Application Guidelines for Ground Fault Protection

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INTRODUCTION

Modern digital relays provide several outstanding methods for detecting ground faults. New directional elements and distance polarization methods make ground fault detection more sensitive, secure, and precise than ever. Advances in communications-aided protection further advance sensitivity, dependability, speed, and fault resistance coverage.

The ground fault detection methods and the attributes of each method discussed in this paper are:

- Directional Zero-Sequence Overcurrent
- Directional Negative-Sequence Overcurrent
- Quadrilateral Ground Distance
- Mho Ground Distance

Comparison of the ground fault detection methods is on the basis of sensitivity and security. The advantages and disadvantages for each method are presented and compared.

Some problem areas of ground fault detection are discussed, including system nonhomogeneity, zero-sequence mutual coupling, remote infeed into high-resistance faults, and system unbalances due to in-line switching. Design and application considerations for each problem area are given to aid in setting the relay elements correctly.

This paper offers a selection and setting guide for ground fault detection on noncompensated overhead power lines. The setting guide offers support in selecting the proper ground fault detection element based upon security, dependability, and sensitivity (high-resistance fault coverage).

Following the body of this paper is an annotated bibliography of publications related to topics discussed in this paper. The list of references allows the reader to further research and build upon the ideas and theory presented in this paper.

Finally, Appendix A discusses how to model in-line switching and open-phase conductors. This appendix presents the effects of in-line switching on sensitive set ground fault detecting elements, as well as corrective measures to ensure secure operation of sensitive set overcurrent elements.

GROUND FAULT DETECTION METHODS

Transmission systems are generally looped systems, that is, there are many sources and current can flow in any direction. Directionality plays an important role in transmission line protection. Using directional relays eases coordination by reducing the number of relays that must coordinate together for a single fault. The information and examples provided in this paper pertain mainly to transmission or looped systems.

A ground relay must detect all phase-to-ground faults within its defined zone of protection under conditions which produce minimum fault current. The ground relay zone of protection can be defined as a current threshold or measured impedance.

The classical method for detecting ground faults on a looped system has been to use directional overcurrent relays that measure the zero-sequence current [7, 15]. Many microprocessor-based relays now offer negative-sequence current elements as a means of detecting ground faults and determining fault direction [4].

Conventional polarization techniques using zero-sequence voltage and current are implemented in nearly all microprocessor-based relays. Many of these relays also offer negative-sequence voltage-polarized directional elements. Selecting the correct directional polarization technique can improve relay performance and sensitivity [11, 17]. For the ease of referral, in the remainder of this paper, the word "relay" refers to microprocessor-based relays.

New developments in directional polarization have improved the directional security and performance of the relay even further [6, 9]. These new elements measure the negative-sequence or zero-sequence source impedances at the relay location. The new impedance-based directional elements can improve the sensitivity and security of the directional element under extreme system conditions [6, 11].

Another common method for detecting ground faults is to use distance-based measuring elements. These ground distance functions measure an apparent impedance to the fault, based upon the ratio of relay voltage to relay current. The most commonly used ground distance characteristic is the mho or the quadrilateral characteristic. As with overcurrent elements, methods for polarizing the distance elements provide different security and high-resistance fault coverage [1, 5, 10, 14, 15, 16].

Zero-Sequence Overcurrent

Sensitive ground fault detection is obtained by using a relay which responds only to the zero-sequence current of the system. Zero-sequence current is caused by an unbalanced fault involving ground. Zero-sequence overcurrent elements can be set very sensitive (i.e., a low pickup setting) because the zero-sequence current generated under load conditions is typically very low.

A common misconception is that zero-sequence current only exists under fault conditions. However, zero-sequence current can and does exist under nonfault, normal load conditions. Unbalanced system conditions, such as those caused by nontransposed transmission lines or unbalanced loading, can cause zero-sequence current to flow. Ground fault protection elements should never be set more sensitive than the normal system unbalance. This setting limitation means that load or system induced zero-sequence current can severely impact the sensitivity of a zero-sequence overcurrent element [11].

A zero-sequence overcurrent relay simply measures the sum of the three phase currents (Equation 1). Zero-sequence current is also commonly referred to as ground or residual current.

$$I_r = 3 \bullet I_0 = I_A + I_B + I_C \qquad \text{Equation 1}$$

Zero-sequence fault quantities are readily available from a fault study. The pickup thresholds are also very simple to determine from the fault study data. The majority of fault studies available today also model intercircuit zero-sequence mutual coupling; thus, the zero-sequence currents obtained from the fault studies already account for these effects.

Zero-sequence overcurrent elements can provide very effective resistive ground fault coverage. These elements are capable of being used either independently with time delays or in pilot tripping schemes. Sensitive zero-sequence overcurrent elements in pilot tripping schemes provide the best, high-speed, resistive fault coverage [13].

Advantages

Zero-sequence overcurrent elements:

- provide outstanding resistive fault coverage
- are easy to set, understand, and visualize
- are not affected by load flow because the load current has very little impact on the zero-sequence current magnitude
- are not affected by phase-to-phase connected load (i.e., delta-wye transformers)

Disadvantages

Zero-sequence overcurrent elements:

- are affected by changes in the power system source
- are affected by zero-sequence mutual coupling
- are affected by normal system load unbalance
- are affected by in-line switching and open-phase conductors which can have a negative impact on the security of the pilot scheme

Negative-Sequence Overcurrent

Negative-sequence overcurrent elements have been gaining popularity as a method for detecting high-resistance ground faults. In the past, protection schemes utilizing negative-sequence current elements were difficult to implement and complex in design. Many relays now offer negative-sequence current elements as a standard feature. Some utilities are using negative-sequence overcurrent elements to improve the sensitivity of their protection schemes [4].

Negative-sequence currents can arise whenever any system unbalance is present. Major sources of system unbalances are faults, nontransposed lines, and load unbalance. As with zero-sequence overcurrent elements, system unbalances can significantly impact the settable sensitivity of a negative-sequence overcurrent element.

Negative-sequence current is derived from the three phase currents and is given by:

$$3 \bullet I_2 = I_A + a^2 \bullet I_B + a \bullet I_C \qquad \text{Equation 2}$$

Where:

$$a = 1\angle 120^\circ \text{ and } a^2 = 1\angle 240^\circ$$

The negative-sequence current is dependent upon phase rotation. Equation 2 assumes an ABC phase rotation. For an ACB phase rotation the I_B and I_C terms are transposed.

Negative-sequence current elements are not affected by intercircuit mutual coupling [4]; therefore, for faults at the remote end of long lines, negative-sequence current elements provide better resistive fault coverage than zero-sequence current elements. The negative-sequence impedance of a transmission line is significantly less than the zero-sequence impedance; thus, faults at the remote end of a long line typically have more negative-sequence current than zero-sequence current [4].

Advantages

Negative-sequence overcurrent elements:

- provide outstanding resistive fault coverage
- provide better resistive fault coverage than zero-sequence overcurrent elements for faults at the end of long lines [4]
- are insensitive to zero-sequence mutual coupling associated with parallel transmission line applications [3, 4]
- are not affected by load flow because the load current has very little impact on the negative-sequence current magnitude
- are preferred over zero-sequence overcurrent elements if the bus behind the relay location is a strong zero-sequence source, because the negative-sequence voltage available at the relay location is typically higher than the zero-sequence voltage

Disadvantages

Negative-sequence overcurrent elements:

- are affected by changes in the power system source
- are affected by normal system load unbalance
- are affected by in-line switching and open-phase conductors which can have a negative impact on the security of the pilot scheme
- are required to coordinate with phase and ground fault detecting elements

Directional Supervision of Negative- and Zero-Sequence Overcurrent Elements

The previous discussion on zero- and negative-sequence overcurrent elements only considered the operating or tripping quantities. These elements must be supervised by directional elements when used on a looped transmission system.

Several methods are available for determining the correct direction of ground fault current. Zero-sequence voltage and current reference quantities are the most commonly used methods to determine directionality. Negative-sequence voltage is also used for directional polarization.

Conventional directional elements operate from torques developed in magnetic circuits. Microprocessor-based relays emulate conventional directional elements by calculating torque-like products [17]. The torque product indicates the direction of fault current flow: a positive torque defines a forward fault and a negative torque defines a reverse fault.

Figure 1 shows the voltage and current vectors for an A-phase-to-ground fault. Phase and zero-sequence voltage and current are shown.

The torque equation for a zero-sequence voltage polarized directional element is:

$$32\mathrm{VT} = |\mathrm{V}_0| \bullet |\mathrm{I}_\mathrm{r}| \bullet \left[\cos\left(\left(\angle -\mathrm{V}_0\right) - \left(\angle \mathrm{I}_\mathrm{r} + \mathrm{MTA}\right)\right)\right]$$

MTA = angle of maximum operating torque, dependent upon relay design

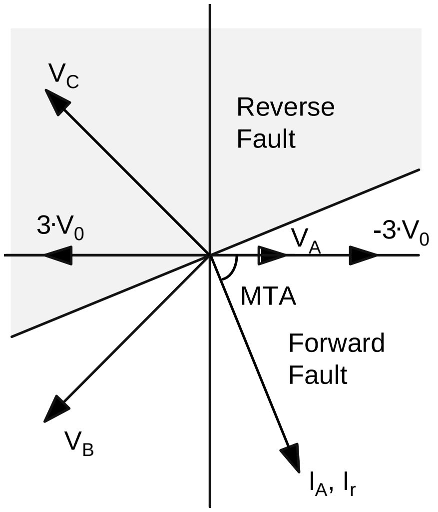


Figure 1: Phase and Zero-Sequence Phasors for a Single-Phase-to-Ground Fault

Negative-sequence directional elements use negative-sequence voltage as the polarizing quantity and negative-sequence current as the operate quantity. As with zero-sequence directional elements, the relay calculates torques to determine the direction of the fault.

Figure 2 shows the voltage and current vectors for an A-phase-to-ground fault. Phase and negative-sequence voltage and current are shown.

The torque equation for a negative-sequence voltage polarized directional element is:

$$32\mathrm{QT} = |\mathrm{V}_2| \bullet |\mathrm{I}_2| \bullet \left[\cos\left(\left(\angle -\mathrm{V}_2\right) - \left(\angle \mathrm{I}_2 + \mathrm{MTA}\right)\right)\right]$$

MTA = angle of maximum operating torque, dependent upon relay design

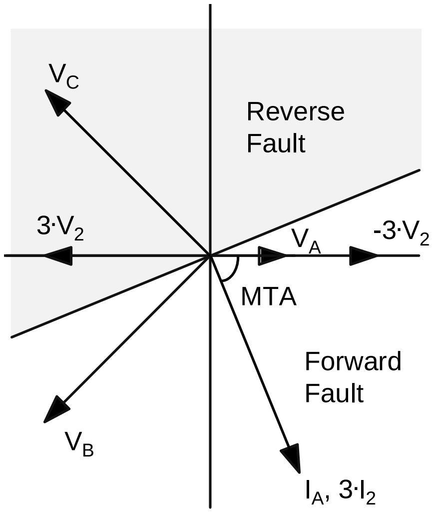


Figure 2: Phase and Negative-Sequence Phasors for a Single-Phase-to-Ground Fault

Some directional elements require the voltage and current to exceed factory-set thresholds before the directional element is allowed to operate. Although these thresholds may improve the security of the directional element against abnormal system conditions (i.e., in-line switching and nontransposed lines), the thresholds can adversely affect high-resistance fault detection [11]. High-resistance faults generate very little unbalance on the power system. It is these unbalances that zero- and negative-sequence directional elements use to operate.

A newly developed negative-sequence directional element measures negative-sequence impedance at the relay location [9, 14]. The measurement is then compared to forward- and reverse-impedance thresholds (Figure 3), which are settings. The direction of the fault is determined as follows:

- Forward (in front of the relay) if the measured negative-sequence impedance is less than the forward-impedance threshold setting.
- Reverse (behind the relay) if the measured negative-sequence impedance is greater than the reverse-impedance threshold setting.

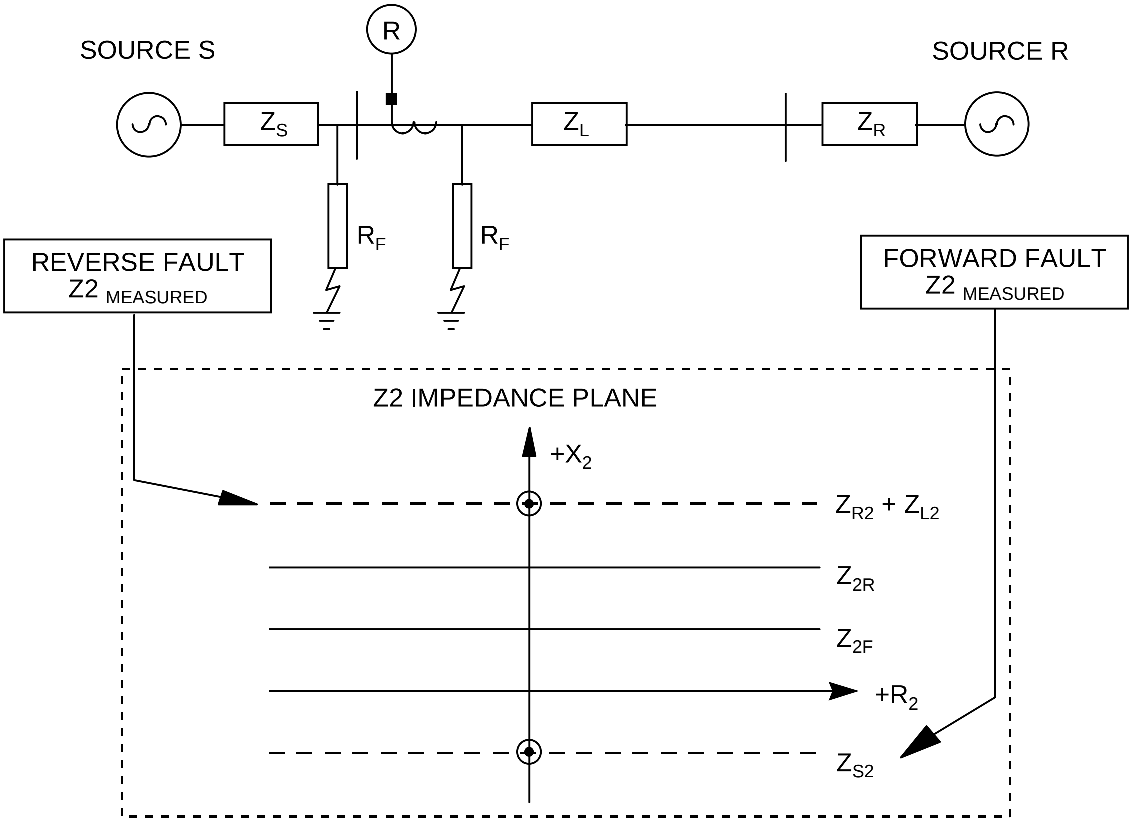


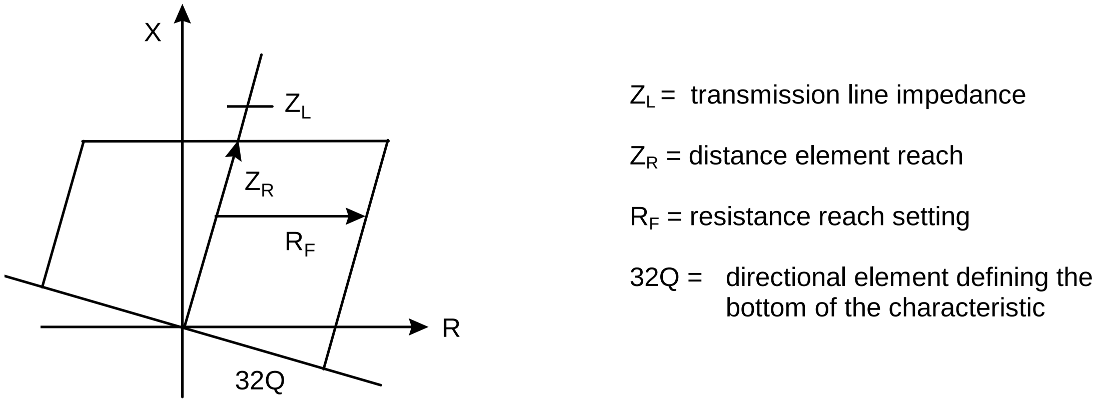
Figure 3: Measured Negative-Sequence Impedance Yields Direction

The impedance-based directional element is more secure and reliable when compared to a conventional negative-sequence directional element which calculates torque. Faults at the end of long lines provide minimal negative-sequence voltage for systems with strong negative-sequence sources, and for that reason, the impedance-based directional element is preferred. A directional element that uses a torque calculation can incorrectly indicate direction when potential device errors are also considered. The impedance-based calculation can provide reliable and secure operation for these conditions [6, 9].

