Distance Protection: Pushing the Envelope

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ABSTRACT

This paper briefly describes various areas where power system protection equipment suppliers and application engineers have attempted (some successfully) to push the technical limits of generic distance relays through a consistent quest to enhance distance protection performance.

Resistive reach limitations of a generic distance relay are also discussed. We introduce new system-impedance ratios, SWIR and SNIR [4], as well as an enhancement on the source-impedance ratio SIR to illustrate the resistive reach limitations, particularly for close-in, reverse phase-to-ground faults. These ratios simplify the visual and mathematical illustration of power system-impedance properties.

INTRODUCTION

In the context of this paper, a generic distance relay is defined as a relay that has impedance characteristics but no faulted phase selection or directional algorithms. A generic distance relay is used as a reference to illustrate the areas in which some distance relays are "pushing the envelope," thereby also illustrating the limitations of generic distance relays and reasons for having enhanced algorithms.

Because this generic impedance-based protection relay does not include phase selection and directional elements, it is not reliable or secure for all power system protection applications or system conditions (i.e., system topology, fault resistance, load contribution, etc.).

GENERIC DISTANCE RELAY MEASUREMENTS

Most distance relays calculate the positive-sequence-impedance to determine the fault position. Equation (1) calculates the positive-sequence-impedance for faults clear of ground, and Equation (2) calculates the positive-sequence-impedance for single-phase-to-ground faults.

Impedance measurements are influenced by factors such as line transposition, mutual coupling to nearby circuits, load flow, and fault resistance. Other problems arise from tapped loads, conductor configuration changes, instrument transformer errors, nonuniform soil resistivity, etc. [1].

- Phase distance element impedance measurements

$$\begin{bmatrix} Z_{AB} \\ Z_{BC} \\ Z_{CA} \end{bmatrix} = \begin{bmatrix} \dfrac{V_A - V_B}{I_A - I_B} \\ \dfrac{V_B - V_C}{I_B - I_C} \\ \dfrac{V_C - V_A}{I_C - I_A} \end{bmatrix} \tag{1}$$

- Ground distance element impedance measurements

$$\begin{bmatrix} Z_{Ag} \\ Z_{Bg} \\ Z_{Cg} \end{bmatrix} = \begin{bmatrix} \dfrac{V_A}{I_A + K_0 I_N} \\ \dfrac{V_B}{I_B + K_0 I_N} \\ \dfrac{V_C}{I_C + K_0 I_N} \end{bmatrix} \tag{2}$$

Where:

$$I_N = I_A + I_B + I_C \tag{3}$$

The zero-sequence compensation factor is defined as:

$$K_0 = \frac{1}{3}\left(\frac{Z_0 - Z_1}{Z_1}\right) \tag{4}$$

Note: Equations (1) and (2) do not constitute the complete set of equations necessary to form a distance relay characteristic.

Slight variations of the above measurements may exist in different distance relays, with the aim of improving the positive-sequence-impedance measurement under different conditions (e.g., when fault resistance exists). Some variations attempt to improve faulted phase measurements but may also influence the healthy phase measurements and, therefore, distance relay performance for particular conditions.

System topology plays a major role in healthy phase measurements and in this paper is defined as the complete power system modeled with symmetrical component values.

DEFINITIONS (SWIR, SNIR, AND SIR)

A common problem power system protection engineers face is how to explain complex solutions in simple terms so that this knowledge may be easily transferred between engineers. Therefore, to simplify the illustration of the effect of different power system-impedance ratios on the resistive reach limitations of the generic distance relay (as indicated in Figure 8 and Figure 9), it is necessary to define two ratios, namely, SWIR and SNIR. These ratios may also be used in other circumstances for ease of illustration. Note that unless otherwise indicated, all formulas and values given are in vector format (magnitude and angle included).

Definition of SWIR [4]

At any particular location in the power system, SWIR represents the respective power system positive-, negative-, and zero-sequence-impedance properties in terms of forward divided by reverse Thevinin equivalent impedance values. Figure 1 shows a single-line system diagram, with relays at A and B, and a point P that indicates any point on the line between the two relays.

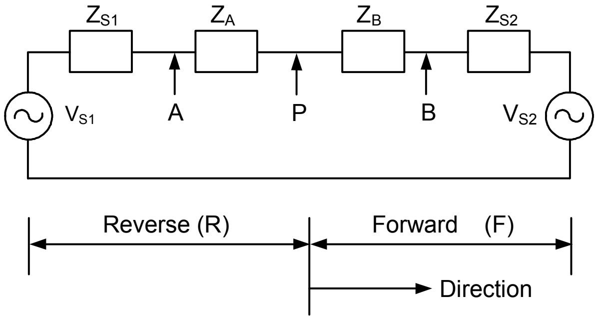


FIGURE 1: System single-line representation

At any particular location in a balanced power system, the Thevinin equivalent circuits can be obtained both in the forward and reverse directions for the independent positive-, negative-, and zero-sequence-impedance of the power system.

