34th Annual Western Protective Relay Conference

Fundamentals of Distance Protection

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1. Introduction

Protection engineers live with terms “mho” or “quad” related to distance protection relays: we apply and set distance relays, test them, and analyze their response under faults and system events. But how well do we understand the operating principles and nuances of distance protection, looking beyond a simplistic mho circle and a quad polygon?

This paper is a tutorial on distance protection. We will first review the basic principles of distance protection.

We will present general rules of implementing distance comparators (phase and amplitude comparators), and explain electro-mechanical, static and digital distance relay technologies.

We will explain factors impacting performance of distance relays focusing on source impedance ratio, transient accuracy, and speed of operation.

The paper will allow junior protection engineers to become familiar with principles of distance protection, and will help seasoned protection practitioners to better understand distance protection, and benefit when applying, testing or troubleshooting distance relays.

2. Fundamentals of electrical measurement of distance to fault

Selective, high-speed clearance of faults on high voltage transmission lines is critical to the security of the power system. Overcurrent relays cannot provide fast, coordinated protection because the transmission system is a mesh network. Line current differential relays can meet the requirements but require complex and expensive communications links. Uniquely, a distance relay measures the apparent impedance derived from locally measured current and voltage. The impedance of a transmission line is generally distributed uniformly over its length. For this reason, a distance relay can discriminate with relatively good accuracy between a fault that is internal to the line and one that is external by measuring apparent impedance during a fault thereby providing a “zone” of protection.

Consider the example circuit shown in Figure 1. There are a total of 11 possible (shunt) fault types in this system: AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABC, and ABCG. The path taken by the fault current from its source to the point of the fault and back to the source is known as a fault loop.

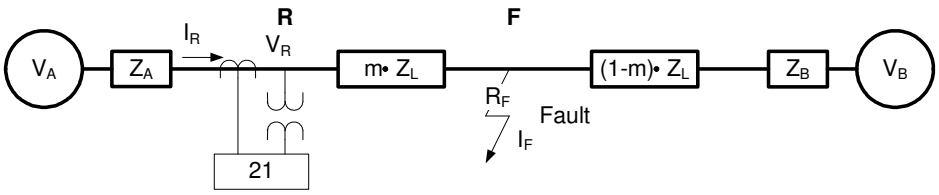

Figure 1 Two Ended Transmission Line

The voltages at the relay location (R) can be expressed as functions of relay currents (R) and voltages at the fault point (F). Using symmetrical components one can write:

$$V_{1R} - I_{1R} \cdot m \cdot Z_{1L} - V_{1F} = 0 \quad (1a)$$

$$V_{2R} - I_{2R} \cdot m \cdot Z_{1L} - V_{2F} = 0 \quad (1b)$$

$$V_{0R} - I_{0R} \cdot m \cdot Z_{0L} - V_{0F} = 0 \quad (1c)$$

Note that the positive and negative sequence impedances of a fully transposed transmission line are equal. Adding the three equations yields:

$$V_{1R} + V_{2R} + V_{0R} - I_{1R} \cdot m \cdot Z_{1L} - I_{2R} \cdot m \cdot Z_{1L} - I_{0R} \cdot m \cdot Z_{0L} - V_{1F} - V_{2F} - V_{0F} = 0 \quad (2)$$

Assuming an AG fault and recognizing that:

$$V_{1R} + V_{2R} + V_{0R} = V_{AR} \quad (3a)$$

$$V_{1F} + V_{2F} + V_{0F} = I_F \cdot R_F \quad (3b)$$

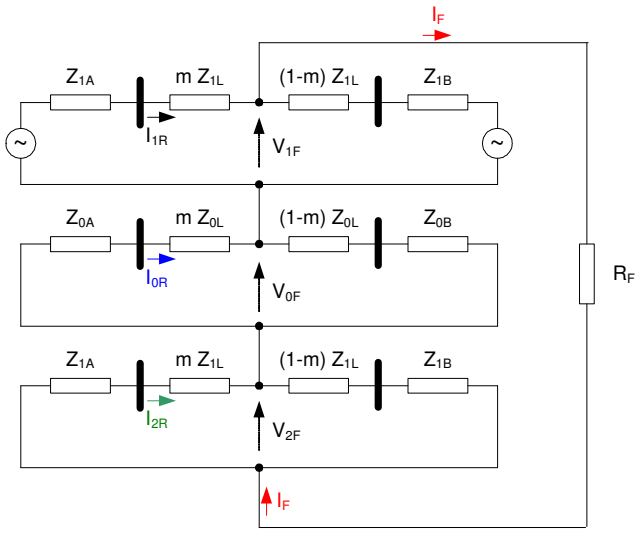

Figure 2 Network equivalent diagram for single-line-to-ground faults

One may re-write equation (2) as follows:

$$V_{AR} - m \cdot Z_{1L} \cdot \left(I_{1R} + I_{2R} + \frac{Z_{0L}}{Z_{1L}} \cdot I_{0R} \right) - I_F \cdot R_F = 0 \quad (4)$$

One may add and subtract the zero-sequence current at the relay without changing the meaning of equation (4):

$$V_{AR} - m \cdot Z_{1L} \cdot \left(I_{1R} + I_{2R} + I_{0R} - I_{0R} + \frac{Z_{0L}}{Z_{1L}} \cdot I_{0R} \right) - I_F \cdot R_F = 0 \quad (5)$$

Recognizing that:

$$I_{1R} + I_{2R} + I_{0R} = I_{AR} \quad (6)$$

One may re-write equation (5) as follows:

$$V_{AR} - m \cdot Z_{1L} \cdot \left(I_{AR} + I_{0R} \cdot \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) \right) - I_F \cdot R_F = 0 \quad (7)$$

Equation (7) leads to the well-known concept of zero-sequence compensation and the zero-sequence compensating factor. Introducing the compensated current:

$$I_{AGR} = I_{AR} + I_{0R} \cdot \left(\frac{Z_{0L}}{Z_{1L}} - 1 \right) = I_{AR} + k_0 \cdot I_{0R} \quad (8)$$

One gets the equation being a foundation of ground distance protection:

$$V_{AR} - m \cdot Z_{1L} \cdot I_{AR} - I_F \cdot R_F = 0 \quad (9)$$

Or

$$m \cdot Z_{1L} \cdot I_{AR} - V_{AR} = -I_F \cdot R_F \quad (10)$$

When R_F is zero equation (9) can be re-written as:

$$m \cdot Z_{1L} = \frac{V_{AR}}{I_{AR} + k_0 \cdot I_{0R}} \quad (11)$$

Thus, for a ground fault under ideal conditions the apparent impedance $V_A/(I_A+k_0 \cdot I_0)$ is equal to the positive sequence impedance between the relay and the fault point and proportional to the distance to the fault.

To derive proper distance equations for phase faults, assume an AB fault:

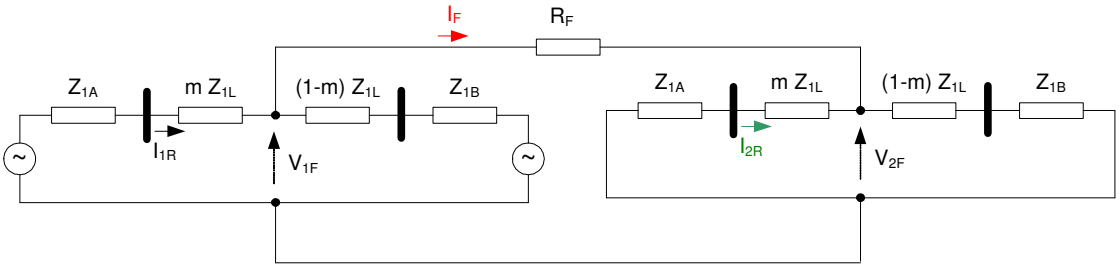

Figure 3 Network equivalent diagram for line-to-line faults

One can write:

$$V_{1F} - V_{1F} = I_F \cdot R_F \tag{12}$$

Substituting equations (1a) and (1b):

$$V_{1R} - V_{2R} - (I_{1R} - I_{2R}) \cdot m \cdot Z_{1L} = I_F \cdot R_F \tag{13}$$

And setting R_F=0 gives

$$m \cdot Z_{1L} = \frac{V_{1R} - V_{2R}}{I_{1R} - I_{2R}} = \frac{(a^2 - a) \cdot V_{BCR}}{(a^2 - a) \cdot I_{BCR}} = \frac{V_{BCR}}{I_{BCR}} \tag{14}$$

This demonstrates that the apparent impedance V_{ABR}/I_{ABR} corresponds once again to the impedance to the fault. Similar exercises show that V_{ABR}/I_{ABR} is equal to $m \cdot Z_{1LR}$ for three phase faults and double-phase-ground faults. Consequently 6 elements can be used to detect all fault types: three for ground faults and three for faults not involving ground.

