 15a system with incremental quantities. Note that this circuit is equal to that of Figure 14b for a balanced system. Then, the measured values of ΔG_0 coincide with those given for G_0 by Equations 30 and 31:

$$\Delta G_0 = - \left(\frac{1}{R_{OS}} + \frac{1}{3R_N} \right) = -(G_{OS} + G_{ON}) \quad (\text{Forward fault}) \quad \text{Equation 33}$$

$$\Delta G_0 = \frac{1}{R_{OL}} = G_{OL} \quad (\text{Reverse fault}) \quad \text{Equation 34}$$

The incremental conductance element compares the measured incremental conductance (real part of the incremental current/voltage ratio) with positive and negative thresholds to discriminate forward faults from reverse faults. It is a directional, ratio-type method that is not affected by system unbalance and that can be used with conventional CTs. Figure 18 depicts the measured incremental conductances for forward and reverse faults and the incremental conductance relay operating characteristic (two parallel straight lines).

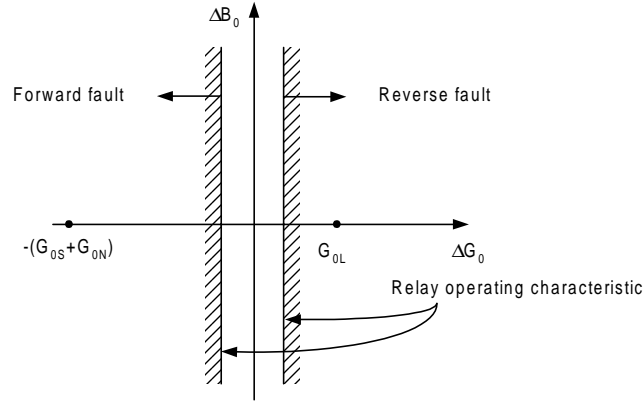


Figure 18 Incremental Conductance Element Operating Characteristic

Adaptive Conductance Method

The incremental conductance method requires the calculation of the incremental values of the zero-sequence current and voltage. Another possibility is to calculate an incremental conductance as:

$$\Delta G_0 = G_{0, \text{FAULT}} - G_{0, \text{PRE-FAULT}} \quad \text{Equation 35}$$

Where:

$$G_{0, \text{FAULT}} = \text{Re} \left[\frac{\vec{I}_{0, \text{FAULT}}}{\vec{V}_{0, \text{FAULT}}} \right] \quad \text{Equation 36}$$

$$G_{0, \text{PRE-FAULT}} = \text{Re} \left[\frac{\vec{I}_{0, \text{PRE-FAULT}}}{\vec{V}_{0, \text{PRE-FAULT}}} \right] \quad \text{Equation 37}$$

For a forward fault:

$$\Delta G_0 = G_{0, \text{FAULT}} - G_{0, \text{PRE-FAULT}} < -\epsilon \quad \text{Equation 38}$$

$$G_{0, \text{FAULT}} < G_{0, \text{PRE-FAULT}} - \epsilon \quad \text{Equation 39}$$

For a reverse fault:

$$\Delta G_0 = G_{0, \text{FAULT}} - G_{0, \text{PRE-FAULT}} > \epsilon \quad \text{Equation 40}$$

$$G_{0, \text{FAULT}} > G_{0, \text{PRE-FAULT}} + \epsilon \quad \text{Equation 41}$$

Equations 36 and 37 suggest an adaptive conductance method. We may compare the present value of the zero-sequence conductance, $G_0[k]$, with an adaptive reference value. This reference is the conductance value calculated n samples before the present value, $G_0[k-n]$. Then, for a forward fault (see Equation 39):

$$G_0[k] < G_0[k-n] - \epsilon \quad \text{Equation 42}$$

For a reverse fault (see Equation 41):

$$G_0[k] > G_0[k-n] + \epsilon \quad \text{Equation 43}$$

Figure 19 depicts the simplified logic diagram for an adaptive conductance element. It retains the advantages of the incremental conductance methods and does not require incremental zero-sequence voltage and current as input information.