Dividing the forward by reverse Thevinin equivalent impedance vectors of each positive-, negative-, and zero-sequence circuit, we obtain the SWIR ratio. This is represented in matrix format as:

$$\mathrm{SWIR} = \begin{bmatrix} Z_{F1}/Z_{R1} \\ Z_{F2}/Z_{R2} \\ Z_{F0}/Z_{R0} \end{bmatrix} = \begin{bmatrix} \mathrm{SWIR}_{11} \\ \mathrm{SWIR}_{22} \\ \mathrm{SWIR}_{00} \end{bmatrix} = \begin{bmatrix} \mathrm{SWIR}_{1} \\ \mathrm{SWIR}_{2} \\ \mathrm{SWIR}_{0} \end{bmatrix} \tag{5}$$

Where:

F = Forward Thevinin equivalent impedance
R = Reverse Thevinin equivalent impedance
1 = Positive-sequence-impedance
2 = Negative-sequence-impedance
0 = Zero-sequence-impedance

With respect to the circuit in Figure 1, the SWIR ratio at point P is equal to:

$$\mathrm{SWIR} = \begin{bmatrix} \mathrm{SWIR}_{1} \\ \mathrm{SWIR}_{2} \\ \mathrm{SWIR}_{0} \end{bmatrix} = \begin{bmatrix} (Z_{B1} + Z_{S21})/(Z_{A1} + Z_{S11}) \\ (Z_{B2} + Z_{S22})/(Z_{A2} + Z_{S12}) \\ (Z_{B0} + Z_{S20})/(Z_{A0} + Z_{S10}) \end{bmatrix} \tag{6}$$

We can also use SWIR to obtain other types of ratios, such as those in Equations (7) and (8):

$$\mathrm{SWIR}_{12} = (Z_{B1} + Z_{S21})/(Z_{A2} + Z_{S12}) \tag{7}$$

$$\mathrm{SWIR}_{10} = (Z_{B1} + Z_{S21})/(Z_{A0} + Z_{S10}) \tag{8}$$

Definition of SNIR [4]

At a particular location, in a particular direction or in general, SNIR represents the power system properties in terms of the difference in magnitude between the positive-, negative-, and zero-sequence-impedance Thevinin equivalent quantities. At any location Equations (9) and (10) apply.

$$\begin{bmatrix} \mathrm{SNIR}_{F10} \\ \mathrm{SNIR}_{R10} \end{bmatrix} = \begin{bmatrix} \begin{Bmatrix} Z_{F1}/Z_{F0} \text{ if } |Z_{F1}| \geq |Z_{F0}| \\ Z_{F0}/Z_{F1} \text{ if } |Z_{F1}| < |Z_{F0}| \end{Bmatrix} \\ \begin{Bmatrix} Z_{R1}/Z_{R0} \text{ if } |Z_{R1}| \geq |Z_{R0}| \\ Z_{R0}/Z_{R1} \text{ if } |Z_{R1}| < |Z_{R0}| \end{Bmatrix} \end{bmatrix} \tag{9}$$

$$\mathrm{SNIR}_1 = \begin{bmatrix} \begin{Bmatrix} |\mathrm{SNIR}_{F10}| \text{ if } |\mathrm{SNIR}_{F10}| \geq |\mathrm{SNIR}_{R10}| \\ |\mathrm{SNIR}_{R10}| \text{ if } |\mathrm{SNIR}_{F10}| < |\mathrm{SNIR}_{R10}| \end{Bmatrix} \end{bmatrix} \tag{10}$$

Where:

F = Forward Thevinin equivalent impedance
R = Reverse Thevinin equivalent impedance
1 = Positive-sequence-impedance
2 = Negative-sequence-impedance
0 = Zero-sequence-impedance

Using the same methodology, SNIR_{F20}, SNIR_{R20}, SNIR_{F12}, and SNIR_{R12} as well as SNIR_2 and SNIR_{12} may be calculated by using negative- and zero-sequence ratios or positive- and negative-sequence ratios, respectively. Thus,

$$\mathrm{SNIR} = \begin{bmatrix} \mathrm{SNIR}_{10} \\ \mathrm{SNIR}_{20} \\ \mathrm{SNIR}_{12} \end{bmatrix} = \begin{bmatrix} \mathrm{SNIR}_{1} \\ \mathrm{SNIR}_{2} \\ \mathrm{SNIR}_{12} \end{bmatrix} \tag{11}$$

In the context of this paper, SNIR_1 is equal to SNIR_2.