Quadrilateral Ground Distance

A quadrilateral ground distance characteristic consists of four elements. Each side of the quadrilateral characteristic shown in Figure 4 represents a different element: the reactance element (top line), positive and negative resistance boundaries (right and left sides, respectively), and the directional element (bottom line). The characteristic shown in Figure 4 represents the typical quadrilateral characteristic for a radial system.

A quadrilateral ground distance characteristic operates if the measured impedance is inside the box defined by the four elements mentioned above (i.e., all four elements must operate).



Z_L = transmission line impedance

Z_R = distance element reach

R_F = resistance reach setting

32Q = directional element defining the bottom of the characteristic

Figure 4: Quadrilateral Characteristic for a Radial System

Equation 3 and Equation 4 define the quadrilateral reactance and resistance element operating characteristics. For details regarding the derivation of this equation see References [14,18].

Reactance Element:

$$XG = m \bullet \left|Z_{1L}\right| = \frac{\mathrm{Im}\left[V_{\phi} \bullet \left(I_r \bullet e^{j \bullet T}\right)^{*}\right]}{\mathrm{Im}\left[1\angle Z_{1L} \bullet \left(I_{\phi} + k_0 \bullet I_r\right) \bullet \left(I_r \bullet e^{j \bullet T}\right)^{*}\right]} \qquad \text{Equation 3}$$

Resistance Element:

$$R_F = \frac{\mathrm{Im}\left[V_{\phi} \bullet \left(1\angle Z_{1L} \bullet \left(I_{\phi} + k_0 \bullet I_r\right)\right)^{*}\right]}{\mathrm{Im}\left[\frac{3}{2} \bullet \left(I_{\phi 2} + I_0\right) \bullet \left(1\angle Z_{1L} \bullet \left(I_{\phi} + k_0 \bullet I_r\right)\right)^{*}\right]} \qquad \text{Equation 4}$$

The amount of fault resistance covered by the quadrilateral element is determined by the resistive reach setting. One relay design has a resistive element that can be set independent of the load flow on the line. Other relay designs are limited by the load flow on the line because the resistance element operates from the phase current. Heavy loading severely restricts the fault resistance coverage offered by relays that use phase current in the resistance calculation.

The quadrilateral distance element is a good choice for protection of underground cables. Underground cables have low zero-sequence impedance angles (i.e., the zero-sequence impedance is mainly resistive) and low positive- to zero-sequence impedance ratios. The small zero-sequence impedance angle makes it difficult to apply a mho distance element for ground fault detection.

Small errors in voltage and current measurements can cause errors in the reactance measurement with extended resistive reach settings. Limiting the resistive reach with respect to the reactance setting ensures that the relay is measuring adequate signals for proper operation.

Differences in the source and line impedance angles can cause overreach or underreach the reactance element. The effect unequal source and line impedance angles have on the reactance element is discussed later in this paper.

Advantages

Quadrilateral ground distance elements:

- provide more fault resistance coverage than the mho element when properly designed [14]
- provide high-speed tripping of resistive faults when a pilot channel is not present
- are fairly immune to in-line load switching
- are good for cable protection

Disadvantages

Quadrilateral ground distance elements:

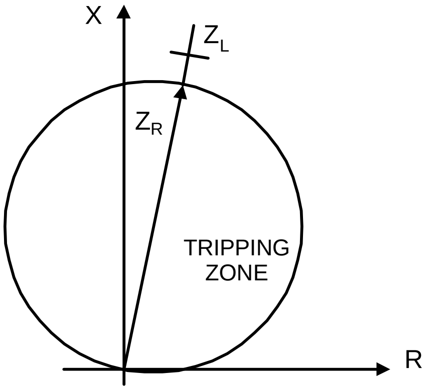
- are affected by errors in the current and voltage measurements when the resistive reach is much greater than the reactive reach
- are affected by system non-homogeneity (i.e., unequal source and line impedance angles) [5,16]
- are affected by zero-sequence mutual coupling in parallel lines

Mho Ground Distance

Mho ground distance characteristics are developed by measuring and comparing the phase angle between the operating voltage signal and the polarizing voltage signal. References [1, 5, 14, 16] provide a more extensive look and comparison of the many mho element polarizing choices available.

A positive-sequence voltage-polarized mho characteristic provides the best security and dynamic expansion [14, 16].

Figure 5 illustrates a Steady-State Mho Characteristic.



Z_L = transmission line impedance

Z_R = distance element reach

Figure 5: Steady-State Mho Characteristic

Equation 5 defines the positive-sequence memory-polarized mho ground distance element operating characteristic. For details regarding the derivation of this equation see references [14, 18].

$$\mathrm{MG} = \mathrm{m} \bullet \left|\mathrm{Z}_{1\mathrm{L}}\right| = \frac{\mathrm{Re}\left[\mathrm{V}_{\phi} \bullet \left(\mathrm{V}_{\phi 1\mathrm{mem}}\right)^{*}\right]}{\mathrm{Re}\left[1\angle \mathrm{Z}_{1\mathrm{L}} \bullet \left(\mathrm{I}_{\phi} + \mathrm{k}_{0} \bullet \mathrm{I}_{\mathrm{r}}\right) \bullet \left(\mathrm{V}_{\phi 1\mathrm{mem}}\right)^{*}\right]} \qquad \text{Equation 5}$$

Mho ground distance elements are much easier to set than quadrilateral ground distance elements. This is because there are fewer settings required and less influence on the mho element by unequal source and line impedance angles.

A mho element using positive-sequence memory-polarization has a dynamic response [1, 14, 16, 18] that improves the resistive fault coverage offered by the relay. Under weak source conditions a mho element can offer better resistive fault coverage for close-in faults than a quadrilateral ground distance element.

Advantages

Mho ground distance elements:

- are easy to set
- are less influenced by system nonhomogeneity than the quadrilateral element
- are capable of providing better resistive fault coverage than the quadrilateral element under certain system conditions

Disadvantages

Mho ground distance elements:

- provide limited resistive fault coverage for faults at the end of the element reach
- provide limited resistive fault coverage for strong source conditions
- are influenced by zero-sequence mutual coupling

COMPARISON NOTES

Distance Versus Overcurrent

The major advantage of distance relays is that the zone of operation is a function of the protected line impedance, which is a constant, and is relatively independent of the current and voltage magnitudes. The distance relay has a fixed reach, as opposed to overcurrent relays for which the zone of protection varies with respect to changes in the source impedance.

One difficulty with mho ground distance relays is their inability to detect high-resistance faults. The voltage measured by the relay is the sum of the line voltage drop to the fault and the voltage drop across the fault resistance. The voltage drop across the fault resistance can change due to current infeed from the other line terminal. On a radial system there is no infeed from another line terminal and the distance relay measures the actual fault resistance. On looped transmission systems there are usually more than one source of current feeding the fault; therefore, the infeed from another line terminal acts as a fault resistance amplifier. The amplifier effect is a function of total current in the fault and the current supplied from the relay terminal. As the total fault current increases with respect to the relay current, the apparent fault resistance also increases. The effect of infeed into resistive faults is covered later in this paper.

Mho Versus Quadrilateral

The mho characteristic is popular because it has a well-defined reach, is inherently directional, and can be made to tolerate fault resistance quite well without serious overreaching errors due to load or unequal source and line impedance angles [14, 16]. Under strong source conditions, a quadrilateral characteristic can provide greater fault resistance coverage than the dynamic characteristic of the mho element.

Mho ground distance relays have dynamic and/or variable characteristics that depend upon the polarizing quantity, fault type, and system parameters [1, 10, 14, 16]. Load flow shifts and expands this variable characteristic. The mho ground relay offers a desirable balance between fault resistance accommodation on internal faults and security against misoperation on external faults. By comparison, the quadrilateral relay provides good fault resistance coverage, but experiences reduced security on remote faults due to unequal source and line impedance angles for these same resistive faults [1, 5, 16]. The affect of unequal source and line angles on a quadrilateral element is discussed later in this paper.

DIFFICULTIES ASSOCIATED WITH GROUND FAULT PROTECTION

The next focus of discussion is on some of the difficulties associated with ground fault protection. In particular, the following issues are covered:

- Unequal source and line impedance angles (system nonhomogeneity)
- Zero-sequence mutual coupling
- Remote infeed into high-resistance faults
- System unbalances due to in-line load switching or line configuration

These difficulties significantly reduce the ability of the ground fault protection to reliably and securely detect high-resistance ground faults.

The Effect of a Nonhomogeneous System on Reactance Elements

A system is homogeneous when the line and source angles are equal in all three sequence networks. The system is also considered homogeneous if the source and line impedances associated with the sequence current used by the reactance element for a polarizing reference have the same angle. For example, in a reactance element that uses zero-sequence current as a polarizing reference, only consider the zero-sequence network. In a reactance element that uses negative-sequence current as a polarizing reference, only consider the negative-sequence network. In this paper, the discussion is restricted to reactance elements that use zero-sequence polarization.

A system is nonhomogeneous when the source and line impedance angles are not the same. In a nonhomogeneous system, the angle of the total current in the fault is different than the angle of current measured at the relay. For a bolted fault (a condition that assumes no resistance in the fault), a difference between the fault current angle and the current angle measured at the relay is not a problem. However, if there is fault resistance, the difference between the fault and relay current angles can cause a ground distance relay to severely underreach or overreach. The effect of system nonhomogeneity has been briefly covered in previous papers [1, 5, 12, 16]. The following pages describe in more detail the effects of unequal source and line impedances on a reactance element used in a quadrilateral ground distance characteristic.

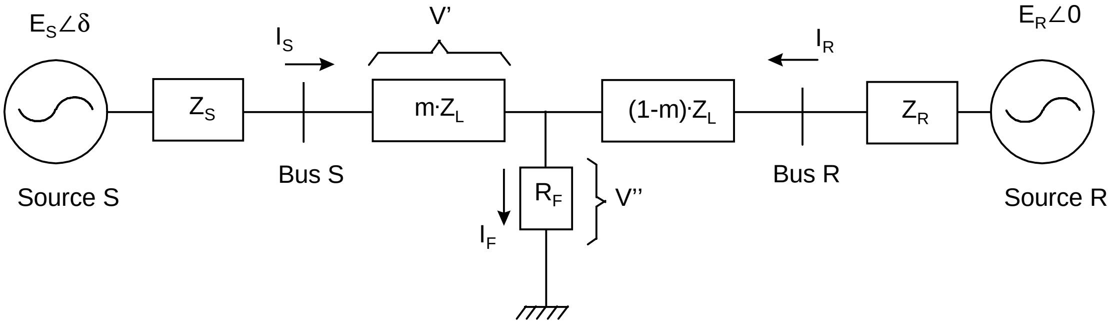


Figure 6: Simple Two-Source System Single Line Diagram

As illustrated in Figure 6, the phase voltage measured by a relay at Bus S can be represented as the sum of two voltage drops: the voltage drop across the transmission line ground loop impedance and the voltage drop across the fault resistance. The sum and definitions of these two voltage drops is given by Equation 6:

$$V_{\phi} = V' + V'' \qquad \text{Equation 6}$$

Where:

$$V' = m \bullet Z_{1L} \bullet (I_{\phi} + k_0 \bullet I_r)$$

$$V'' = R_F \bullet I_F$$

Z_{1L} = positive-sequence line impedance

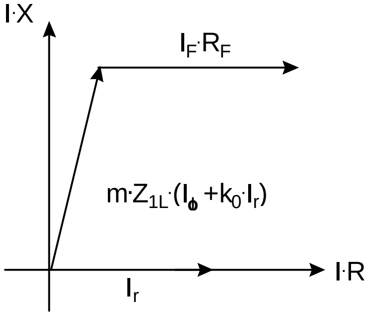
I_{ϕ} = phase current associated with the faulted phase voltage

m = per unit distance to the fault

k_0 = ground distance relay zero-sequence compensation factor: $\dfrac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}}$

I_r = ground current measured by the relay ($3 \cdot I_0$)

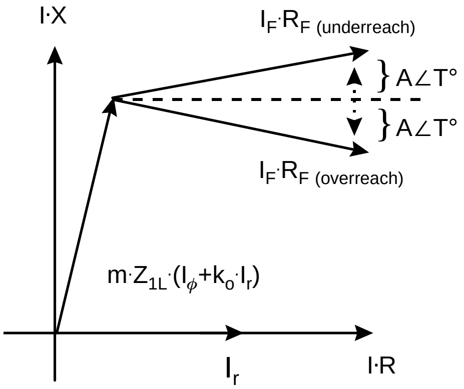
An error term, V”, which is caused by the voltage drop across the fault resistance is introduced into the reactance element measurement. Figure 7 shows a voltage diagram for a resistive fault on a homogenous or radial system.



When the system is homogeneous or radial, the voltage drop across the fault resistance is purely resistive and in phase with the polarizing current I_r. The $R_F \bullet I_F$ term is effectively removed from the reactance element measurement.