Table 1 Distance Element Input Quantities

Element	Voltage	Current
AG	V_{AR}	I_{AR}, I_{0R}
BG	V_{BR}	I_{BR}, I_{0R}
CG	V_{CR}	I_{CR}, I_{0R}
AB	V_{ABR}	I_{ABR}
BC	V_{BCR}	I_{BCR}
CA	V_{CAR}	I_{CAR}

3. Phase and Magnitude Comparators

Section 2 demonstrated that certain combinations of currents and voltages at the relay location allow measuring the apparent impedance between the relay and the fault point on the line. Relay designers face the challenge of building an apparatus that would measure such impedance based on the current and voltage inputs and compare it against the intended user settings. This is true in any technology: electromechanical, static or digital.

This relay design or implementation challenge can be conceptualized, however, regardless of the applied technology using the concept of a comparator as discussed in this section.

At the core of every protective relay is a comparator. A comparator takes two or more analog input signals and produces a Boolean output (0 or 1).

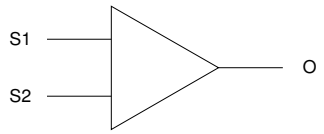

Figure 4 Basic Comparator

In a distance element the comparator produces an output (1) when the apparent impedance for a particular fault loop is "less" than the characteristic impedance (Z_C) of the comparator. In a perfect world the comparator of a distance relay might have the following shape when plotted in the impedance plane.

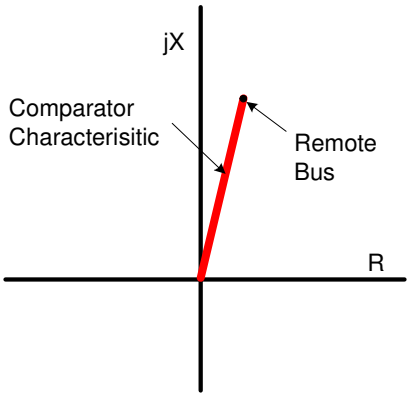

Figure 5 Ideal Distance Comparator

There are several reasons why the characteristic shown in Figure 5 cannot be used in a practical device. Because of fault resistance, the apparent impedance measured at the relay is not a faithful representation of the fault location. This will be illustrated in section 4. As will also be shown (section 5), the characteristic impedance (which determines how far the element looks) cannot be set exactly equal to the length of the protected line. Finally, the shape of the characteristic has been limited by what was practically achievable in electromechanical devices - specifically to circles and straight lines in the impedance plane.

Distance elements have historically been implemented using phase and magnitude comparators. As their names suggest, a phase comparator makes a decision based on the phase angle difference between the 2 input signals and a magnitude comparator makes a comparison based on the ratio of the two magnitudes. These two basic comparator types can be shown to be equivalent [1].