Definition of Enhanced SIR

Typically, SIR represents the source impedance divided by the line impedance. Using the system representation indicated in Figure 1, the system-impedance ratios for the relay at A and up to point P are defined (and enhanced) as:

$$(\text{Enhanced SIR}) = \begin{bmatrix} \text{SIR}_1 \\ \text{SIR}_2 \\ \text{SIR}_0 \end{bmatrix} = \begin{bmatrix} \left|Z_{S11} / Z_{A1}\right| \\ \left|Z_{S12} / Z_{A2}\right| \\ \left|Z_{S10} / Z_{A0}\right| \end{bmatrix} \qquad (12)$$

All of the SWIR, SNIR, and SIR ratios have directionality associated with them.

GENERIC DISTANCE RELAY MEASUREMENT OBSERVATIONS

The following observations can be made regarding the different impedance values measured by a generic distance relay for different system topologies:

- System topology is the most important factor influencing healthy phase-impedance measurements.
- The healthy phase-impedance measurement may encroach on and enter the set phase-impedance characteristic during a close-in reverse fault where the $|\text{SWIR}_1|$ is greater than the $|\text{SWIR}_0|$.
- A minimum reactive reach is required for protective relays using generic-based impedance measurements for faulted phase selection.
- A generic distance relay may perform poorly due to the effect of load on faulted and healthy phase-impedance measurements.
- Poor performance of generic distance protection may be expected for extremely high resistance faults.
- The risk of a generic distance relay misoperation increases as either of the following occurs:
  - The length of the feeder or cable being protected decreases.
  - Load current magnitude increases with respect to fault-current magnitude.

RULE-OF-THUMB GUIDELINES FOR GENERIC DISTANCE RELAY APPLICATIONS

The following may not necessarily be valid for all distance relays due to advanced supervision functions in numerical distance relays.

Generic distance relays that use generic impedance measurements are not recommended for feeder protection under the following conditions:

- Feeder or cable to be protected is less than approximately 5 to 10 km in length.
- Measured fault-current magnitude is less than approximately 6 to 10 times the measured prefault load-current magnitude.

The main reason for these guidelines is to give the engineer, in practical or application-related terms, an indication as to when the performance of a generic distance relay may significantly deteriorate in terms of:

- Fault resistive coverage capabilities without sacrificing security
- Faulted phase selection
- Fault direction determination
- Over- and underreaching

FAULTED PHASE SELECTION IMPORTANCE

For security, distance relay schemes must consider the behavior of the distance elements in all six calculated measurement loops (Ag, Bg, Cg, AB, BC, and CA) under very broad and general system, load, and fault conditions [2]. Some major concerns are as follows:

- Ground distance elements can overreach for a phase-to-phase-to-ground fault [3].
- Phase distance elements can operate for a close-in reverse phase-to-phase-to-ground fault [4].
- Phase distance elements may operate for a phase-to-phase-to-ground fault with heavy loading [4].
- Phase distance elements can operate for a close-in phase-to-ground fault [3] [4].
- Ground distance elements can operate for a close-in reverse phase-to-ground fault [4].
- Phase distance elements can operate for a close-in reverse phase-to-phase fault [5].

Following is a discussion of the major concerns listed above. Note that the discussions apply to both mho characteristics and quadrilateral characteristics, but only mho characteristics are shown for brevity.

Ground distance elements can overreach for a phase-to-phase-to-ground fault [3]

During a phase-to-phase-to-ground fault, system topology can result in a healthy ground-distance element measuring a lower value than the faulted phase-distance element. This may result in a phase-to-ground-distance element overreaching. The faulted phase measurement (Zbc) by the relay remains constant throughout because no load is present.

With fault resistance equal to zero, the ground-distance elements measure correctly. As fault resistance increases, the measurements of the involved phase-to-ground-distance elements become erroneous. With high fault resistance, a healthy phase measurement (e.g., Zab) may also pick up, particularly when set to high-impedance values.

Some distance relays that use an impedance starter characteristic or impedance-based faulted phase selection characteristic, require a minimum reactive reach to ensure that overreaching will not occur under high fault-resistance conditions. Overreaching of the ground-distance elements for a phase-to-phase-to-ground fault is more likely to occur for a large system-impedance ratio (SIR) and as fault resistance increases. This overreaching is illustrated in Figure 2:

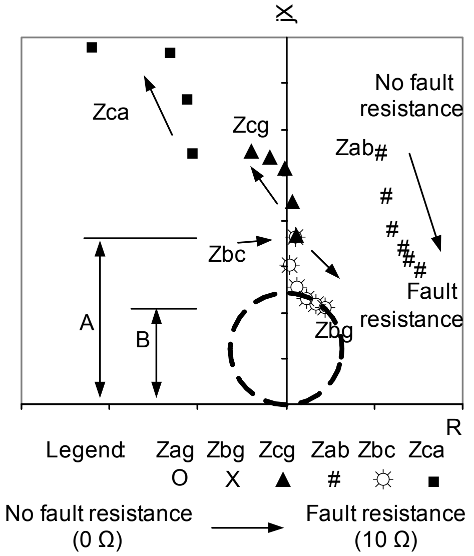


FIGURE 2: Faulted phase (Zbc) impedance appears larger than healthy ground (Zbg) impedance

The ratio A/B, indicated in Figure 2, varies with fault position (or line length for a fault at the end of the line). The ratio A/B is extremely important for relays that use an impedance starter characteristic for faulted phase selection algorithms because the reactive reach must be set far enough to "see" the phase impedance for a phase-to-phase-to-ground fault beyond the line. For such relays, compile a guideline, using the SWIR, SNIR, or SIR ratios previously defined [4].