Figure 7: Voltage Vector Diagram for a Resistive Fault in Homogeneous and Radial Systems

When the system is nonhomogeneous, the voltage drop across the fault resistance is no longer in phase with the polarizing quantity (in this case the zero-sequence current at Terminal S in Figure 6). Figure 8 illustrates the voltage vectors for a resistive fault in a nonhomogeneous system.



In a nonhomogeneous system, the voltage drop across the fault resistance includes both real and imaginary terms. The imaginary part can cause the reactance element to overreach or underreach. The reactance element error is defined as A∠T°. The reactance element will:

Underreach - If I_F leads I_r
Overreach - If I_F lags I_r

where I_r is the polarizing quantity for the reactance element.

Figure 8: Voltage Vector Diagram for a Resistive Fault in a Nonhomogeneous System

Error Term Calculation

Referring to Figure 9, the total zero-sequence current in the fault is a function of the contributions from the source behind Bus S, the source behind Bus R, and the location of the fault on the line. Figure 8 shows that the tilt in the voltage drop across the fault resistance causes an error in the reactance element measurement. The degree to which the voltage across the fault resistance tilts is determined by the difference of the fault current angle and reactance element polarizing referencing angle. The reactance element measurement error is then a function of the ratio of the total zero-sequence fault current to the zero-sequence current measured in the relay. Equations 7 and 8 show two different methods for calculating the error term shown in Figure 8.

The error term calculated in Equation 7 and Equation 8 are with respect to a relay at Bus S. To calculate the error term for a relay at Bus R, replace the “S” subscripts in Equation 7 and Equation 8 with “R”.

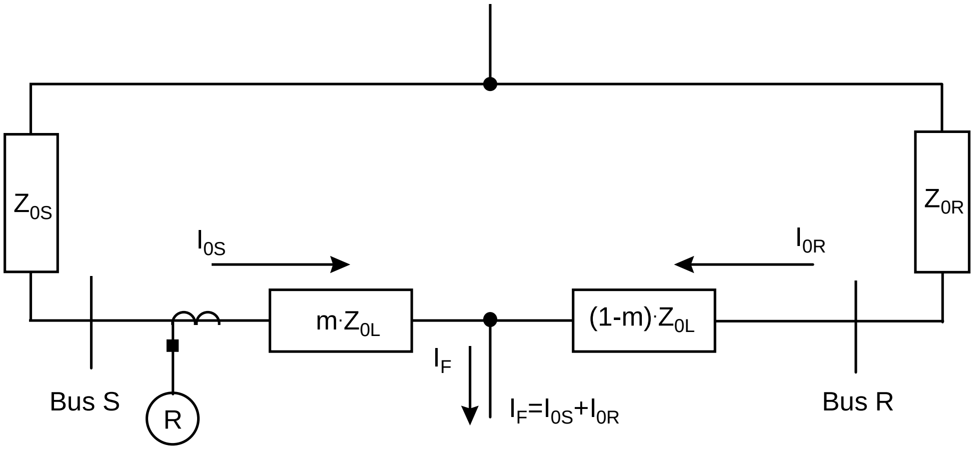


Figure 9: Zero-Sequence Network for Single a Phase-to-Ground Fault

1. A theoretical approach to calculating A∠T° is to use Equation 7. This method is more complex and requires calculating the zero-sequence source impedance at each end of the line.

$$A\angle T^\circ = \left[\frac{Z_{0S} + Z_{0L} + Z_{0R}}{(1-m)\bullet Z_{0L} + Z_{0R}}\right] \qquad \text{Equation 7}$$

2. A more practical and simpler approach is to divide the total zero-sequence fault current by the zero-sequence current seen by the relay.

$$A\angle T^\circ = \frac{I_{0F}}{I_{0S}} \qquad \text{Equation 8}$$

The A∠T° term shown in Equation 8 can easily be calculated from data available in fault study. In some fault studies, the zero-sequence current is expressed in terms of $3 \cdot I_0$. The error term shown in Equation 8 can be calculated using $3 \cdot I_0$ current providing that the numerator and denominator terms are consistent.

Reactance Measurement Error Caused by Fault Resistance

The effective reactance measurement can be determined by including the voltage drop across the fault resistance shown in Equation 6 in the reactance calculation shown in previous papers [14 and 18]:

$$\frac{\mathrm{Im}\left\{V_{\phi S} \bullet I_r^*\right\}}{\mathrm{Im}\left\{1\angle Z_{1L} \bullet \left(I_{\phi S} + k_0 \bullet I_r\right) \bullet I_r^*\right\}} = m \bullet \left|Z_{1L}\right| + R_F \bullet \frac{\left|I_r\right|^2 \bullet \left|A\right| \bullet \sin(T)}{\mathrm{Im}\left[1\angle Z_{1L} \bullet (I_{\phi S} + k_0 \bullet I_r) \bullet I_r^*\right]} \qquad \text{Equation 9}$$

The second term, on the right side of Equation 9, is the error caused by the voltage drop across the fault resistance. The fault resistance induced error can be defined as:

$$\Delta X = R_F \bullet \left[\frac{\left|I_r\right| \bullet \left|A\right| \bullet \sin(T)}{\left|I_\phi\right| \bullet \sin(\angle Z_{1L} + \angle I_\phi - \angle I_r) + \left|k_0\right| \bullet \left|I_r\right| \bullet \sin(\angle Z_{1L} + \angle k_0)}\right] \qquad \text{Equation 10}$$

Where:

R_F = actual fault resistance at the fault location

I_r = ground current measured by the relay ($3 \cdot I_0$) for a bolted fault

A = magnitude of the result in Equation 7 or Equation 8

T = angle of the result in Equation 7 or Equation 8

I_ϕ = phase current measured at the relay for a bolted fault

Z_{1L} = positive-sequence line impedance

k_0 = ground distance relay zero-sequence compensation factor: $\dfrac{Z_{0L} - Z_{1L}}{3 \cdot Z_{1L}}$

Calculating the reactance measurement error is easily accomplished by using data available in a fault study and the relay settings. Knowing the reactance measurement error caused by fault resistance allows the protection engineer to properly set the reach on a quadrilateral reactance element to prevent overreaching and underreaching.

Correcting the Reactance Measurement Error Caused by Fault Resistance

Correcting the polarizing reference in the ground reactance calculation by the angle calculated in Equation 7 or Equation 8 can prevent overreach of Zone 1 elements [14]. Adjusting the polarizing reference is equivalent to setting the variable ‘T’ in Equation 9 and Equation 10 to zero, thus removing the error introduced by the fault resistance voltage drop. Most relays with a quadrilateral element have a fixed angle, however, there is one relay [14, 18] that provides a setting for adjusting the polarizing reference angle with respect to the system.

Reducing the Zone 1 reactance reach by the fault resistance induced error calculated in Equation 10 can also prevent overreach on external faults. The fault resistance induced error is a function of the magnitude of fault resistance in the fault. The worst case fault resistance induced error can be calculated using the Zone 1 resistance reach setting. By limiting the Zone 1 resistive reach, the amount of reactance element overreach caused by fault resistance induced error is also reduced. Conversely, increasing the resistive reach allows the Zone 1 element to detect higher resistance faults and increases the potential of reactance element overreach for external faults.

Zero-Sequence Mutual Coupling

Zero-sequence mutual coupling between parallel circuits can cause a ground distance relay to overreach or underreach. Zero-sequence overcurrent elements are also affected by zero-sequence mutual coupling. Numerous papers have been written that discuss the effects of zero-sequence mutual coupling on ground distance relays [1, 3, 5] and others discuss the options available to address the problems associated with mutual coupling [3, 4, 17]. The intent of this paper is to provide the protection engineer with the tools necessary to recognize that zero-sequence mutual coupling exists and to what extent the ground-fault protection is affected.

The Effect of Zero-Sequence Mutual Coupling on Ground Distance Elements

If the transmission lines are in relatively close proximity to each other, some zero-sequence mutual coupling exists. The magnitude of the zero-sequence mutual coupling is a function of the spacing of the transmission lines (i.e., how close they are to each other) and the voltage at which the lines are operating [3].

The ground distance measurement can appear to be greater than or less than the true distance to fault impedance when there is zero-sequence mutual coupling. Zero-sequence mutual coupling causes an increase or a decrease in the voltage and current measured at the relay which affects the ground distance measurement.

Figure 10 represents a simple system with parallel lines that are mutually coupled. For faults at the remote bus (Bus R), the ground distance elements underreach. Underreaching means that the impedance measured by the relay is greater than the actual distance to fault impedance. When a distance element underreaches, Zone 2 elements that are set to overreach the remote bus may not operate for faults at the remote end of the line. Failure of the Zone 2 element to operate can result in failure to trip or delayed tripping at one end of the line.

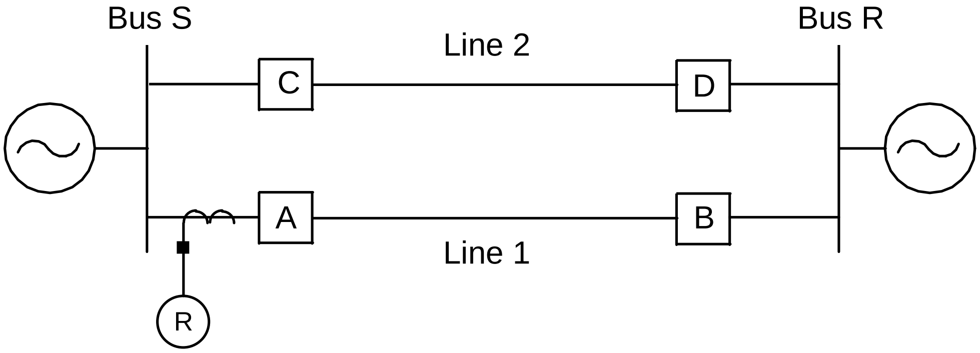


Figure 10: Example System with Parallel Lines

Ground distance relays can also overreach under certain conditions. Overreaching means that the measured impedance is less than the distance to fault impedance. Measuring an impedance less than the real distance to fault impedance can cause incorrect operation of underreaching Zone 1 relays.

Referring to Figure 10, a Zone 1 distance element can overreach if the parallel line is removed from service, grounded at both ends, and there is a close-in external ground fault [1, 3] . A ground distance relay can also overreach in cases where the zero-sequence current in the unfaulted line is a large percentage of the zero-sequence current in the faulted line [1, 3, 5]. In both cases, the zero-sequence mutual coupling effect causes an increase in the current on the unfaulted line which results in Zone 1 overreach. Reference [13] provides methods for determining the amount of overreach for the conditions discussed in this paragraph.

Ground Distance Element Measurement Error Caused by Mutual Coupling

Reference [3] develops a method to determine the apparent impedance seen by a ground distance relay for a fault at the remote end of two parallel lines. Equation 11 is the equation developed in Reference [3] and can be used for setting overreaching Zone 2 distance elements. The extended reach required to accommodate mutual coupling may cause coordination problems with downstream time-delayed tripping relays when the parallel line is removed from service. However, if the distance element is used exclusively in a pilot protection scheme, there are no coordination concerns.

$$\frac{Z_{APP}}{Z_{1L}} = 1 + \frac{\frac{Z_{0M}}{Z_{1L}}}{\left[\frac{2K_1}{K_0}\right] + p} \qquad \text{Equation 11}$$

Where:

Z_{APP} = apparent loop impedance

Z_{1L} = positive-sequence line impedance

Z_{OM} = zero-sequence mutual coupling impedance

$$K_1 = \frac{I_{1RELAY}}{I_{1FAULT}}$$

$$K_0 = \frac{I_{0RELAY}}{I_{0FAULT}}$$

$$p = \frac{Z_{0L}}{Z_{1L}}$$

The method described in Reference [3] works correctly and reliably for lines that are terminated at common buses and coupled with only one other circuit. When the lines are not terminated at common buses or the line is coupled with more than one circuit, an apparent impedance calculation is recommended. The apparent impedance can be calculated using Equation 12.

$$Z_{APP} = \frac{V_{\phi}}{I_{\phi} + k_0 \bullet I_r} \qquad \text{Equation 12}$$

Where:

V_{ϕ} = faulted phase voltage measured by the relay

I_{ϕ} = faulted phase current measured by the relay

I_r = ground current measured by the relay

k_0 = ground distance element zero-sequence compensation factor

The underreaching effect caused by zero-sequence mutual coupling can also be corrected by adjusting the zero-sequence compensation factor used for the overreaching distance elements. Many relays offered today allow separate zero-sequence compensation factor settings for the underreaching and overreaching distance zones. Calculate the overreaching zero-sequence compensation factor to accommodate mutual coupling as follows:

$$k_{0M} = \frac{Z_{0L} - Z_{1L} + Z_{0M}}{3 \bullet Z_{1L}} \qquad \text{Equation 13}$$

Where:

Z_{0L} = zero-sequence line impedance

Z_{1L} = positive-sequence line impedance

Z_{0M} = zero-sequence mutual coupling impedance

Using Equation 13 for the ground distance calculation compensates the distance element reach such that faults at the end of the line are measured correctly (i.e., they represent the true line impedance). However, it is necessary to be cautious in using this method for correcting ground distance element underreach. When the parallel line is removed from service the ground distance element is over-compensated and can severely overreach the remote terminal.

The Effect of Zero-Sequence Mutual Coupling on Ground Overcurrent Elements

Zero-sequence mutual coupling also affects the performance of ground overcurrent elements that use zero-sequence current as an operating quantity. The mutual coupling affect can reduce the sensitivity of zero-sequence overcurrent elements in detecting faults at the remote end of the line.

The mutual coupling of the two circuits causes a reduction in the zero-sequence current in each line for remote faults. Faults at the remote end of the line are the worst case since the mutual coupling between the two circuits is at the maximum.

Zero-sequence overcurrent elements can also overreach for sequentially cleared out-of-section faults. As illustrated Figure 10, a phase-to-ground fault close in to Breaker C will be cleared first by Breaker C and then by Breaker D. Once Breaker C opens, the zero-sequence mutual coupling between the two circuits causes an increase in the zero-sequence current flowing in the unfaulted line (Line A-B). Setting the direct tripping zero-sequence overcurrent elements above the maximum out-of-section fault current quantity (caused by mutual coupling), compensates for the increase in zero-sequence current flowing in the unfaulted line.

High-Resistance Fault Coverage and Remote Infeed

The amount of resistive fault coverage by any relay is influenced by a number of factors:

- distance element reach
- directional sensitivity
- remote infeed and, thus, the source impedance behind the relay location
- line length
- normal system unbalance

- load flow (in some distance relay designs)

References [11 and 13] discuss resistive fault coverage with respect to directional element sensitivity and pilot scheme selection. The two referenced papers show resistive fault coverage for a simple two ended system with a single line. The system shown in Figure 6 is representative of the systems used for study in these two papers.

In Reference [11], the authors show how directional element sensitivity affects the ability of the relay to detect high-resistance faults and how to determine how much resistive fault coverage a particular directional element provides. The paper discusses current and voltage transformer accuracy and performance and how these devices can have a significant impact on directional element performance, especially for high-resistive faults. And finally, the paper explains how system unbalance, due primarily to the line conductor configuration and spacing, can have adverse affects on directional elements for faults other than ground faults (in particular, three-phase faults).