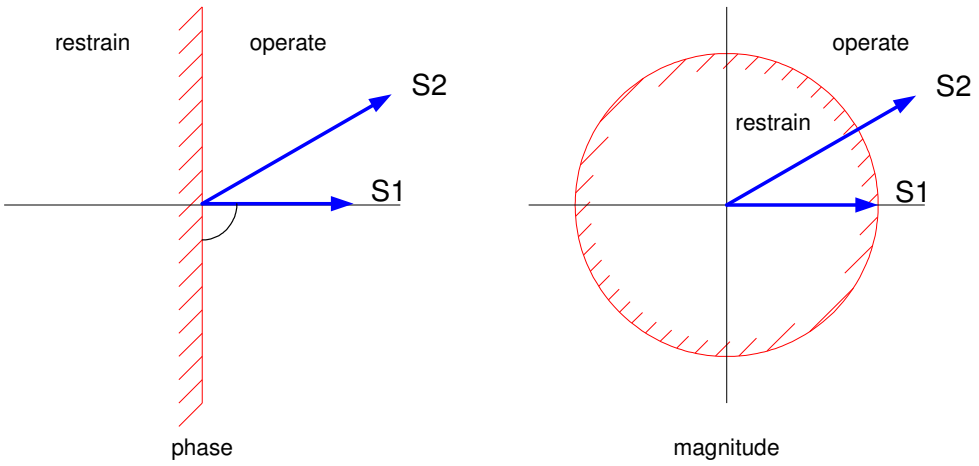

Figure 6 Phase and Magnitude Comparator Operating Characteristics

3.1. Phase comparator operating characteristics

In the phase comparator of Figure 2 the output will be asserted when $|\angle S_1 - \angle S_2| < 90°$. In a distance element, the inputs to the comparator have been traditionally designated as the operating signal, S_{OP} and the polarizing signal S_{POL}. Distance functions require linear combinations of currents and voltages as per section 2 above. Defining V_R and I_R as voltage and current measured at the relay with voltage taken as a reference then the general equations for a phase comparator can be written as:

$$S_{OP} = k_1 \cdot I_R \angle \phi + k_2 \cdot V_R \angle 0 \qquad (15a)$$

$$S_{POL} = k_3 \cdot I_R \angle \phi + k_4 \cdot V_R \angle 0 \qquad (15b)$$

Where k_1–k_4 are complex constants.

When k_2 and k_4 are fixed at -1, the comparison ($S_{OP} - S_{POL} < LA$) produces an operating characteristic that can be represented as a circular arc in the impedance plane [2]. This angle is commonly known as the comparator limit angle (see Figure 7). The comparison ($S_{OP} - S_{POL} > -LA$) produces a second arc. When the limit angle is fixed at 90 the centers of each arc coincide and a circular shape is formed. Similarly, a limit angle less than 90° produces a lens shape and an angle greater than 90° forms a tomato shape.

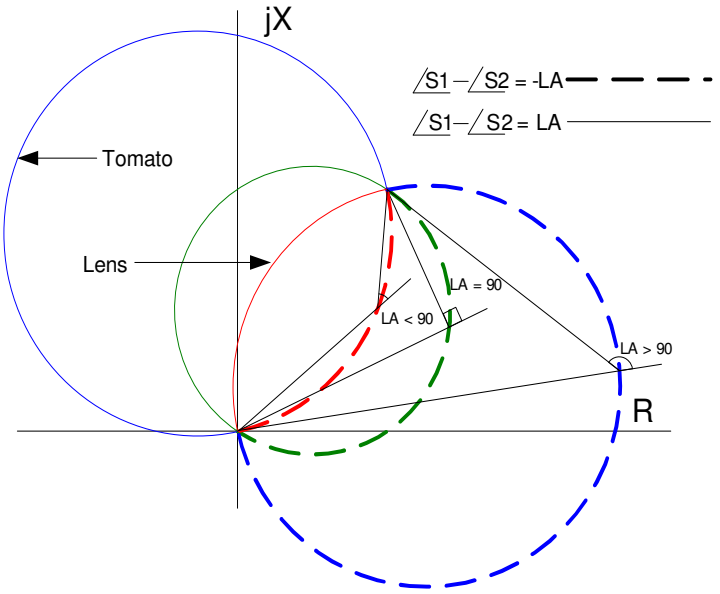

Figure 7 Impact of the Limit Angle on the Mho Characteristic

When $k_1 = k_3 = Z_C\angle\theta$ then an impedance characteristic is produced with its center at the origin and a radius equal to Z_C. Design constants $k_1 = Z_C\angle\theta$ and $k_3 = 0$ produce the Mho characteristic and design constants $k_1 = Z_C\angle\theta_C$ and $k_3 = Z_R\angle\theta_R$ result in an offset Mho