Phase distance elements may operate for a phase-to-phase-to-ground fault with heavy loading [4]

Figure 3 illustrates measurements, with varying load and zero fault resistance. As load increases, the reactive component of the impedance measured by the Zab element decreases.

The ground fault measurements Zbg, Zcg, and Zbc, lie exactly at the same point for each different load value. In this example, the ratio of faulted phase current to healthy (load) phase current varied from infinity (no load) to approximately 6 (heavy loading).

From Equations (1) and (2), it follows that heavy loading may also cause a phase-impedance element to pick up for a phase-to-ground fault [4]. On heavily loaded systems, a healthy phase measurement may become "visible," which would result in tripping both faulted and healthy phase measuring elements, with subsequent incorrect alarms and indications of faulted phases.

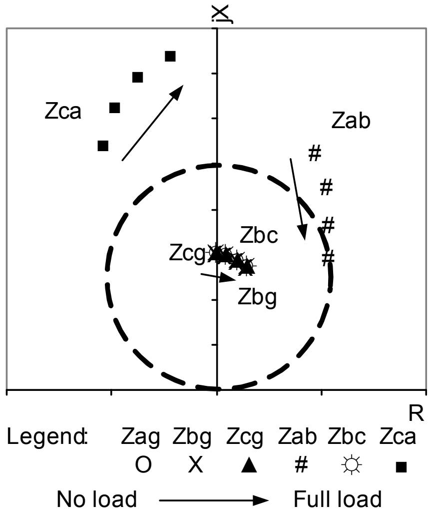


FIGURE 3: Phase-to-phase-to-ground fault (varying load)

Phase distance elements can operate for close-in reverse phase-to-phase-to-ground faults [4]

For high-resistance reverse phase-to-phase-to-ground faults, the healthy phase measurement (Zca) can approach the forward directional characteristic angle, which is used to form the quadrilateral characteristic.

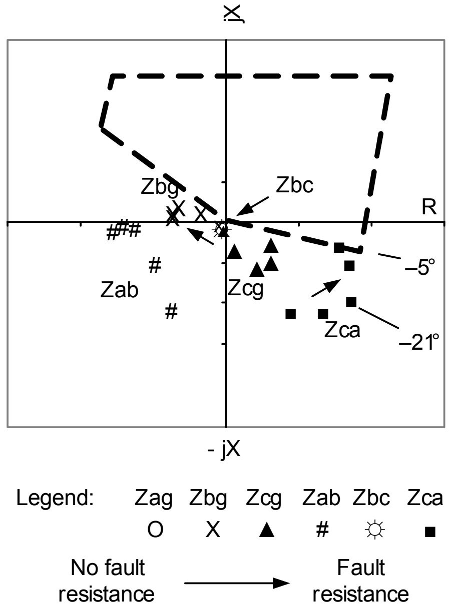


FIGURE 4: Reverse phase-to-phase-to-ground fault

With high fault resistance, the healthy phase measurement (Zca) could appear as being forward for distance elements where the directionality relies on impedance measurements falling outside of the quadrilateral impedance characteristic. Note how angle Zca changes from –21 to –5 degrees as fault resistance increases [4]. For distance relays that operate on this principle, the setting of the forward directional impedance characteristic angle becomes critical for security.

The above implies that one could expect improved performance from a distance element where the directional and impedance elements are separated and operate on different principles.

Phase distance elements can operate for close-in phase-to-ground faults [3] [4]

The healthy phase measurements are in the first and second quadrants, close to the actual faulted phase impedance as shown in Figure 5 for no load impedance.

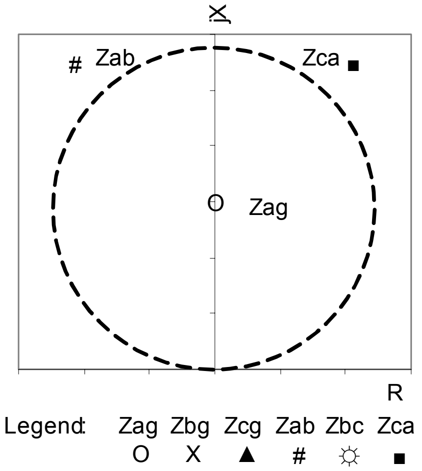


FIGURE 5: Phase-to-ground fault (no load or fault resistance)

Figure 6 illustrates a forward phase-to-ground fault, with constant load applied and varying fault resistance. Note how the loop-impedance, Zca, reduces its reactive-impedance as fault resistance increases.