In Reference [13], the various pilot schemes are discussed and a method is presented for measuring the performance of these schemes. One of the measures of performance stated in the paper is how well the pilot scheme detects high-resistance faults. The evaluation is based on using directional ground overcurrent relays for high-resistance fault coverage in a pilot scheme and a channel-independent distance element. Plots are provided showing high-resistive fault coverage for a particular system with respect to the fault location on the line.

References [11 and 13] are excellent guides for evaluating directional element, distance element, and pilot scheme performance. The papers also provide detailed information concerning the limits of each element on a simple two-ended system.

In this paper we are going to focus on the distance and directional element performance on the example system shown in Figure 10. Plots are provided demonstrating high-resistance fault coverage with respect to fault location and element type.

Directional Overcurrent and Distance Element Performance for High-Resistance Faults

To evaluate the directional and distance element fault-resistance coverage, the long line and short line system models shown in Figure 11 and Figure 15 are used. In both cases only the fault resistance coverage for ground faults is considered. The following settings are used for distance elements, ground overcurrent elements, and negative-sequence elements. All setting are in secondary quantities.

Zero-Sequence Directional Overcurrent (67N) = 0.5 amp (I_r current)

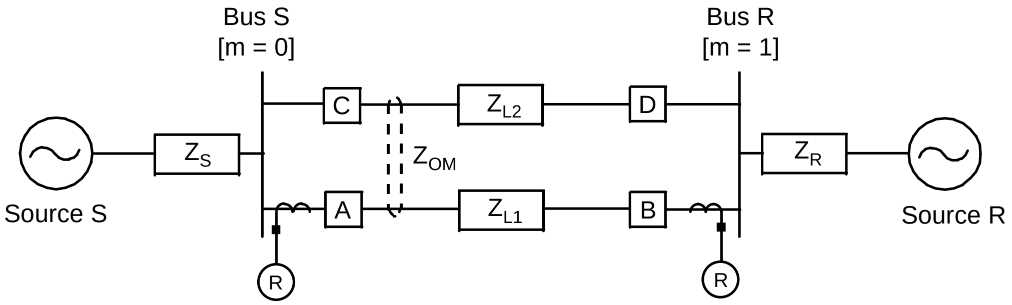
Negative-Sequence Directional Overcurrent (67Q) = 0.5 amp ($3 \cdot I_2$ current)

Mho Ground Distance (21G) = $2 \cdot Z_{1L1}$ ohms

Quadrilateral Ground Distance (21X) = $2 \cdot Z_{1L1}$ ohms, reactance reach

Quadrilateral Ground Distance (21X) = 50 ohms, resistance reach

The sensitivity of the directional overcurrent elements is limited by the specified pickup value, not the directional element operation. The operation of the ground distance elements is limited by the impedance settings, not the supervisory elements used with the distance elements. The quadrilateral reactance element is assumed to be corrected for system nonhomogeneity caused by a fault at the remote end of the line.



$Z_{1S} = 2\angle 88° \Omega$ $Z_{1L1} = Z_{1L2} = 8\angle 84° \Omega$ $Z_{1R} = 2\angle 88° \Omega$

$Z_{0S} = 2\angle 88° \Omega$ $Z_{0L1} = Z_{0L2} = 24\angle 80° \Omega$ $Z_{0R} = 2\angle 88° \Omega$

$Z_{0M} = 16\angle 78° \Omega$

Figure 11: Example System for a Long Line

Figure 12 shows the resistive fault coverage using ground overcurrent and negative-sequence overcurrent elements on a long line. As the fault location moves away from the bus, the amount of fault resistance detected by the zero-sequence overcurrent element (67N) decreases while the negative-sequence overcurrent element (67Q) increases. The change in fault resistance coverage is due to mutual coupling and differences in the line zero- and negative-sequence impedances [14].

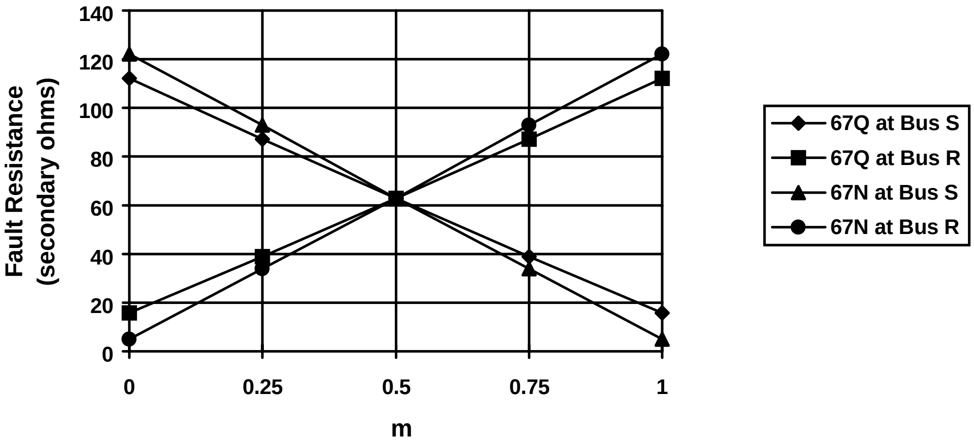


Figure 12: Long Line High Fault Resistance Detection Using 67N and 67Q Elements

Figure 13 shows the resistive fault coverage using mho and quadrilateral ground distance elements on a long line.

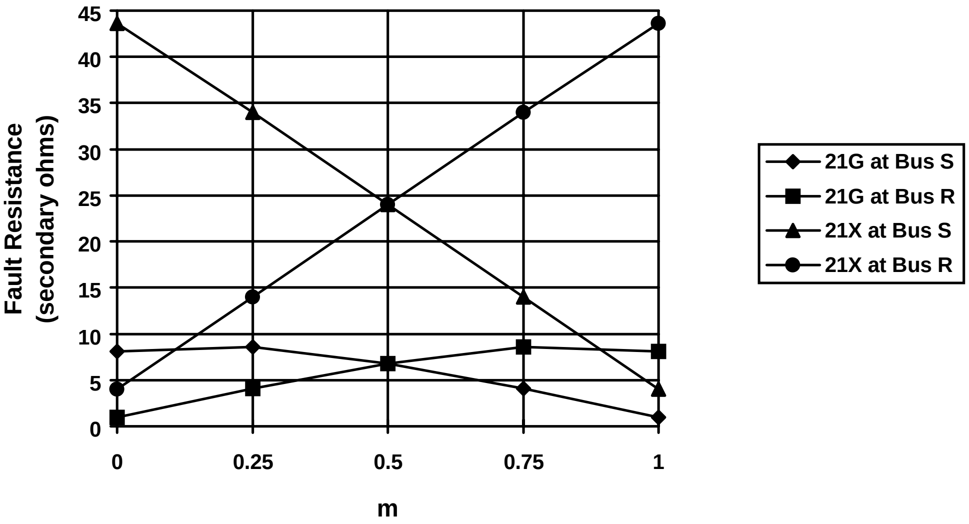


Figure 13: Long Line High Fault Resistance Detection Using 21G and 21X Elements

Figure 14 provides a comparison of the resistive fault coverage using only ground distance or ground overcurrent functions on a long line. In Figure 14 the ground distance and overcurrent functions are applied in a pilot scheme. The pilot scheme selected for the plot shown in Figure 14 is a new pilot scheme developed in Reference [13]. Reference [13] also provides additional information on pilot scheme comparisons with respect to fault-resistance coverage.

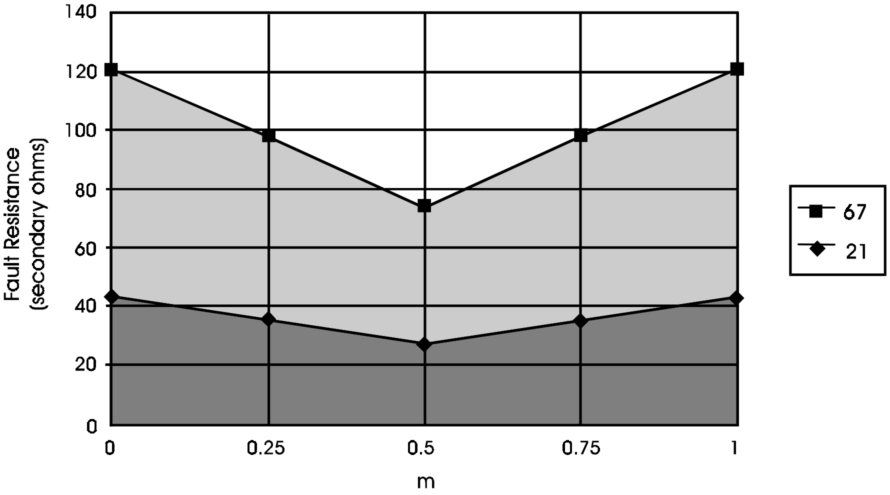
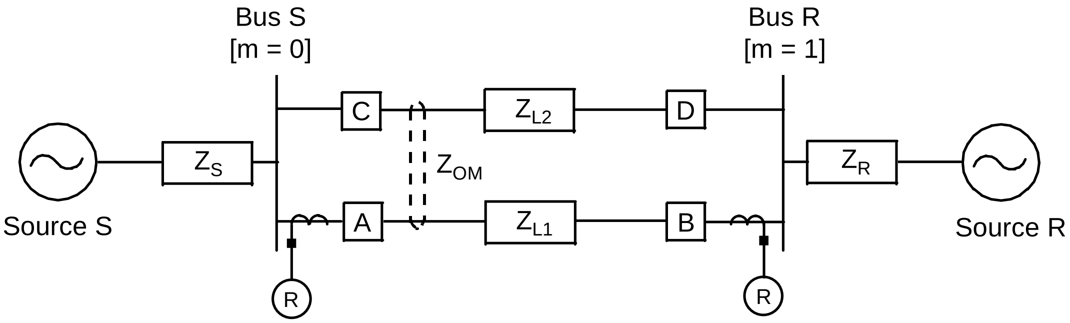


Figure 14: Long Line High Fault Resistance Detection, 21 versus 67 Elements



$Z_{1S} = 2\angle 88° \ \Omega$ $Z_{1L1} = Z_{1L2} = 0.5\angle 84° \ \Omega$ $Z_{1R} = 2\angle 88° \ \Omega$

$Z_{0S} = 2\angle 88° \ \Omega$ $Z_{0L1} = Z_{0L2} = 1.5\angle 80° \ \Omega$ $Z_{0R} = 2\angle 88° \ \Omega$

$Z_{0M} = 1\angle 78° \ \Omega$

Figure 15: Example System for a Short Line

Figure 16 shows the resistive fault coverage using ground overcurrent and negative-sequence overcurrent elements on the short line shown in Figure 15. As in the long line fault coverage, when the fault location moves away from the bus, the zero-sequence sensitivity decreases and the negative-sequence sensitivity increases.

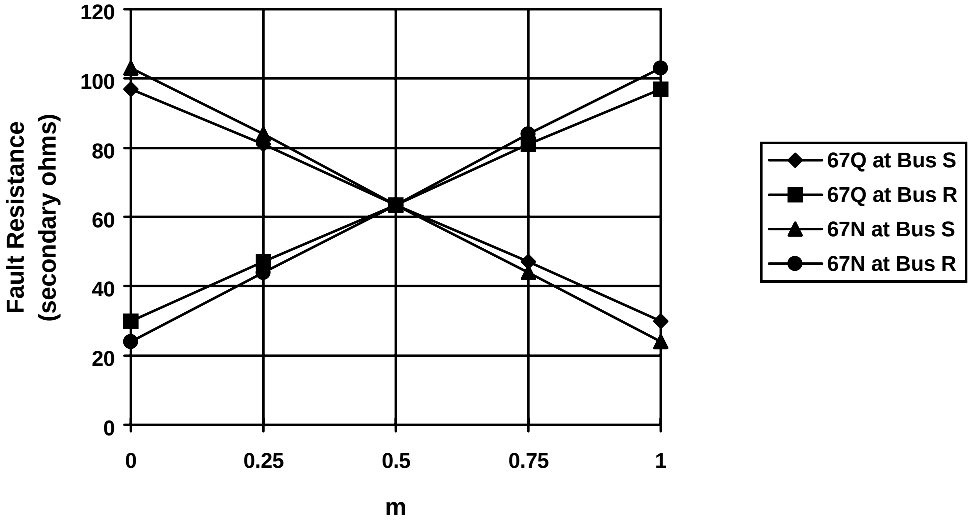


Figure 16: Short Line High Fault Resistance Detection Using 67N and 67Q Elements

Figure 17 shows the resistive fault coverage using a mho and quadrilateral ground distance elements on a short line.

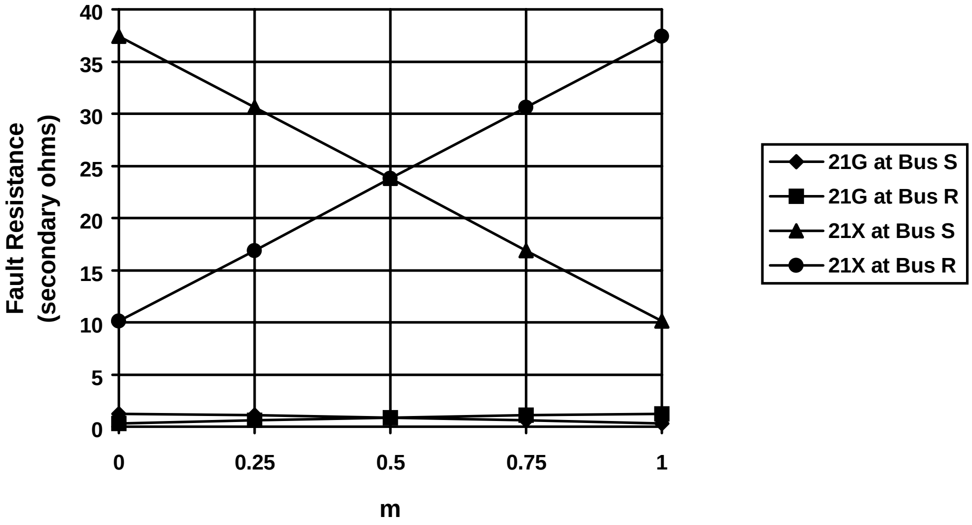


Figure 17: Short Line High Fault Resistance Detection Using 21G and 21X Elements

Figure 18 provides a comparison of the resistive fault coverage using only ground distance or ground overcurrent functions on a short line. In Figure 18 the ground distance and overcurrent functions are applied in a pilot scheme. The pilot scheme selected for the plot shown in Figure 18 is a new pilot scheme developed in Reference [18].