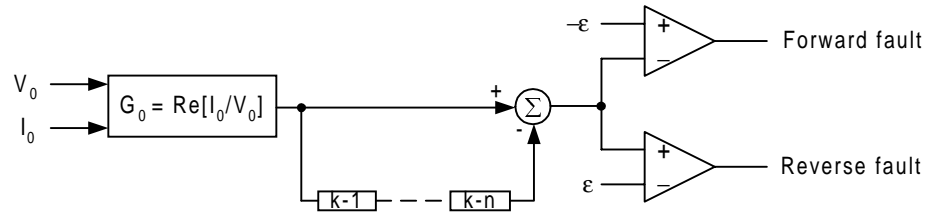


Figure 19 Simplified Logic Diagram of an Adaptive Conductance Element

COMPENSATED SYSTEM DIRECTIONAL ELEMENT PERFORMANCE

To demonstrate the performance of this new ground directional element we modeled a distribution power system using EMTP (Electromagnetics Transients Program) and played the results through a relay simulation program. The simulated system includes a 132 kV 3-phase balanced source, a delta-wye 132-11kV step-down transformer, a Petersen Coil with a 1.25 k Ω shunt resistor, and three feeders. All three overhead line feeders have the same tower structure (see Figure 20) but different line lengths as shown in Figure 21.

At 100 percent tuning, the total zero-sequence capacitive current from all feeders equals to the inductive current provided by the Petersen Coil in the normal unfaulted system condition. The Petersen Coil inductance is 7.53 henries with an X/R ratio of 15.

Because of the high zero-sequence impedance presented by the Petersen Coil resonant system, the fault voltage and current profiles are almost identical for close-in and remote faults.

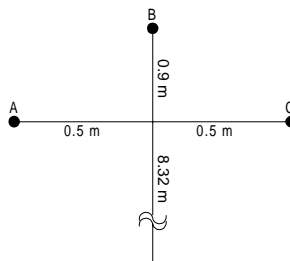


Figure 20 Tower Configuration of Simulated System

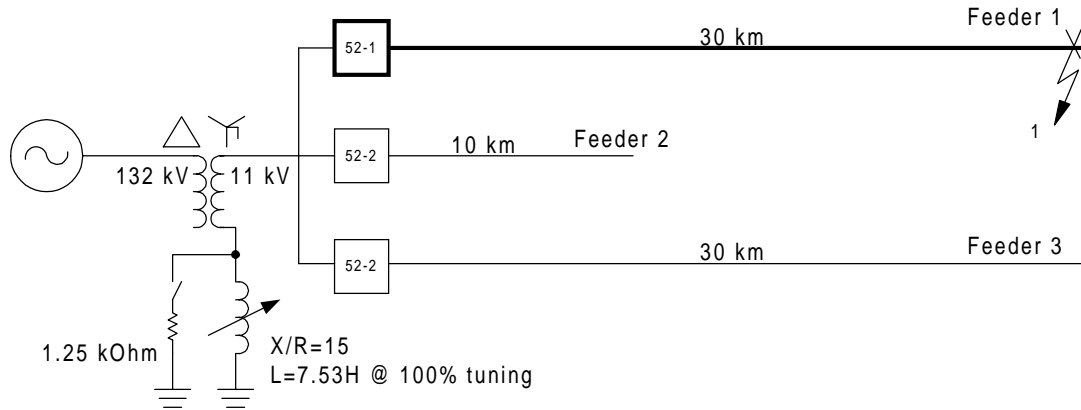


Figure 21 Simulated Power System Single-Line

This example simulates transient and restriking faults occurring on different phases of Feeder 1. The fault resistance in all cases is 40 kΩ primary. The faults are all self-clearing. Figure 22 shows the zero-sequence voltage and current for all three feeders. The initial A-phase-to-ground fault occurs at cycle 24 and self-extinguishes at cycle 30. The fault restrikes on B-phase at cycle 54 and self-clears at cycle 60. Another C-Phase fault restrike occurs at cycle 84 and again self-extinguishes at cycle 108. From Figure 22, notice that the standing zero-sequence voltage (V_0) is 750 V. Recall that the traditional wattmetric directional element requires that $|V_0|$ exceeds $0.2 \cdot V_{nom}$ (or 1270 V in this application) to be enabled. This standing voltage is already 60 percent of the enabling threshold. Note too that the $|V_0|$ for the A-Phase fault is much lower than that for the B- and C-Phase ground faults. This difference in magnitude is caused by differing fault inception point-on-wave and the phase relationship of the fault-induced zero-sequence voltage and the standing voltage.