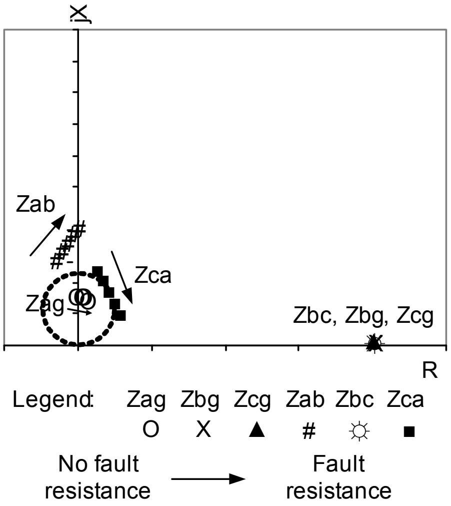


FIGURE 6: Overreaching of phase element for phase-to-ground fault with high fault resistance and load

Ground distance elements can operate for a close-in reverse phase-to-ground fault [4]

During a reverse A-to-ground fault with $SWIR_1$ greater than $SWIR_0$, a C-to-ground-distance element may operate. This is illustrated in Figure 7. The healthy phase-impedance Zcg decreases as the magnitude of I_0 increases with respect to I_1 and I_2.

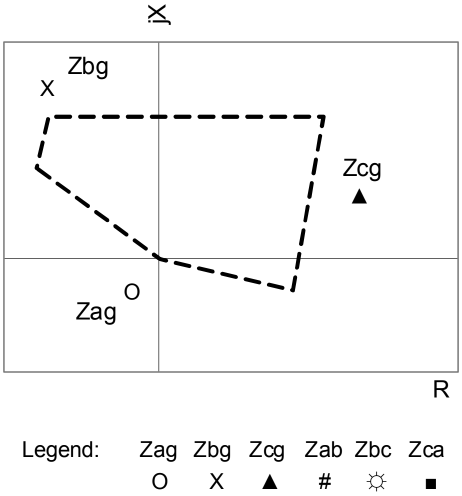


FIGURE 7: Reverse phase-to-ground fault impedance measurements

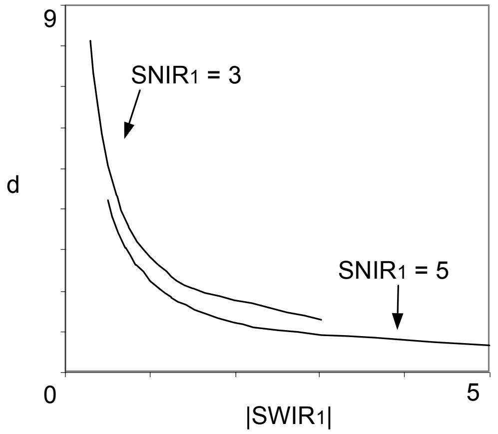
It is possible to determine the resistive part of the generic impedance measurement for the different ratios $SWIR_1$ and $SWIR_0$. These measurements may be used to determine the resistive reach limitations of a generic distance relay to remain secure for close-up reverse phase-to-ground faults.

One solution to this problem is to supervise the ground elements with an independent directional element [5]. Another solution is to limit the resistive reach setting of the relay, depending on the particular system topology and conditions.

Resistive reach setting guidelines or limitations can be compiled for a generic distance relay [4]. Figures 8 and 9 show examples of these setting guidelines for either meshed systems (Figure 8) or radial systems (Figure 9).

These guidelines assist with fault investigations of incorrect distance relay operations and provide an application guide for a generic distance relay to assist protection personnel involved with the design and setting of distance relays [4].

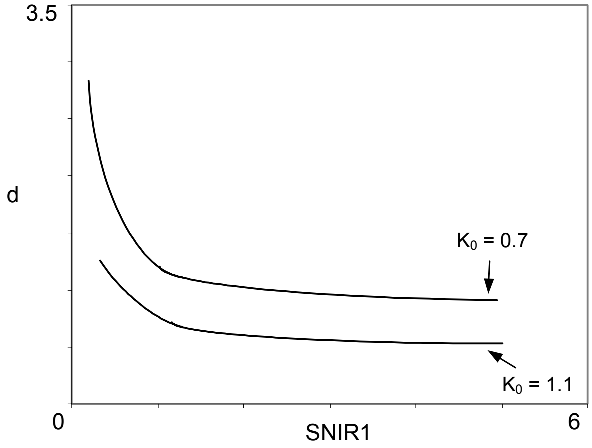
Figures 8 and 9 can be compiled once the system parameters are known, calculating the resistance as measured by Zcg for a close-in reverse phase-to-ground fault (no impedance between relay and fault position), assuming zero fault resistance, and using a selected, faulted phase-impedance angle (i.e., –120 degrees) by varying the ratios $SNIR_1$ and $|SWIR_1|$. Note that the aim is to obtain *d*, indicated as a multiple of the system forward Thevinin equivalent impedance. In Figure 8, with a selected $SNIR_1$ ratio equal to 3 and as $|SWIR_1|$ increases, the maximum resistive reach of the generic relay characteristic can be determined (as indicated by the factor *d*). $SWIR_1$ and $SNIR_1$ are defined by Equations (6) and (10), respectively.