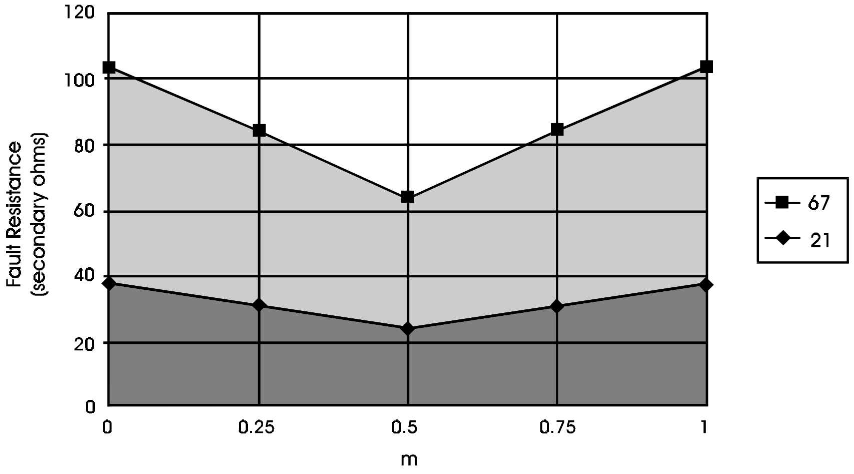


Figure 18: Short Line High Fault Resistance Detection, 21 Versus 67 Elements

Figures 12, 13, 16 and 17 show that as the fault moves away from the bus, the amount of fault resistance detected by the overcurrent and distance elements decreases. The decrease in fault resistance detection is due to current infeed from the other line terminal. The current infeed from the other terminal acts as a fault resistance amplifier. As the fault gets closer to the remote terminal, the amount of current contributed from the terminal nearest to the fault contributes a greater portion of the total fault current. The terminal furthest away from the fault contributes a very small portion of the total fault current.

The measured fault resistance can be approximated by dividing the total current in the fault by the current measured in the relay. To approximate the measured fault resistance for a remote fault (where the amplification for the fault resistance is at its greatest), apply a bolted fault at the remote bus and take the ratio of the total fault current to the fault current measured at the relay. Use the same currents in the ratio calculation as the relay uses in the distance relay resistive measurement. Multiply the current ratio by the fault resistance value to evaluate the ability of the distance relay to detect the remote, high-resistance fault.

Reference [11] shows how to calculate the maximum fault resistance detected by a zero- or negative-sequence overcurrent element based upon the element setting.

System Unbalances Due to Line Configuration or In-Line Load Switching

System unbalances caused by line configuration, in-line load switching, or unbalanced loads can affect the sensitivity of zero- and negative-sequence overcurrent elements. Ground distance elements are relatively immune to system unbalances primarily because they cannot be set as sensitive as overcurrent elements.

Reference [11] discusses in detail the limits of directional element performance for high-resistance faults, instrument transformer error, and transmission line configuration. Reference [11] also presents a method to determine the maximum resistive fault coverage based upon directional element operating parameters and system impedances.

The pickup threshold for fault detecting elements should always be set greater than the normal unbalance on the power system. Given that high-resistance faults generate very low operating voltages and currents, any load-generated system unbalance can affect the sensitivity of a ground fault detecting element, in particular, zero-sequence and negative-sequence elements. Setting these elements too sensitive can result in unwanted operations.

Load or in-line switching also generates system unbalances. Switching via a circuit breaker does not have a significant impact on sensitive fault detecting elements because the breaker poles all open at nearly the same time. However, when load-break switches are used for switching, there could be a number of cycles between each phase interruption. This means that while the load-break switch is opening, unbalances are generated that could cause directional and overcurrent element operation. If no corrective action is taken, the relay scheme may misoperate and trip during the switching operation.

Open phase conductors also generate system unbalances and can be treated the same as in-line switching. For this case it is assumed that the conductor has opened, but has not made contact with ground.

Appendix A provides details on calculating the sequence components for in-line load switching and open conductors. This appendix also offers options for preventing misoperation of the relay during in-line switching operations.

SELECTING THE BEST GROUND FAULT DETECTING ELEMENT

The data presented in this paper and published in previous papers [2, 6, 11, 13] clearly show that using zero-sequence and negative-sequence overcurrent elements in a pilot scheme provides the best protection with respect to security, dependability, and sensitivity (high-resistance fault coverage).

Using a combination of zero- and negative-sequence overcurrent elements provides the maximum fault resistance coverage for long or short lines, with and without mutual coupling. Zero- and negative-sequence overcurrent elements are likewise fairly immune to load flow and system nonhomogeneity. However, the sensitivity of zero- and negative-sequence overcurrent elements can be affected by system unbalance and in-line load switching as previously described.

Distance elements provide fair fault resistance coverage and are more tolerant to system unbalance and in-line load switching. However, mho elements provide little or no fault resistance coverage and can also be adversely affected by zero-sequence mutual coupling. The quadrilateral distance elements, while providing better fault resistance coverage than mho elements, are also affected by zero-sequence mutual coupling.

Quadrilateral distance elements are extremely sensitive to system nonhomogeneity if corrective measures are not taken. One relay has improved the quadrilateral reactance element design against overreaching caused by system nonhomogeneity. The improved design is compensating the polarizing reference based upon the system and not a factory-fixed correction factor.

The following tables highlight the benefits and application for each of the ground-fault detecting elements discussed in this paper. Table 1 compares the performance of the ground-fault detecting elements for specific applications. Table 2 should be used as a guide for selecting ground fault detecting elements.

Table 1: Application Performance of Ground Fault Detecting Elements

PERFORMANCE IN SPECIFIC APPLICATIONS	67N	67Q	21X	21G
Short Line Applications	☆☆☆	☆☆☆	☆	☆
Long Line Applications	☆☆☆	☆☆☆	+	☆
Parallel Line Applications	☆	☆☆☆	+	+
Channel Independent Direct Tripping - Instantaneous	☆	☆	☆☆☆	☆☆☆
Channel Independent Direct Tripping - Time Delay	☆	☆	☆☆☆	☆☆☆
Pilot Scheme	☆☆☆	☆☆☆	☆	☆

☆☆☆ = best selection
☆ = satisfactory
\+ = satisfactory but requires further study

67N = directional zero-sequence overcurrent element
67Q = directional negative-sequence overcurrent element
21X = quadrilateral ground distance element
21G = mho ground distance element

Table 2: Ground Fault Detection Element Selection Guide

PERFORMANCE IN THE PRESENCE OF:	67N	67Q	21X	21G
System nonhomogeneity *{pages 11-15}*	☆☆☆	☆☆☆	+	☆
High Fault Resistance (R_F) *{pages 18-23}*	☆☆☆	☆☆☆	☆	-
Strong Source *{pages 18-20}*	☆☆☆	☆☆☆	☆	☆
Weak Source *{pages 21-23}*	☆	☆	☆	☆
Zero-Sequence Mutual Coupling *{pages 15-17}*	☆	☆☆☆	+	+
Load Flow *{references 9,15}*	☆☆☆	☆☆☆	+	☆☆☆
In-Line Load Switching *{Appendix A}*	+	+	☆☆☆	☆☆☆
Nontransposed Transmission Lines *{reference 3}*	☆	+	☆☆☆	☆☆☆
Unbalanced Loading	☆	+	☆☆☆	☆☆☆

☆☆☆ = best selection
☆ = satisfactory
\+ = satisfactory but requires further study
\- = unsatisfactory

67N = directional zero-sequence overcurrent element
67Q = directional negative-sequence overcurrent element
21X = quadrilateral ground distance element
21G = mho ground distance element

Reference [15] provides one utility's perspective on selecting ground fault protection. The author states that the preferred method is ground overcurrent elements because they are simple and reliable. When the polarizing quantities available are inadequate for reliable relay operation, then ground distance is used. In addition, guidelines for determining adequate polarizing quantities is shown.

The ground fault protection selection criteria outlined in Reference [15] are valid for relays using directional elements that use conventional torque calculations. References [6, 9, and 14] show an improved directional element design using an impedance-based directional element. The impedance-based element design overcomes limitations of conventional torque elements and expands the application of zero- and negative-sequence overcurrent elements.

RECOMMENDATIONS FOR SETTING GROUND FAULT DETECTING ELEMENTS

Direct-Tripping Overcurrent Elements (Instantaneous Elements)

Direct-tripping zero-sequence overcurrent elements should be set greater than the maximum out-of-section fault current.

In circumstances where the line is mutually coupled with other transmission lines the maximum zero-sequence current may be for a fault at the end of a parallel line with the breaker close-in to the fault open (sometimes referred to as end-of-line faults). The end-of-line fault current could result in the maximum external fault current because the mutual coupling between circuits is at its maximum.

If the line is not mutually coupled, the maximum fault current is typically for faults at the remote bus.

Direct tripping negative-sequence overcurrent elements should be set greater than the maximum out-of-section fault current considering both phase and ground faults.

Negative-sequence current is generated for all unbalanced faults. Zero-sequence mutual coupling does not affect the negative-sequence overcurrent element and end-of-line faults are not considered.

The maximum out-of-section fault current must be evaluated for phase faults as well as ground faults since negative-sequence current is generated for all unbalanced faults. Carefully evaluate the negative-sequence overcurrent element setting parameters since they may be in terms of I_2 or $3 \bullet I_2$ current.

Set the direct tripping element greater than the maximum external fault current plus some margin.

The margin is determined by the steady-state and transient overreach error of the protective relay. *Refer to the protective relay support documentation or contact the relay manufacturer for this information.* Additional margin should be added to the setting to account for fault study, line modeling, and current transformer errors (typically 5 to 10% is adequate). Set the direct tripping element using Equation 14:

$$\text{Pickup} = I_F \bullet \left(1 + \frac{\varepsilon_{SS}}{100} + \frac{\varepsilon_T}{100} + 0.05\right) \qquad \text{Equation 14}$$

Where:

I_F = maximum external fault current

ε_{SS} = percent of steady-state error

ε_T = percent of transient error

0.05 = additional 5% margin to account for modeling and ct errors.

Direct Tripping Distance Elements (Zone 1)

Direct tripping distance elements should be set to underreach faults at the remote bus.

Direct tripping distance elements are generally set based on the true line impedance. Mutual coupling effects and remote infeed are typically not considered when setting the direct tripping distance elements. The steady-state and transient reach errors of the relay should be considered when setting the distance element to underreach the remote terminal.

Capacitive voltage transformer (CVT) transient errors must be considered while determining the reach setting for direct tripping distance elements.

Capacitive voltage transformers (CVTs), have a transient response that may cause a distance element to overreach [8]. The overreach error caused by the CVT transient response is a function of the source impedance ratio (SIR, which is the source impedance divided by the distance element setting or line impedance), CVT ferroresonance circuit design, and distance relay design. The direct tripping element reach must be reduced or time-delayed to avoid operation on external faults. *Refer to the protective relay support documentation or contact the relay manufacturer for information on CVT transient response.*

The following steps show the calculations for determining the CVT overreach error.

1. Calculate the positive-sequence source impedance behind the relay. The positive-sequence source impedance can be calculated using a fault study. One approach is to determine a thevenin equivalent of the system with respect to the buses. The source impedance can also be calculated by applying a three-phase bus fault, removing the current contribution from the subject line, and dividing the line-to-neutral nominal system voltage by the adjusted total fault current. The source impedance should be calculated under the weakest source condition.
2. Calculate the source to line impedance ratio (SIR) by dividing the calculated source impedance by the line positive-sequence impedance.
3. From the SIR calculated in Step 2, estimate the reach reduction from data provided by the relay manufacturer. Reference [6] provides a graph for reducing the Zone 1 reach based upon the CVT design. *The graph presented in Reference [6] applies to one relay design. The specific relay manufacturer should be contacted for information concerning CVT transient overreach.*

Direct Tripping Mho Ground Distance Elements

The following steps show the reach settings calculations for direct tripping mho ground distance elements:

1. Determine the minimum line impedance to the next line section or bus.
2. If CVTs are not used, go to Step 3. If CVTs are used, reduce the impedance obtained in Step 1 by the factor determined from the CVT overreach calculations.
3. Set the reach using Equation 15:

$$Z_R = Z1_{MIN} \bullet \left(1 - \frac{\varepsilon_{SS}}{100} - \frac{\varepsilon_T}{100} - 0.05\right) \qquad \text{Equation 15}$$

Where:

Z_R = distance relay reach setting

$Z1_{MIN}$ = minimum line impedance from Step 1 or 2

ε_{SS} = percent of steady-state error

ε_T = percent of transient error

0.05 = additional 5% margin to account for line modeling, ct, and pt errors

Direct Tripping Quadrilateral Ground Distance Elements

Quadrilateral distance elements must be set considering unequal source and line impedance angles.

Unequal source and line impedance angles can cause a reactance element to over- or underreach when fault resistance is present. The reactance element over- or underreach can be calculated using Equation 10. The error term calculated in Equation 10 assumes a zero-sequence polarized reactance element. The nonhomogeneous system error must be considered when setting underreaching quadrilateral distance elements to prevent overreaching on external, high-resistance faults.

Adjust the polarizing reference or reduce the Zone 1 reach to accommodate unequal source and line impedance angles.

Adjusting the polarizing quantity is sometimes shown as tilting the reactance characteristic. While adjusting the characteristic by a fixed angle helps improve the overreach error, it does not improve the reactance element performance for all systems.

Providing a settable adjustment works very well for a particular fault location and system condition. In those cases where the system source angle can dramatically change due to changing operating conditions, further study is required.

The adjustment angle can be calculated using Equation 7 or 8 for a zero-sequence polarized reactance element.

Limiting the resistive reach of the Zone 1 element reduces the possibility of overreach due to resistive faults and unequal source and line impedance angles.

Using an extended Zone 1 resistance reach increases the possibility of the Zone 1 reactance element overreaching due to resistive faults. Equation 10 shows that increasing the amount of fault resistance detected by the Zone 1 element can increase the fault resistance induced error.

The fault resistance coverage required by the Zone 1 element can be determined from historical fault data, the tower footing resistance, or by calculating the arc resistance. Some relay manufacturers provide guidelines on limiting the resistive reach as a function of the reactance setting. These guidelines should be consulted when determining the Zone 1 resistive reach setting.

Selecting an arbitrary resistive setting is also valid, given that the fault resistance induced error in the reactance measurement is carefully evaluated.

Follow these steps in calculating the reach setting for a direct tripping quadrilateral ground distance element:

1. Determine the minimum line impedance to the next line section or bus.
2. If CVTs are not used, go to Step 3. If CVTs are used, reduce the impedance obtained in Step 1 by the factor determined from the CVT overreach calculations shown earlier.

3. Calculate the nonhomogeneity adjustment factor (this factor has a magnitude and angle) using Equation 7 or 8 by applying a fault at the remote bus under normal operating conditions (set the "m" value in Equation 7 to 1).

4. In a relay that allows a settable adjustment to the polarizing reference, use the angle obtained from the nonhomogeneity adjustment factor calculated in Step 3. Continue with Step 5 using the nonhomogeneity adjustment factor angle as the fixed polarizing reference angle. Evaluate various system conditions that result in a change in the nonhomogeneity angle. Select the worst case change in the nonhomogeneity angle and use it in the following steps.