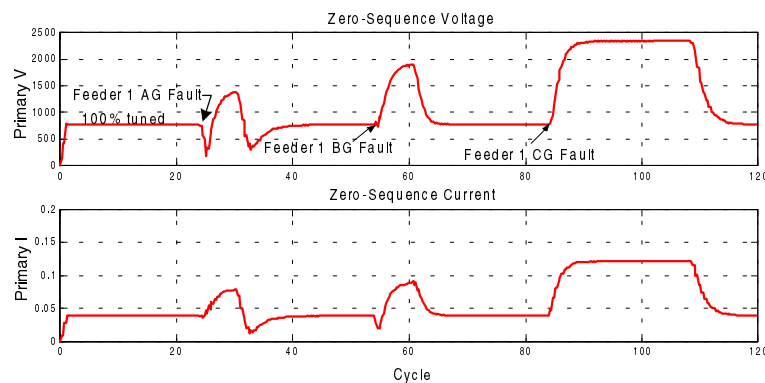


Figure 22 Zero-Sequence V_0 and I_0 Plots for 10 kΩ AG Fault on Feeder 1

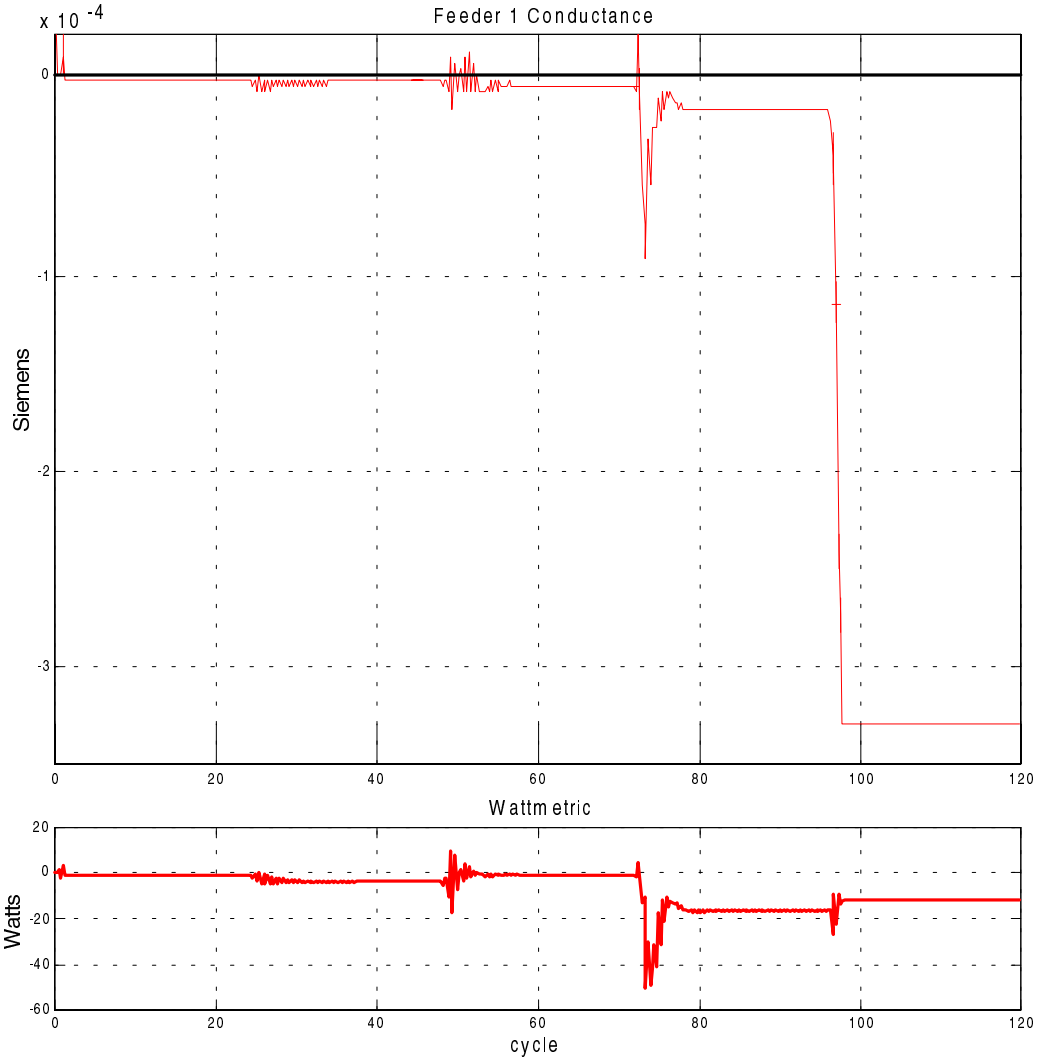


Figure 23 Feeder 1 Conductance and Wattmetric Element Outputs for Case 1

Figure 23 shows the conductance and wattmetric directional calculations and elements for a relay installed on Feeder 1. In actual practice, the most likely scenario is for the fault to restrike on the same phase. We illustrate faults on different phases to indicate the flexibility of the logic in detecting subsequent faults. Note that both directional elements correctly detected the high-impedance faults: i.e. both produced negative results for a forward fault.

IMPROVED BROKEN DELTA VOLTAGE TRANSFORMER CONNECTION

Modern relays accept many different configurations for voltage transformers (VTs): three-phase four-wire, open-delta, and broken delta. The latter VT connection is suitable for ground directional element applications and is very common in most of the existing ungrounded and resonant grounded systems. However, this standard broken-delta connection can present a unique set of problems outside of ferroresonance. Figure 24 shows a classical broken-delta VT connection.

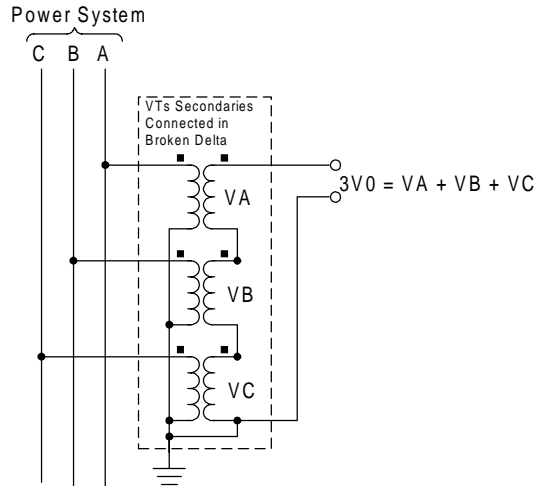


Figure 24 Traditional Broken Delta VT Connection Diagram

While the broken-delta VT connection does provide zero-sequence voltage for measurement during ground faults, the nominal output voltage for a bolted ground fault on the ungrounded or Petersen system can be over $360 V_{AC}$ if the nominal voltage for each phase transformer of the broken delta is $120 V_{LN}$. Such a high voltage is higher than most relay input ratings. Because the ideal pre-fault zero-sequence voltage magnitude is zero, it is difficult to detect a blown VT fuse. Given that many ground directional elements require a minimum zero-sequence voltage, a blown VT fuse could defeat ground protection.

Many installations require maintaining the broken-delta VT connection for existing control devices. Thus, the challenge is to extract three-phase four-wire voltage signals from an existing broken-delta connection. It is also very desirable to have a relaying system applicable to a standard three-phase, four-wire VT application. Figure 25 shows a simple, patent pending solution. This solution requires connecting the relay input transformers as shown. With this connection, the relay can then measure each phase voltage and calculate the necessary $3V_0$ for the zero-sequence directional element described earlier.