Legend: d = Resistive Reach as Multiples of Z_{F1}

FIGURE 8: Resistive reach for a meshed system (fixed earth fault compensation factor K_0)

Similar to Figure 8, Figure 9 illustrates the maximum resistive reach that can be set for a generic relay characteristic to avoid incorrect operations for a reverse close-in phase-to-ground fault in a radial system.



Legend: d = Resistive Reach as Multiples of Z_{F1}

FIGURE 9: Resistive reach for a radial system (with fixed earth fault compensation factor K_0)

Phase distance elements can operate for a close-in reverse phase-to-phase fault [5]

For a close-in reverse C-to-A-phase fault, a forward-reaching B-to-C-phase element can sense the fault due to the effect of the C-phase current. We can use a negative-sequence directional element to supervise phase distance elements and avoid such misoperations.

GENERIC DISTANCE RELAY FAULTED PHASE SELECTION CONTRADICTION

Evaluation of the different faulted and healthy phase-impedance measurements leads to the following contradictions:

- For a phase-to-ground fault, a healthy (unfaulted) phase distance element may incorrectly pick up.
- For a phase-to-phase-to-ground fault, a healthy ground distance element may incorrectly pick up.
- The phase-to-phase distance element is the most accurate loop impedance measurement during a phase-to-phase or a phase-to-phase-to-ground fault.
- During phase-to-phase-to-ground faults, it is common practice to block or ignore the ground distance element to avoid misoperation.

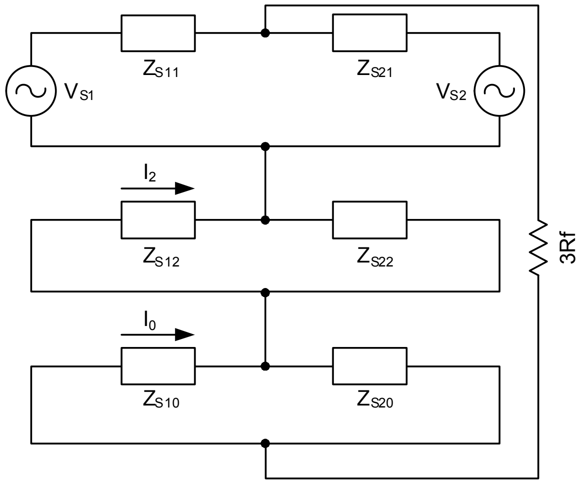
To avoid incorrect operation, the distance relay must block the phase distance element for a phase-to-ground fault but allow phase distance element operation for a phase-to-phase or a phase-to-phase-to-ground fault. Generic impedance-based faulted phase selection algorithms may operate incorrectly or may sacrifice sensitivity to achieve security. Differentiation between phase-to-phase and phase-to-ground faults is required.

Phase selection algorithm [2]

Phase selection is an algorithm used extensively in single-pole tripping schemes. Operation of individual ground distance elements is not sufficient to select the pole to trip [2]. In three-pole tripping schemes, phase selection is important to ensure that the correct phase distance element is selected. Modern numerical relays determine the faulted phase using the angular difference between the zero-sequence current and the negative-sequence current.

Figure 10 illustrates the phase selection of an A-to-ground fault. For the ideal case shown, the A-phase negative-sequence component aligns with the zero-sequence component. The two components are nearly in phase, although a small angle variation is expected. Similarly, the B-phase and C-phase components behave the same for faults in the respective phases [2].

The phase selection algorithm selects the proper faulted phase for single phase-to-ground faults, but the phase selection logic should also consider that a B-to-C-to-ground fault would have the I_2 and I_0 components in phase as well. Fortunately, other indicators in the power system can be used to determine if it is an A-to-ground or a B-to-C-to-ground fault, and the relaying scheme will make the appropriate phase selection [2].