5. In relays with a fixed polarizing reference adjustment, calculate the resistance error by subtracting the fixed reactance line tilt from the angle calculated in Step 3 or 4. Subtract a negative angle for a downward fixed tilt. Subtract a positive angle for a upward fixed tilt.

6. *This step is a data gathering procedure to obtain the data required for Step 7.* Apply a bolted single-phase-to-ground fault at the remote bus under normal operating conditions. Obtain the fault currents (phase and ground currents) from the fault study. Use the angle calculated in Step 5 for the "T" variable. Use the magnitude of the adjustment factor calculated in Step 3 for the "A" variable. Use the selected resistance setting used for the Zone 1 quadrilateral element for the "R_F" variable.

7. Calculate the reactance error using the data obtained in Step 6 and Equation 10.

8. Subtract the reactance error obtained in Step 7 from the impedance calculated in Step 2. If the reactance error calculated in Step 7 is negative, the relay will overreach for resistive faults. If the error term calculated in Step 7 is positive, it can be ignored since it will cause the relay to underreach for resistive faults.

9. If the result of Step 8 is less than zero, the reactance reach setting cannot be reduced to accommodate the fault resistance induced error. The resistive reach setting must be reduced and a new reactance error must be calculated starting at Step 7 to obtain the new resistive reach setting.

10. Set the resistive reach to the value determined from Step 7 or Step 9, which ever is less or gives the least reactance reach error.

11. Set the reactance reach using Equation 16:

$$Z_R = Z1_{MIN} \bullet \left(1 - \frac{\varepsilon_{SS}}{100} - \frac{\varepsilon_T}{100} - 0.05\right) \qquad \text{Equation 16}$$

where:

Z_R = distance relay reach setting

$Z1_{MIN}$ = minimum impedance determined in Step 8

ε_{SS} = percent of steady-state error

ε_T = percent of transient error

0.05 = additional 5% margin to account for line modeling, ct, and pt errors

Overreaching Overcurrent Elements

Sensitive set tripping elements should be set above normal system load unbalance or the unbalance caused by line asymmetry under balanced fault conditions.

Overreaching current elements used in pilot protection schemes can be set very sensitive to detect high-resistance ground faults. However, to maintain scheme security, the sensitive set elements should be set above normal load unbalance.

It is difficult to theoretically determine the normal system load unbalance on the power system. Reference [11] presents methods for determining the load generated zero- and negative-sequence current caused by line asymmetry.

It is also possible to take measurements at the time of relay installation, but setting adjustments may be required in the field to decrease the sensitivity of overcurrent elements.

A limiting factor to ground fault detection is the directional element sensitivity. The directional element sensitivity should be evaluated while determining the amount of fault resistance coverage required for a particular application.

Reference [11] indicates that there is no advantage to setting overcurrent tripping elements more sensitive than the directional element sensitivity. In fact, setting the overcurrent element to low (i.e., very sensitive) may cause the relay to over trip for external faults. Review Reference [11] for more information on directional element sensitivity.

Set directional element supervisory elements to maximize sensitivity, but do not set less than the load unbalance caused by line asymmetry.

Directional element sensitivity in some designs [6, 9, 11] can be controlled by ratios of sequence currents typically referred to as restraint factors.

In one design, the ratio of the negative-sequence current magnitude to the positive-sequence current magnitude (referred to as the a2 ratio factor) is used to control operation of the directional element. If high-resistance ground coverage is not required, it is recommended that a2 be set to no less than **0.15**.

Reference [11] shows a2 ratio factors for vertical and horizontal line construction with different conductor phasing. These figures illustrate that an a2 ratio factor of **0.1** is adequate for the majority of phasing configurations. However, line configuration should be evaluated to determine the actual a2 ratio factor.

The a2 ratio factor can be determined from a measurement of the phase currents on the line and calculating the a2 ratio factor under load conditions. It is valid to assume that a2 ratio factor remains constant for maximum load values.

The a2 ratio factor can be determined by using the line impedance as shown in Reference [11] and calculating the a2 ratio factor from the line impedance data.

If it is not convenient to calculate the line impedance or the a2 ratio factor from the line impedance data, then set the a2 ratio factor to **0.1**.

The tripping elements should be set to provide maximum fault resistance coverage as well as maximum security under external fault conditions.

It is recommended that tripping elements should be set to no less than **0.5 amps secondary** unless further study is performed. The lower limit of 0.5 amps applies to both zero-sequence and negative-sequence overcurrent elements. The zero-sequence overcurrent elements are set in terms of $3 \cdot I_0$ (I_r) and the negative-sequence overcurrent elements are set in terms of $3 \cdot I_2$.

Overreaching Ground Distance Elements

Ground distance elements should be set to minimize operating time when used exclusively in a pilot scheme.

Traditionally, overreaching Zone 2 elements are set from 120% to 150% of the protected line impedance. The same Zone 2 element that is used in the pilot scheme is typically used as a time-delayed backup element. Newer relay designs allow separately set Zone 2 pilot and Zone 2 backup elements. The pilot zone can be set from 300% to 500% of the line impedance without coordination concerns, thus minimizing the element operating time. The backup zone can be set to the more traditional reaches.

When using extended pilot zone reaches, set the relay load encroachment logic to avoid operation under heavy load conditions.

Overreaching time-delayed backup distance relays should be set less than the next line section Zone 1 element.

Setting the overreaching time-delayed backup zone less than the next line section Zone 1 element ensures proper coordination. If a long line is terminated into a substation with short lines, the time-delayed element reach or coordination margin may have to be reduced.

When heavy mutual coupling is present, it may be necessary to set the ground distance relay from 200% to 300% of the positive-sequence line impedance to overreach the remote terminal.

For cases with heavy mutual coupling, using a ground distance relay as a dedicated pilot zone does not present a problem. However, if the ground distance element is used for time-delayed backup, it is recommended that other options be explored.

Relays that offer separate zero-sequence compensation for the underreaching and overreaching zones can compensate such that the ground distance element measures the correct impedance for faults at the end of the line.

Adjusting the zero-sequence compensation to correct for the effects of mutual coupling only works well when the line is coupled with one other line and both ends of the lines are terminated at the same buses. The zero-sequence compensation must be changed when the parallel line is out-of-service. Relays with multiple setting groups work very well for this application. The relay can be wired to change setting groups when the parallel line is removed from service using a breaker auxiliary contact from the parallel line. The zero-sequence compensation factor used for the alternate setting group should be set based upon the line impedance only.

Follow these steps in calculating the reach setting for an overreaching ground distance element:

1. Determine the maximum positive-sequence line impedance to the next line section or bus without considering infeed or mutual coupling (i.e., actual line impedance values).
2. If the circuit is not mutually coupled, go to Step 4. If the circuit is mutually coupled with one other parallel line, calculate the apparent impedance seen for a bolted single phase-to-ground fault at the remote bus using Equation 11, otherwise go to Step 3.
3. If the circuit is mutually coupled with more than one line or the mutually coupled lines are not terminated at the same substations, calculate the apparent impedance for a bolted fault at the remote bus using Equation 12.
4. If the overreaching ground distance element is used exclusively as a pilot tripping zone, set reach from **three** to **five** times the impedance calculated in Step 1, 2, or 3. When using the extended reach setting it is always recommended that the relay load encroachment logic be set to avoid operation under load conditions.
5. If the overreaching ground distance element is used for time-delayed backup as well as pilot protection, set the reach from **120 to 150%** of the impedance calculated in Step1, 2, or 3.

Calculating True Quadrilateral Fault Resistance Coverage

A quadrilateral distance element cannot detect the fault resistance specified by the resistive element reach setting due to current infeed into the fault resistance from the other line terminal.

The amount of fault resistance detected by a quadrilateral element is not necessarily the resistance element setting. On a radial system, the fault resistance measured by the quadrilateral resistance element is the actual fault resistance because the relay measures the only current contribution to the fault. On a looped system, current can be supplied from two or more sources. Multiple sources supplying current into a high-resistance fault amplify the actual fault resistance with respect to one of the sources supplying fault current.

Follow these steps in calculating the approximate fault resistance detected by the quadrilateral distance element:

1. Apply a bolted fault at the remote bus. The measured resistance is maximum for a remote fault.
2. Divide the total fault current by the fault current measured in the relay. In the ratio calculation use the same currents the relay uses in the resistive element measurement.
3. Divide the resistive element setting by the current ratio calculated in Step 2. The result is an approximation of the true fault resistance detected by the resistance element.

CONCLUSIONS

1. Never set ground fault protection elements more sensitive than normal system unbalance due to line asymmetry or unbalanced loading.
2. Use combined zero-sequence and negative-sequence overcurrent elements in a pilot protection scheme to obtain the best high-resistance fault coverage.
3. Use ground mho elements when high-resistance fault coverage is not a concern.
4. Ground distance relays provide good ground fault protection independent of the pilot protection scheme.
5. Quadrilateral ground elements can provide good fault resistance coverage, but require special study to ensure that underreaching (or direct tripping elements) do not overreach for resistive faults.
6. Zero-sequence mutual coupling can cause ground distance elements to under- or overreach under certain conditions. The effects of mutual coupling should be evaluated and considered when setting ground distance elements.
7. In-line load switching creates unbalances that can cause sensitive overcurrent elements to operate and possibly trip. Corrective action must be taken to desensitize or block these elements during the switching operation.

REFERENCES

1. G. E. Alexander and J. G. Andrichak, "Ground Distance Relaying: Problems And Principles," 18th Annual Western Protective Relay Conference, Spokane, Washington, October 20, 1991.

   The operating principles of ground distance functions and some of the limitations, or problems, that can be encountered in their application are discussed in this paper. The development of the mho characteristic is presented along with details regarding different choices of polarizing signals. The effects of mutual induction on ground distance relays and the effect of fault resistance is also presented. The paper goes one step further and presents typical problem areas for ground distance relays including single phase tripping considerations.

2. Walter A. Elmore, "Current Differential and Phase Comparison Relaying Compared with Pilot Distance Schemes," 48th Annual Protective Relaying Conference at the Georgia Institute of Technology, Atlanta, Georgia, May 4-6, 1994.

   Current differential and phase comparison relaying are compared with pilot distance schemes. The paper points out the qualities of each system.

3. Walter A. Elmore, "Zero-Sequence Mutual Effects on Ground Distance Relays and Fault Locators," 46th Annual Protective Relaying Conference at the Georgia Institute of Technology, Atlanta, Georgia, April 29 - May 1, 1992.

   This paper covers the concerns associated with zero-sequence mutual effects. The paper describes the phenomenon in basic terms and provides some assistance in evaluating the severity of its influence on ground distance relays and fault locators.

4. Ahmed F. Elneweihi, "Useful Applications for Negative-Sequence Overcurrent Relaying," 22nd Annual Western Protective Relay Conference, Spokane, Washington, October 24-26, 1995.

   This paper presents some practical applications on the B.C. Hydro system where negative-sequence overcurrent elements offer a much better sensitivity than zero-sequence elements in detecting single-line-to-ground faults. A wider use of the negative-sequence overcurrent elements for detecting single-line-to-ground fault is proposed.

5. A.T. Giuliante, J.E. McConnell, S.P. Turner, "Considerations for the Design and Application of Ground Distance Relays," 22nd Annual Western Protective Relay Conference, Spokane, Washington, October 24-26, 1995.

   This paper explores how ground distance relays are designed and applied for protection of the power system. Methods of polarization and the measurement of the impedance by the ground distance relay is reviewed. The paper includes discussion of the classical R-X diagram.

6. Armando Guzman, Jeff Roberts, and Daqing Hou, "New Ground Directional Elements Operate Reliably for Changing System Conditions," 23rd Annual Western Protective Relay Conference, Spokane, Washington, October 15-17, 1996.

   A new ground directional relay (GDR) that selects among zero-sequence current polarized, negative-sequence voltage polarized, or zero-sequence voltage polarized directional elements according to system conditions is described. The paper uses system examples to show how this GDR selects the optimal directional element for each system condition. The results are increased sensitivity, improved security, and setting simplicity.

7. C.F. Henville, “Combined Use of Definite and Inverse Time Overcurrent Elements Assists in Transmission Line Ground Relay Coordination,” 20th Annual Western Protective Relay Conference, Spokane, Washington, October 19-21, 1993.

   This paper discusses the background to the application of the inverse time ground overcurrent relay characteristics and definite time relay characteristics , including the particular strengths of each type. The benefits of combined use are explored. Two examples are shown where combined use has improved achievable speed and sensitivity settings while maintaining adequate coordination margins.

8. Daqing Hou and Jeff Roberts, “Capacitive Voltage Transformers: Transient Overreach Concerns and Solutions for Distance Relaying,” 22nd Annual Western Protective Relay Conference, Spokane, Washington, October 24-26, 1995.

   This paper discusses capacitive voltage transformers (CVTs) and how microprocessor-based relays respond to them. The source impedance ratio (SIR) affects on the CVT transient response is reviewed. The paper discusses improvements in relaying logic, which detects the CVT transients. The new method of detecting CVT transients is more precise than past detection methods and does not penalize distance protection speed for close-in faults.

9. Jeff Roberts and Armando Guzman, “Directional Element Design and Evaluation,” 21st Annual Western Protective Relay Conference, Spokane, Washington, October 18-20, 1994.

   Basic directional element designs are presented. The paper evaluates various directional element input combinations and analyzes how the combinations perform for simple and complex faults. It addresses directional element security, and an improved negative-sequence directional element which out-performs traditional directional elements in difficult applications.

10. J. Roberts, A. Guzman, and E.O. Schweitzer, III, “Z=V/I Does Not Make a Distance Relay,” 20th Annual Western Protective Relay Conference, Spokane, Washington, October 19-23, 1993.

    This paper examines the Z=V/I approach and shows the degradations due to load flow and fault resistance. Calculating Z=V/I and testing Z against a circle passing through the origin is shown to be equivalent to a self-polarized mho element. Methods used in numerical relays and emphasis that these methods have their roots in sound polarization methods is also presented.

11. Jeff Roberts, Edmund O. Schweitzer, III, Renu Arora, and Ernie Poggi, “Limits to the Sensitivity of Ground Directional and Distance Protection,” 22nd Annual Western Protective Relay Conference, Spokane, Washington, October 24-26, 1995.

    This paper reveals that the directional element not the pickup setting typically limits sensitivity. It also addresses that sensitivity is not entirely limited by the relay, but is limited by the rest of the system: system unbalance, instrument transformer accuracy and ratings, grounding practices, and source strengths. The paper identifies these limits, analyzes them, and offers practical solutions.

12. Edmund O. Schweitzer, III, "Evaluation and Development of Transmission Line Fault-Locating Techniques Which Use Sinusoidal Steady-State Information," 9th Annual Western Protective Relay Conference, Spokane, Washington, October 26, 27, 28, 1982.