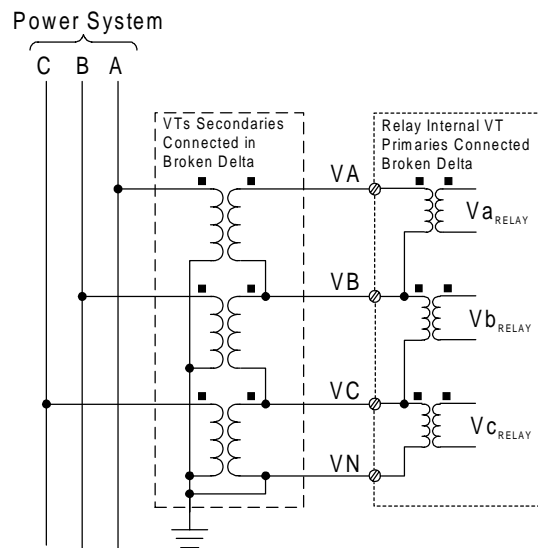


Figure 25 Single-Line Diagram and New Broken-Delta VT Connection Diagram

The benefits of this new VT connection approach are:

1. No relay input transformer has to be rated for $360 V_{AC}$.
2. The relay system can now check for blown potential fuses. In a relay using the traditional broken-delta connection on a system with little or no unbalance, the $3V_0$ measurable before and after a blown secondary fuse is the same (i.e., zero volts).
3. The relay can measure each individual phase voltage and calculate the necessary sequence components. This allows the relay to use the same VTs for phase and ground directional control elements.
4. It does not require disturbing existing wiring for devices using the broken-delta voltage output. Simply add wires from the B- and C-Phase polarity marks of the VT secondaries to the respective inputs on the relay.
5. It allows dual phase directionality from differing VTs: Main 1 could use this new connection from the broken-delta system while Main 2 could use the existing open-delta VTs for polarizing.

CONCLUSIONS

1. Ungrounded systems are connected to ground through the line-to-ground capacitances. Single line-to-ground faults shift the system neutral but leave the phase-to-phase voltage triangle intact. Self-extinction of ground faults in overhead-ungrounded lines is only possible for low values of ground fault current.
2. Zero-sequence, or three-phase voltage relays can detect ground faults in ungrounded systems. However, this method is not selective. A sensitive, directional ground varmetric element is the classic solution to ground fault detection in ungrounded systems.
3. A new ground directional element for ungrounded systems (patent pending) measures the zero-sequence reactance and compares its value with two settable thresholds. For a forward ground fault the element measures the zero-sequence capacitive reactance of the equivalent system behind the relay. For reverse faults the new element measures the series combination of the protected line zero-sequence series impedance and the line capacitive reactance. The new directional element includes a security supervision logic that requires the ratio of residual current to positive sequence current to exceed a minimum scalar threshold value. The benefit of this supervision as compared to the traditional $3V_0$ security supervision is that the minimum sensitivity of each feeder relay is not dependent upon the total system unbalance.
4. The new ground directional element was extensively tested by digital simulation using EMTP (Electromagnetic Transients Program). The new element exhibits very stable directional decisions for ground faults with fault resistance values as high as 10-20 k Ω .
5. Compensated systems are grounded through a variable impedance reactor, which compensates the system phase-to-ground capacitance. The system remains operational during ground faults. Resonant grounding provides self-extinction of the arc in overhead lines for about 80 percent of temporary ground faults. Then, ground faults that clear without breaker tripping represent more than 50 percent of all faults in overhead lines.
6. The wattmetric method is the most widely used solution to ground fault detection in compensated systems. The relay element responds to the in-phase (real) component of the dot product of the zero-sequence voltage and current. The requirement of V_0 detection limits the sensitivity of the wattmetric method for high-resistance faults. All known fundamental-

frequency methods that provide high sensitivity (for example, the admittance method) require information on all feeders and/or some sort of control on the Petersen coil or current injection.

7. We may provide high-resistance coverage by measuring the zero-sequence conductance in the protected feeder. This method works well in balanced systems and for low CT errors (using flux-summation CTs, for example). An enhancement to this method is to calculate the incremental conductance as the real part of the ratio of the incremental zero-sequence current to the incremental zero-sequence voltage. A further development is the adaptive conductance method, which calculates the incremental conductance as the difference between the fault- and pre-fault-conductance values. All these conductance-related methods are inherently directional, exhibit high fault resistance coverage and are applicable in a stand-alone feeder relay.
8. We conducted extensive digital simulation testing of a new adaptive conductance ground directional element for compensated systems using EMTP. The relay element performed well even for high-resistance faults and transient, restriking faults. The new element detected faults with resistance values over 40 k Ω .

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