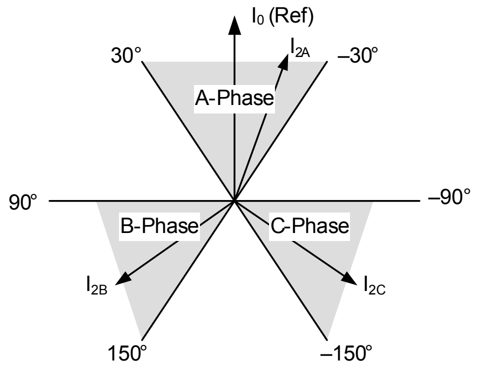


FIGURE 10: Phase selection algorithm

Faulted phase selection through differentiation of phase current magnitude

A simplistic method of distinguishing faulted phases is to compare phase-current magnitudes. The principle is to compare the phase-current magnitudes between all phases and only allow the elements to operate with magnitudes greater than a threshold or percentage compared to each other. It would be advantageous if this threshold value could be dynamically determined when a fault is detected. One method of accomplishing this is to superimpose quantities on the phase currents.

Some problems with generic distance relay behavior could be avoided by setting current supervision element pickups (if available) to a couple of multiples of maximum load current [4]. Suppliers use different methods for faulted phase selection, each with its own positive and negative attributes.

Faulted phase selection techniques, based on any current with respect to voltage ratios (either using phase quantities or symmetrical components), may require application and setting studies to ensure optimum relay performance. A combination of different phase selection techniques enhances distance relay performance.

DIRECTIONAL SECURITY OR INTEGRITY

General overview

Some major reliability and security concerns for distance relay operation can be avoided through proper fault direction determination. Elements used for fault direct determination include, but are not limited to, the following:

- Positive-sequence directional elements
- Negative-sequence directional elements
- Zero-sequence directional elements

Negative-sequence directional elements have noticeable advantages over zero-sequence directional elements because of the following [3]:

- Insensitive to mutual coupling.
- Generally, more negative-sequence current exists than zero-sequence current for remote ground faults with high fault resistance. This allows higher sensitivity with reasonable and secure sensitivity thresholds.
- Insensitivity to VT neutral shift, possibly caused by multiple grounds on the VT neutral.

Series-compensated feeders

The location of the VT for end-line series-compensated lines can influence the performance of the directional elements if voltage inversion occurs. The directional element design can mitigate or eliminate this problem. This is why distance relays use memory voltage polarization.

Supervision of Distance Protection

Directional elements add security to distance elements. Some methods used to mitigate incorrect distance element operation are discussed earlier in this paper. Forward-reaching mho phase distance elements lack security for reverse three-phase faults under particular conditions. A solution to this problem is to supervise the three-phase forward-reaching distance elements with a positive-sequence directional element [5].

This paper has discussed several problems concerning directional elements. Following are some recommendations for the type of directional elements to be used [5].

- Replacing the traditional collection of three-phase directional elements with positive- and negative-sequence directional elements improves security.
- Positive-sequence directional elements must include polarizing memory to assure operation for close-in three-phase faults.
- Zero-sequence mutual coupling adversely affects zero-sequence polarizing ground di-

rectional elements in applications where the zero-sequence sources are isolated.
- Settable forward and reverse thresholds for the sequence-impedance directional elements increase the scope of applications.
- Supervising directional calculations with overcurrent elements avoids decisions based on unbalanced load.

To conclude, discrete directional elements perform poorly if they are allowed to act on their own for all fault types. Merging all directional elements into one numerical relay package permits the relay to determine which directional decision is best for the application. Improved phase directional element designs are available and discussed [5], and cater to extreme conditions. Figure 11 shows an example of such a directional element, based on a negative-sequence-impedance measurement [2].

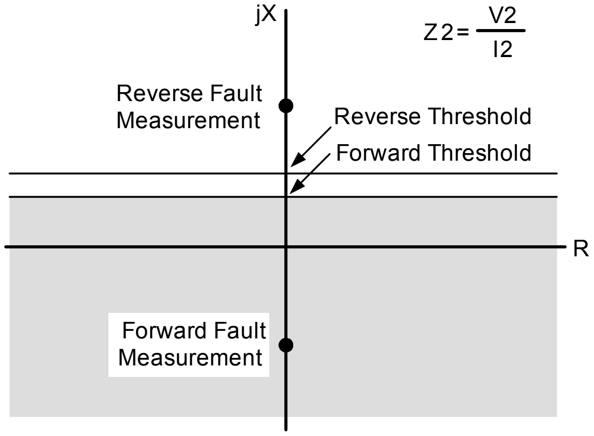


FIGURE 11: Negative-sequence directional element

FAULT RESISTANCE COVERAGE

The amount of resistive fault coverage by any relay is influenced by several factors [9]:

- 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)

Directional element sensitivity affects the ability of a directional or distance relay to detect high-resistance faults [11]. CT and VT accuracy and performance have a significant impact on directional element performance, especially for high-resistance faults [11].