    This paper analyzes and compares fault-location algorithms which use steady-state data. A modification to the Takagi method of computing the apparent reactance seen from one end of the faulted line is presented. The modification provides a simple method of improving the performance of the Takagi algorithm when some system data are available. A two-ended algorithm is presented, which requires no assumptions on system parameters outside the monitored line.

13. Edmund O. Schweitzer, III, John J. Kumm, "Statistical Comparison and Evaluation of Pilot Protection Schemes," 23rd Annual Western Protective Relay Conference, Spokane, Washington, October 15-17, 1996.

    This paper quantifies the likelihood of misoperations (overtripping, time-delayed tripping), fault resistance coverage, operating times, and complexity for several popular protection schemes. A new communications-aided protection scheme is proposed, which provides faster operation, better fault resistance coverage, and minimizes the risks of misoperations.

14. E.O. Schweitzer, III and Jeff Roberts, "Distance Relay Element Design," 19th Annual Western Protective Relay Conference, Spokane, Washington, October 19-22, 1992.

    Basic distance and directional element design is presented. The paper also discusses classical element-security problems and remedies, and presents a new directional negative-sequence element. This paper provides a useful table summarizing the different mho element polarizing choices and the affect on the dynamic performance of the mho element.

15. Edgar R. Terlau, II, "Experience With the Application and Setting of Ground Distance Relaying," 17th Annual Western Protective Relay Conference, Spokane, Washington, October 23-25, 1990.

    This paper briefly outlines the steps that are usually employed in specifying ground distance relays in the Pacific Gas and Electric Co. (PG&E) system, and covers in greater detail the methods used in applying and setting ground distance relays.

16. William Z. Tyska, "Polarization of Ground Distance Relays," Western Protective Relay Conference, Spokane, Washington, October 21-23, 1986.

    This paper investigates the significance of different polarizing quantities on ground distance relay performance, the relay characteristic is used to visualize relay response. The following are covered in the paper: mho unit analysis, application considerations regarding polarizing quantities, a comparison of mho and quadrilateral characteristics, and a performance comparison evaluating the relay performance.

17. Karl Zimmerman and Joe Mooney, "Comparing Ground Directional Element Performance Using Field Data," 20th Annual Western Protective Relay Conference, Spokane, Washington, October 19-21, 1993.

> *Differences between negative-sequence and zero-sequence polarization techniques, with emphasis on selecting the correct polarization method is presented in this paper. Event reports, along with mathematical analysis, are presented to demonstrate the following: how the directional elements behave during a fault with a voltage neutral shift, how a zero-sequence voltage polarized element can be affected by mutual coupling with a parallel line, and how selection of the proper polarizing method can be dependent upon system operating conditions.*

18. S.E. Zocholl, "Three-Phase Circuit Analysis and the Mysterious K_0 Factor," 48th Annual Conference for Protective Relay Engineers at Texas A&M University, College Station, Texas, April 3-5, 1995.

> *Three-phase circuit analysis of the transmission circuit is presented. Each step in the document is furnished in a MathCAD 5.0 file. The reader is lead through calculating voltage and current phasors and using the data to determine relay performance.*

APPENDIX A - MODELING IN-LINE SWITCHING AND OPEN PHASE CONDUCTORS

This appendix discusses how to model in-line switching and open phase conductors. The effects in-line switching and open phase conductors have on sensitive set ground fault detecting elements is presented, along with protective relay corrective measures to ensure secure operation of sensitive set overcurrent elements.

MODELING IN-LINE SWITCHING OR OPEN-PHASE CONDUCTOR CONDITIONS

Assume that a load break switch is sectionalizing the line or that a conductor can open anywhere along the protected line section. In these cases, any one solution must not be dependent upon the location of the switch or open conductor. For simplicity, assume a switch is opening in the middle of the line at m = 0.5 for the system shown in Figure A.1 (where m = per-unit line length).

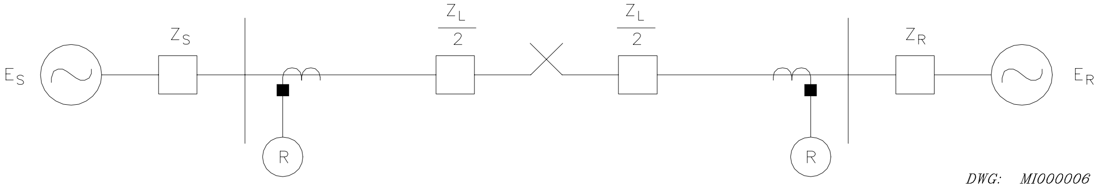


Figure A.1: Single Line Diagram of Example System

For the example example system shown in Figure A.1, assume the following parameters:

- $Z_{1S} = Z_{1R} = 1 \angle 90° \ \Omega$
- $Z_{0S} = Z_{0R} = 3 \angle 90° \ \Omega$
- $Z_{1L} = 3 \angle 90° \ \Omega$
- $Z_{0L} = 9 \angle 90° \ \Omega$
- $|E_S| = |E_R| = 66.4$ V

Adjust the angle of E_S such that 5 A of secondary load current flows from Source S to Source R before the switch opens or the jumper fails. For this system, the angle of E_S is 21.7° leading E_R.

The symmetrical components connection for a single-phase open condition is shown in Figure A.2. The connection diagram shown in Figure A.2 is very similar to that of a mid-line phase-to-phase-to-ground fault (Figure A.3).

In Figure A.2, the through load positive-sequence current divides between the negative- and zero-sequence networks (i.e., $I_1 = -(I_2 + I_0)$). The relationship of $I_1 = -(I_2 + I_0)$ is identical to that obtained for a phase-to-phase-to-ground fault on a radial system with the remote breaker open. The relays at both ends of the line are also subjected to the same sequence currents since I_1, I_2, and I_0 are the equivalent for both ends of the line.

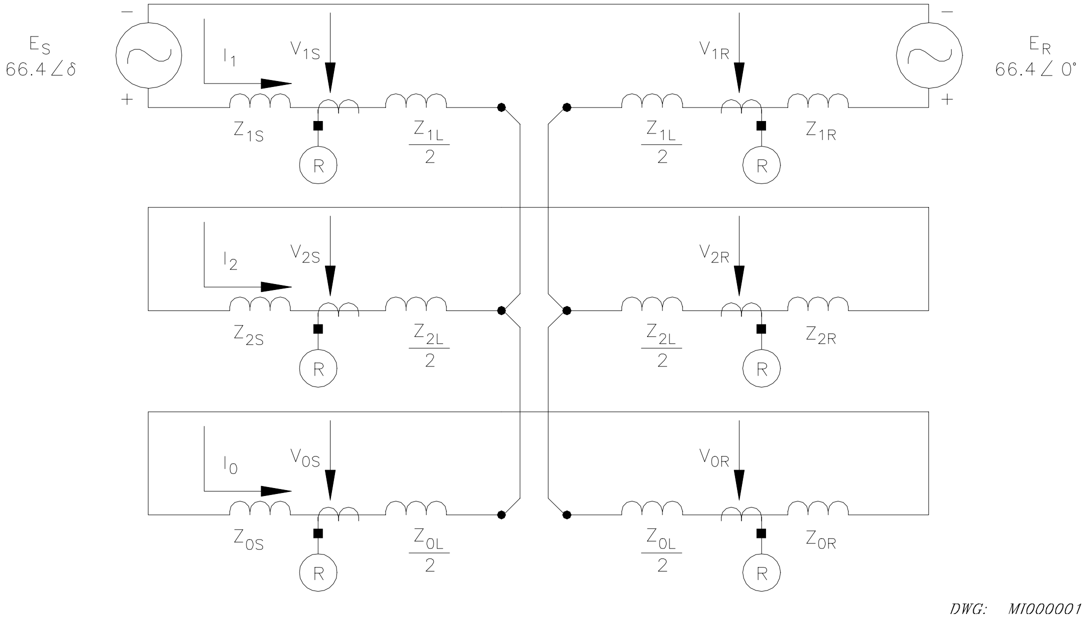


Figure A.2: Symmetrical Components Connection for Single-Phase Open Condition

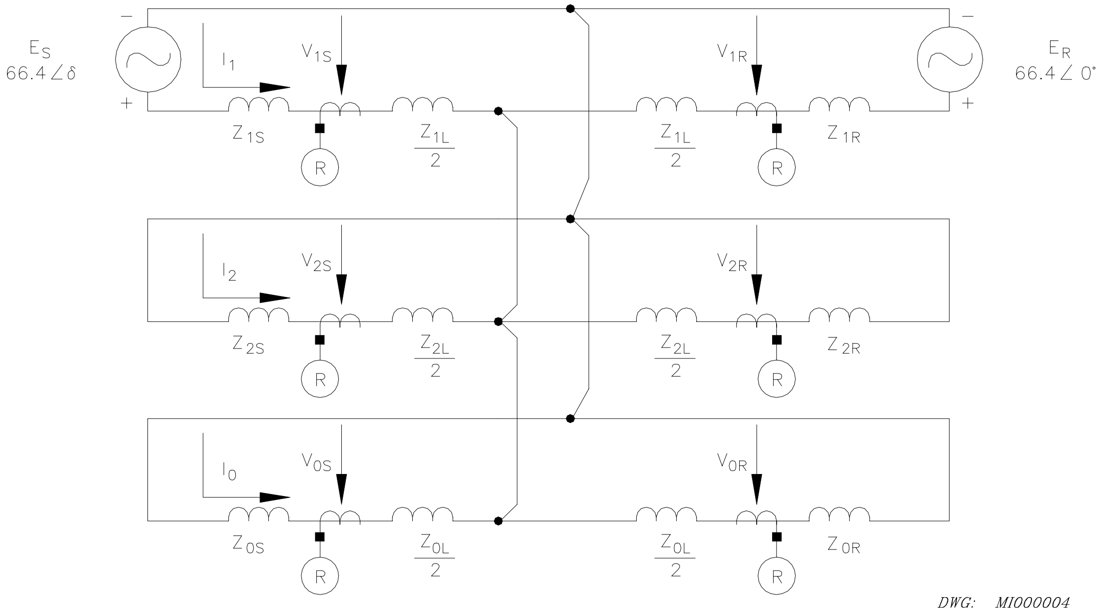


Figure A.3: Symmetrical Components Connection for Phase-Phase-Ground Fault

The symmetrical component connection in Figure A.2 can be reduced to a parallel connection of the negative- and zero-sequence networks in series with the positive-sequence line and source impedances shown in Figure A.4. Reducing the network shows the negative- and zero-sequence currents are flowing in opposite directions on the supply bus (the bus supplying prefault load current) and the load bus for this system.

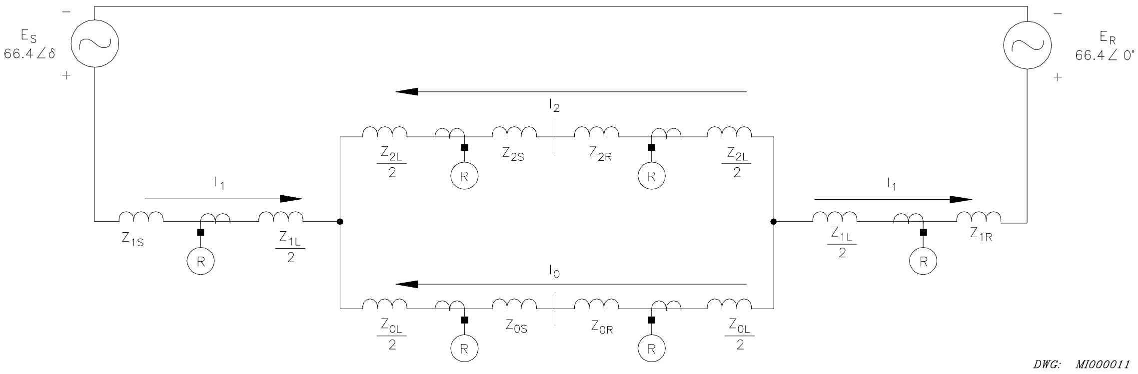
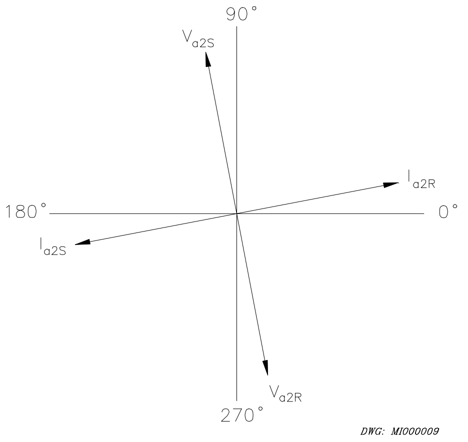


Figure A.4: Simplified Parallel Connection, Negative- and Zero-Sequence Networks

A single-phase open condition during load presents the relays at both ends of the line with negative- and zero-sequence currents and voltages. The magnitudes of negative- and zero-sequence currents and voltages produced are determined by the load flow and the strength (magnitude and angle) of the sources. If the load flow is zero, no sequence current operating quantities are supplied to the relays. As load flow increases, the sequence current operating quantities available to the relays become larger.

The negative- and zero-sequence voltages and currents produced for a single-phase open condition from the example given in Figure A.1 are shown in Figure A.5 and Figure A.6, respectively.



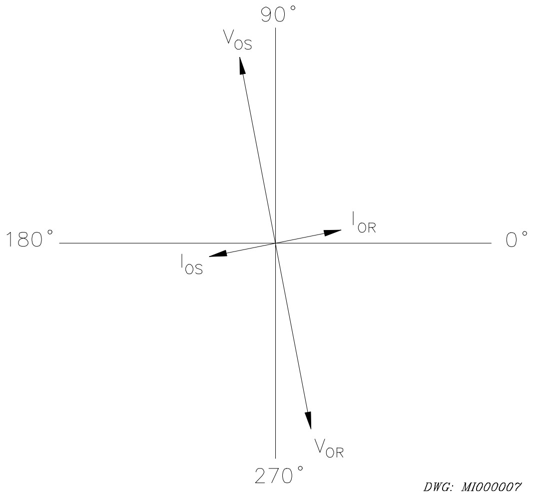
V_{a2S} = 2.14 volts ∠100.85°

I_{a2S} = 2.14 amps ∠190.85°

V_{a2R} = 2.14 volts ∠280.85°

I_{a2R} = 2.14 amps ∠10.85°

Figure A.5: Negative-Sequence Voltages and Currents for a Single-Phase Open Condition



$V_{0S} = 2.14\angle 100.85^\circ$ volts

$I_{0S} = 0.713\angle 190.85^\circ$ amps

$V_{0R} = 2.14\angle 280.85^\circ$ volts

$I_{0R} = 0.713\angle 10.85^\circ$ amps

Figure A.6: Zero-Sequence Voltages and Currents for a Single-Phase Open Condition

The diagram in Figure A.7 shows the symmetrical component connection for a two-phase open condition. The connection diagram shown in Figure A.7 is similar to that of a phase-to-ground fault where the negative- and zero-sequence networks are connected in series. The series connection of the negative- and zero-sequence networks are connected in series with the positive-sequence line and source impedances. Figure A.7 shows the negative-sequence current equals the zero-sequence current.