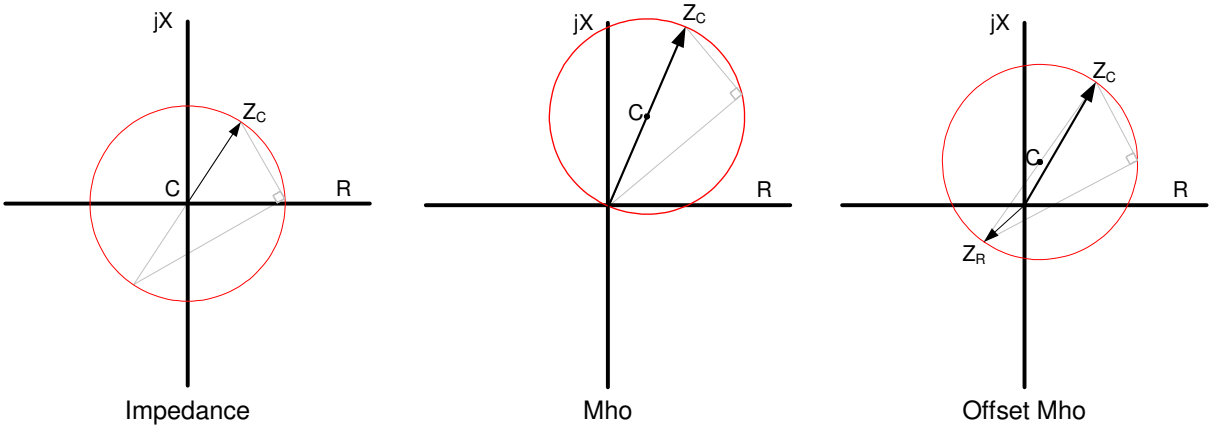

Figure 8 Impedance, Mho, and Offset Mho

Referring again to equations 1a and 1b, when k_4 is set to 0 and when $k_1 = k_3 = Z_C\angle\theta_C$ then the operating and polarizing signals will have the following general form.

$$S_{OP} = I_R\angle\phi \cdot Z_C\angle\theta - V_R\angle 0 \qquad (16a)$$

$$S_{POL} = I_R\angle\phi \cdot Z_C\angle\theta \qquad (16b)$$

A constant angle between S_{OP} and S_{POL} produces a straight line in the impedance plane. When $\theta_C = 90$ or 270 degrees the characteristic is known as a reactance line. $\theta_C = 0$ or 180 degrees produces a blinder.

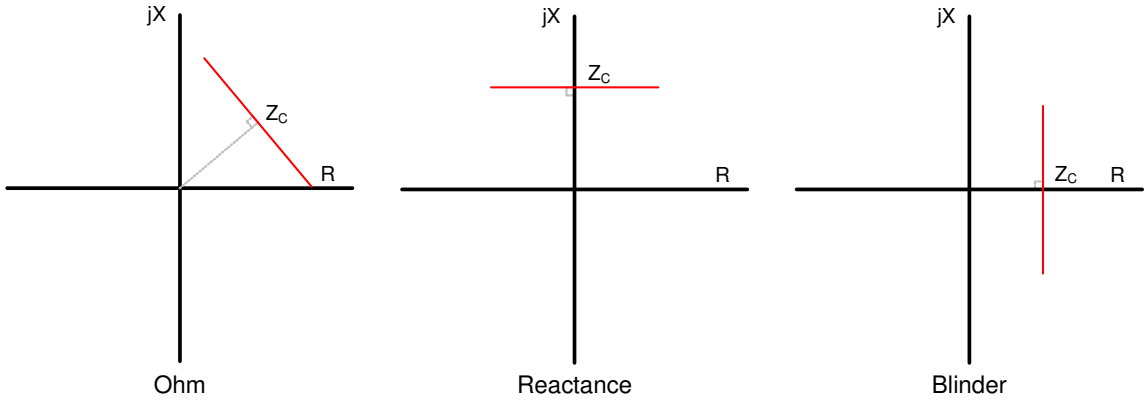

Figure 9 Ohm, Reactance, and Blinder Characteristics

3.2. Magnitude Comparator Operating Characteristics

The operating characteristics that were developed in the previous section can also be realized using magnitude comparators. In the magnitude comparator of Figure 6 the output will be asserted when $|S_1|>|S_2|$. Design constants $k_2 = 2$ and $k_4 = 0$ give

$$S_{OP} = k_1 \cdot I_R \angle\phi + 2 \cdot V_R \angle 0 \quad (17a)$$

$$S_{POL} = k_3 \cdot I_R \angle\phi \quad (17b)$$

A magnitude comparator using these signals as inputs operates when

$$\frac{S_{OP}}{S_{POL}} = e^{j\theta} \quad (18)$$

Where $e^{j\theta}$ is a unit circle centered at the origin in the complex plane. Substituting (17) and solving for V_R/I_R

$$\frac{V_R}{I_R} = \frac{k_3 \cdot e^{j\theta}}{2} - \frac{k_1}{2} \quad (19)$$

Design constants $k_1 = 0$ and $k_3 = 2 \cdot Z_C \angle\theta$ therefore produces an impedance characteristic. Setting $k_1 = k_3 = Z_C \angle\theta$ produces the mho and the offset mho is produced when $k_1 = (Z_C \angle\theta_C + Z_R \angle\theta_R)/2$ and $k_3 = (Z_C \angle\theta_C - Z_R \angle\theta_R)/2$.