Improvements in distance and directional element design attempt to enhance faulted phase selection and increase fault resistance coverage. However, care should be taken to ensure that relay reliability and security are not compromised [4].

PRIMARY SYSTEM DESIGN INFLUENCES ON THE DISTANCE RELAY

The previous sections dealt with faulted phase selection and directionality. The next section focuses on other distance relay element influences caused by primary system design, layout, and enhancements in distance relays to correct for such influences.

Series capacitor effects on distance relays [7]

Some distance relays may be applied on series-compensated feeders and respond adequately to voltage reversal conditions [7]. Figure 12 illustrates typical forward and reverse faulted phase-impedance measurement areas when series capacitors do not bypass [7].

Quadrants 1 and 3 represent normal system typical faulted phase-impedance measurements while Quadrants 2 and 4 represent other possible faulted phase-impedance measurements (e.g., when end-of-line compensation is applied with VTs installed on the bus side of the series capacitor).

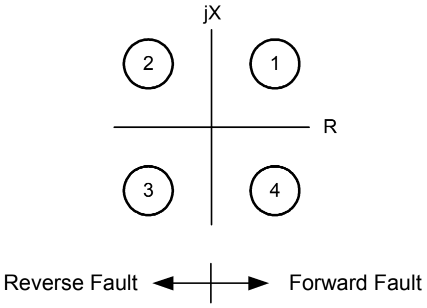


FIGURE 12: Typical positive-sequence-impedance measured by impedance relays under different system conditions

Primary system design influences ground fault and distance protection performance, in particular during the following conditions:

- System nonhomogeneity
- Zero-sequence mutual coupling
- System unbalances

System nonhomogeneity [9]

A system is homogeneous when the line and source angles are equal in all three symmetrical sequence circuits. 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 [9]. 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 under- or overreach as indicated in Figure 13 [9]. This is because the voltage drop across the fault resistance includes both real and imaginary terms.

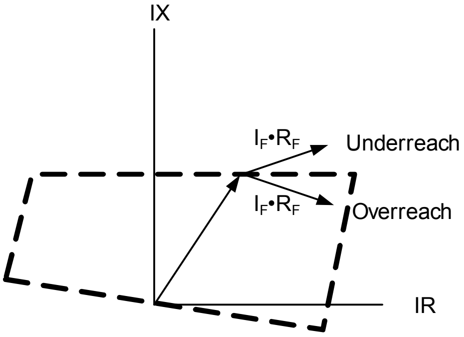


FIGURE 13: The effective reactance measurement can be determined by including the voltage drop across the fault resistance [9]

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 over- and underreaching [9].

Zero-sequence mutual coupling

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 that affects the ground distance measurement [9].

The magnitude of zero-sequence mutual coupling is a function of the spacing between transmission lines (i.e., how close they are to each other) and the voltage at which the lines are operating. Mutual coupling is influenced by parallel line switching and grounding [9]. Methods to determine and compensate for mutual coupling exist, such as the relay's separate zero-sequence compensation factor settings for the under- and overreaching distance zones.

Feedback of parallel feeder status may be required to adapt distance relay elements to ensure optimum performance. In such a case, the zero-sequence compensation factor becomes:

$$K_{0m} = \frac{1}{3}\left(\frac{Z_0 - Z_1 + Z_{0m}}{Z_1}\right) \tag{13}$$

Where:

Z_{0m} = the zero-sequence mutual coupling impedance

System unbalances

System unbalance, due primarily to the line conductor configuration and spacing but also to in-line load switching or unbalanced loads, can have adverse effects on directional elements for faults other than ground faults (in particular, three-phase faults) [9]. Such unbalance affects the sensitivity of zero- and negative-sequence overcurrent elements. Traditionally, ground distance elements are relatively immune to system unbalances, primarily because they cannot be set as sensitively as overcurrent elements [9].

When directional elements do not account for system unbalance, misoperation of the distance relay elements are possible. Some distance relays have directional elements that respond to extreme conditions by monitoring and automatically selecting the best directional element to use under varying system conditions. In such distance relays, the user may have some influence in adjusting the preference logic and monitored values, termed "best choice" directionality.

THE OUTER LIMITS

Many other conditions and enhancements may exist to "push the envelope" of distance relays in analog and digital filter techniques; sampling rates and methods; transient immunization; wide area system information, distribution, and usage; frequency tracking; adaptive algorithms; etc. but these and others are left to the reader to explore.

OVERALL CONCLUSIONS

- Power system distance protection suppliers and engineers are on a constant quest to "push the envelope" of distance relays. Failure to stay "inside the envelope" may lead to undesired operations.
- Distance relays from various suppliers may perform differently in the same system because of differences in implementing directionality, faulted phase selection, and other algorithms.
- System topology, directionality, and faulted phase selection form an important part of distance relay performance to avoid incorrect healthy phase-impedance measurement operations and improved relay performance.

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