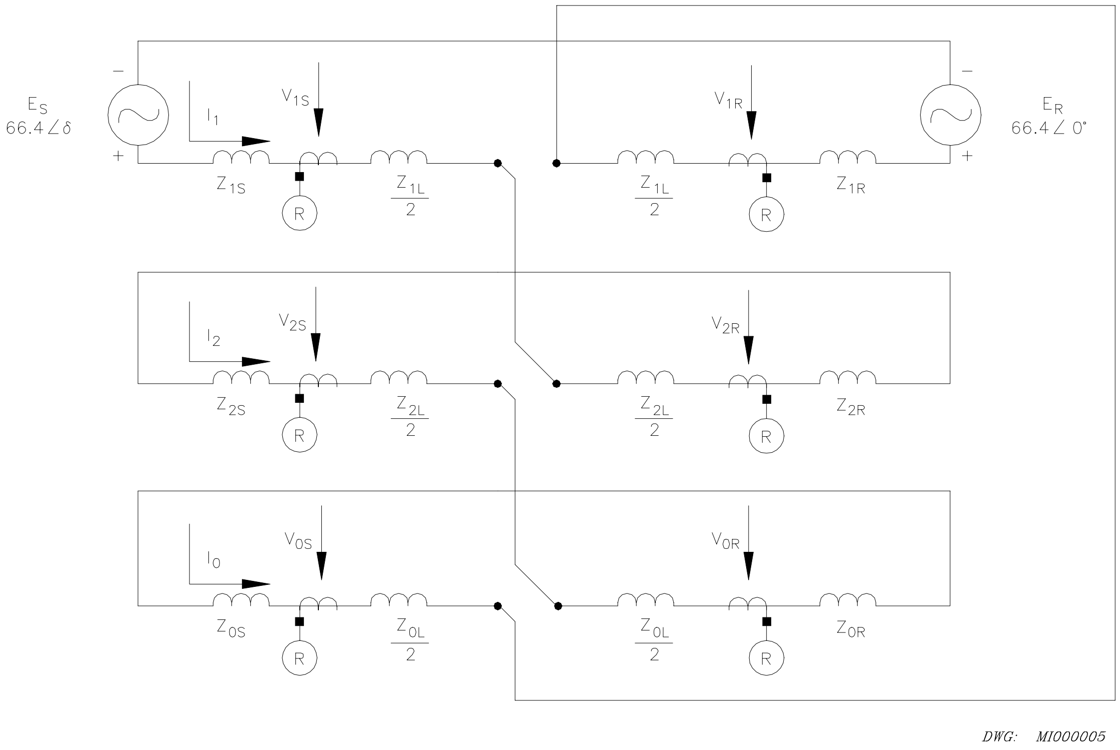
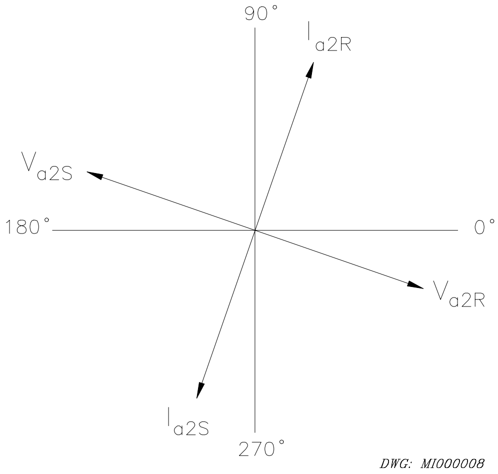


Figure A.7: Symmetrical Components Connection for Two-Phase Open Condition

As with a single-phase open condition, the negative- and zero-sequence currents in Figure A.7 are flowing in opposite directions for two phases open. Like the single-phase open case, while the negative- and zero-sequence currents are 180 degrees out-of-phase, so are the negative- and zero-sequence voltages produced by these currents.

Examining the magnitudes of the operating quantities produced for this two-phase open condition reveals that, as before, the magnitudes depend heavily on the amount of load flow and the source impedances at either end of the line.

For the example system shown in Figure A.1, the negative- and zero-sequence voltages and currents produced for a two-phase open condition are given in Figures A.8 and A.9 respectively.



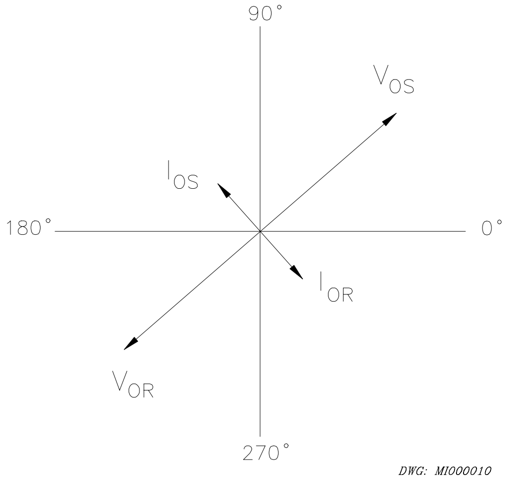
$V_{a2S} = 1 \angle 160.85^\circ$ volt

$I_{a2S} = 1 \angle 250.85^\circ$ amp

$V_{a2R} = 1 \angle 340.85^\circ$ volt

$I_{a2R} = 1 \angle 70.85^\circ$ amp

Figure A.8: Negative-Sequence Voltages and Currents for Two-Phase Open Condition



V0S = 3 $\angle 40.85^\circ$ volts

I0S = 1 $\angle 130.85^\circ$ amp

V0R = 3 $\angle 220.85^\circ$ volts

I0R = 1 $\angle 310.85^\circ$ amps

Figure A.9: Zero-Sequence Voltages and Currents for Two-Phase Open Condition

This analysis shows that single-phase and two-phase open conditions produce negative- and zero-sequence voltages and currents. The magnitude of these quantities can easily be calculated using simple symmetrical component analysis techniques.

Table A.1 is a comparison summary showing the negative-sequence quantities for the single- and two-phase open conditions previously presented. The directional element torques are also shown for a conventional directional element.

Table A.1: Negative-Sequence V and I Measured by Both Relays for Open Phase Conditions

Open Conductors	$\lvert V_{A2} \rvert$	$\lvert I_{A2} \rvert$	T32Q
Single-Phase Condition	2.14 volts secondary	2.14 amps secondary	+ 4.6 VA
Two-Phase Condition	1.00 volts secondary	1.00 amps secondary	+ 1.0 VA

Table A.2 is a comparison summary showing the zero-sequence quantities for the single- and two-phase open conditions previously presented. The directional element torques are also shown for a conventional directional element.

Table A.2: Zero-Sequence V and I Measured by Both Relays for Open Phase Conditions

Open Conductors	$\lvert V_0 \rvert$	$\lvert I_r \rvert$	T32V
Single-Phase Condition	2.14 volts secondary	2.14 amps secondary	+ 4.6 VA
Two-Phase Condition	3.00 volts secondary	3.00 amps secondary	+ 9.0 VA

Tables A.1 and A.2 show that not only do the directional elements operate in the forward direction at both ends of the line, but the operating quantities are significant. In addition, using threshold checks to supervise the directional element, such as those shown in Reference [11], may not prevent operation of the directional element for certain systems.

PREVENTING OPERATION OF SENSITIVE OVERCURRENT ELEMENTS FOR IN-LINE SWITCHING

This section discusses some of the options available for preventing operation of sensitive directional elements under in-line switching conditions. To prevent operation during the switching, you may want to reduce the element sensitivity, time-delay the sensitive set element, or disable the sensitive overcurrent elements.

Desensitizing Overcurrent Elements for In-Line Switching

Raising the ground overcurrent or negative-sequence current threshold prevents operation for in-line switching. Furthermore, raising the pickup threshold also reduces the ability of the overcurrent element to detect high-resistance faults. Therefore, raising the pickup threshold of sensitive set overcurrent elements defeats the original purpose of having sensitive set elements.

Using a voltage threshold on the directional element is a way to reduce the directional element sensitivity. Placing a voltage threshold on the directional decision dramatically reduces the fault resistance coverage of the relay [11] and is essentially equivalent to raising the overcurrent element pickup. Selecting an arbitrary threshold works in some cases but not all; therefore, the task at hand is to determine where the voltage threshold should be set. From the previous exercise, the negative and zero-sequence voltage magnitudes changed with respect to source and load flow. Consequently, it is difficult to determine a setting for the voltage threshold that addresses all systems and conditions.

Time Delay the Overcurrent Elements for In-Line Switching

Use time delay to give the necessary security for the sensitive overcurrent elements. Using a time delay to coordinate with the switch opening can work well since the opening of the switch is equivalent to a transient condition (i.e., the unbalance is only momentary). Using a time-step function provides good coordination with the opening of the switch as well as high-resistance fault coverage.

Determine the maximum loading on the line (this is also the approximate maximum residual current the relay sees for a pole open condition), and the maximum pole scatter time for the load break switch. Plot maximum load current versus the load break switch operating time on a Time versus Current axis. For all currents greater than the maximum residual unbalance for a pole open condition, the relay should respond immediately because the current magnitude is high enough to indicate a fault condition. For all currents less than maximum pole open unbalance, it could be a switching condition and the relay needs to wait for the maximum pole disagreement time before the relay considers the unbalance condition to be a fault.

Figure A.10 shows a Time versus Current plot with an inverse time curve and a time-step curve. Although an inverse curve would also work, it can be seen that the area under the time-step curve is much smaller. The defined point of maximum unbalance and pole disagreement time is the defined point calculated from the maximum line loading and the load switch operating time.

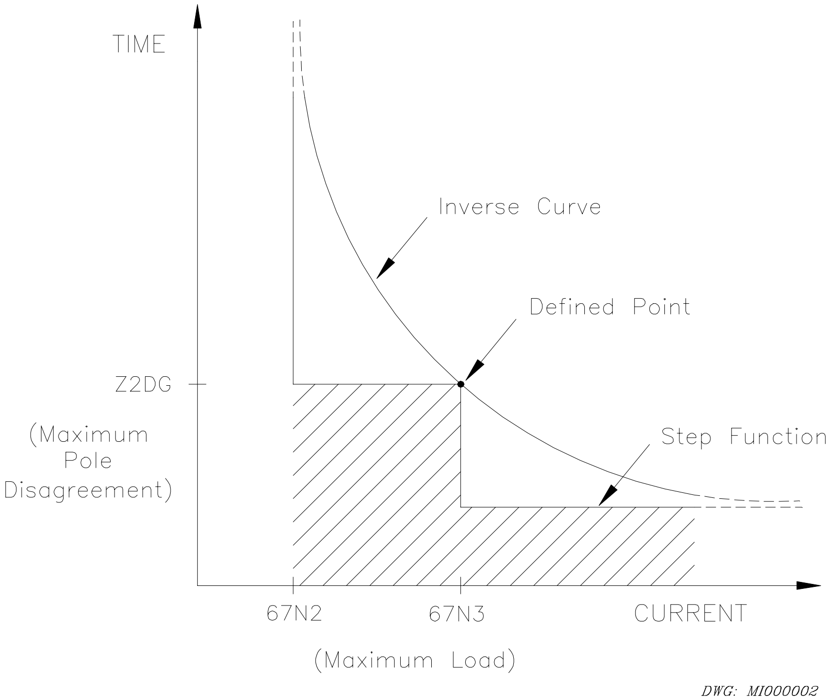


Figure A.10: Step Function Versus Inverse Curve

Use a multilevel current approach to achieve the characteristic shown in Figure A.10. Reference [7] details how one utility uses combined inverse overcurrent elements and definite-time elements to improve coordination on their power system.

Use on overcurrent element as a high-set instantaneous element (shown as 67N3 in Figure A.10). Set the high-set element above the maximum load and program the high-set element to operate in a conventional pilot tripping mode. Any unbalance of this magnitude is considered to be a fault.

Use a second overcurrent element for sensitive protection set to a lower value for detecting high-resistance faults. Time delay the sensitive element by the maximum pole disagreement time of the load break switch plus a small safety margin of two cycles. The two-cycle margin allows some additional time for the overcurrent element to drop out after the load break switch has fully opened.

In a Permissive Overreaching Transfer Tripping (POTT) pilot scheme, use the instantaneous output of the sensitive set element to key permissive trip. Use the high-set element and the time-delayed sensitive set element to trip with receipt of the permissive trip signal.

In a Directional Comparison Blocking (DCB) scheme use the high-set element plus the carrier coordination delay to trip without receipt of the block trip signal. Use the time delay calculated from the load break switch operating time plus the carrier coordination time to trip for low magnitude faults. Use a reverse-reaching element that is set more sensitive than the forward element for keying the block trip signal.

Blocking Operation of Sensitive Overcurrent Elements

To prevent operation of sensitive set elements in a pilot scheme, block the pilot scheme operation during the time of the load break operation. Blocking the pilot scheme operating depends upon the type of pilot scheme being used. When the pilot scheme is blocked, the relay trips by time delay if the fault is outside the Zone 1 reach.

For a DCB scheme, simply energize the BLOCK TRIP received input on the relay. Energizing the BLOCK TRIP received input prevents operation of the DCB scheme, which is equivalent to continuously receiving a block trip signal.

For a POTT scheme, block the receipt of the permissive trip signal by opening the circuit path, or prevent transmitting the permissive trip signal by blocking the output contact from the relay to the communications equipment. Both options require opening the circuit between the relay and the communications equipment.

OPERATION OF SENSITIVE OVERCURRENT ELEMENTS FOR OPEN PHASE CONDUCTORS

Preventing operation of sensitive overcurrent elements for an open phase conductor is more difficult. In many cases, the conductor opens when the load current is low. As the load increases, so does the amount of sequence current, until the sequence currents reach the pickup threshold on the sensitive set relays. In addition, the open phase condition could exist for a long period of time before it is detected.

Some relays offer programmable logic that can be used to detect the open phase condition. Sequence voltage and current threshold are used with appropriate time delays to block sensitive elements and/or issue an alarm notifying personnel of the open phase condition. Unfortunately, preventing operation of sensitive set elements is difficult and an open phase conductor may result in an unwanted relay operation.

BIOGRAPHIES

Joseph B. Mooney, P.E. received his B.Sc. in Electrical Engineering from Washington State University in 1985. He joined Pacific Gas and Electric Company upon graduation as a System Protection Engineer. In 1989, he left Pacific Gas and Electric and was employed by Bonneville Power Administration as a System Protection Maintenance District Supervisor. In 1991, he left Bonneville Power Administration and was employed by Schweitzer Engineering Laboratories as an Application Engineer. Shortly after starting with SEL, he was promoted to Application Engineering Manager where he remained for nearly three years. He is currently a Power Engineer in the Transmission and Distribution Engineering Group in the Research and Development Engineering Division at Schweitzer Engineering Laboratories. He is a registered Professional Engineer in the State of California.

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