Setting, $k_2 = k_4 = 1$, and $k_3 = 0$ gives

$$S_{OP} = k_1 \cdot I_R \angle\phi + V_R \angle 0 \quad (20a)$$

$$S_{POL} = V_R \angle 0 \quad (20b)$$

With $k_1 = 2 \cdot Z_C \angle \theta_C$, magnitude comparator produces a straight line in the impedance plane with the same characteristics shown in Figure 9.

The equivalency principle says a phase comparator with Sop and Spol is equivalent to mag comparator with Sop+Spol and Sop-Spol. This can be demonstrated by substitution of the equations developed earlier in this section.

Various relay design technologies implement either a phase or magnitude comparator in their respective domains, either by balancing a flux (electromagnetic), comparing phase or magnitude of low-energy voltage signals using amplifiers and comparators (static), or via explicit calculations (microprocessor-based relays). The linear combinations of currents and voltages required for deriving the operating and polarizing signals are implemented by using transactors (electromechanical), integrating circuits (static), or via calculations (microprocessor-based relays). These implementations are described in greater detail in section 11.

4. The Influence of Fault Resistance

Referring again at the circuit of Figure 1 and considering fault resistance, from equation (9) the voltage at the relay is:

$$\begin{aligned} V_R &= I_R \cdot m \cdot Z_{1L} + I_F \cdot R_F \\ &= I_R \cdot \left(m \cdot Z_{1L} + \frac{I_F}{I_R} \cdot R_F \right) \end{aligned} \tag{21}$$

And the apparent impedance is

$$Z_R = m \cdot Z_{1L} + \frac{I_F}{I_R} \cdot R_F \tag{22}$$

With no load, I_F and I_R are in phase and the fault resistance will push the apparent impedance to the right as shown in

Figure 10.When load is flowing out of the terminal (export) the fault resistance will be shifted down on the RX plane; causing a static distance element to under-reach. When load is flowing into the terminal the fault resistance is tilted up, causing a static distance element to over-reach. The reader may refer to A1 of the appendix for a sample calculation showing the impact of fault resistance.

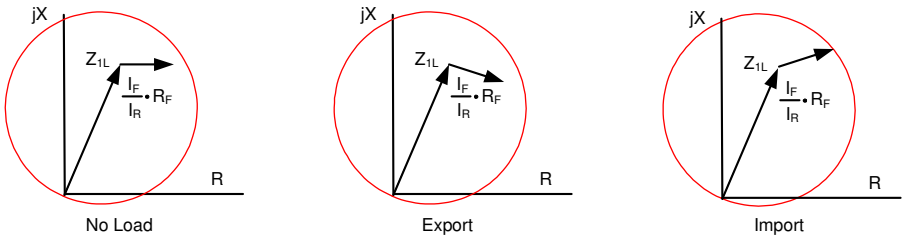

Figure 10 Impact of Fault Resistance on Apparent Impedance

5. Voltage polarization and directional integrity

In addition to fault resistance close-in faults also create problems for the self-polarized mho function. Since the polarizing signal is the fault voltage, if this signal collapses to a small value then the element may respond erratically such as fail to operate or pickup for reverse faults under heavy load conditions. These problems are addressed by a making a different choice for the polarizing voltage. Several methods of polarization have been employed in the past [3]:

- Faulted phase polarization with memory
- Cross polarization without memory
- Cross polarization with memory
- Positive sequence polarization with memory

A memorized polarizing signal uses the value taken prior to the inception of the fault. Cross polarization refers to the use of a signal that remains healthy during the fault. For instance a cross-polarized AB mho element would use V_C as a polarizing signal. Each of the methods listed above produce a characteristic that dynamically expands for a forward fault and contracts for a reverse fault. Z_{ES} represents an equivalent source impedance that defines the expansion (Figure 11) and is a function of the source impedance and the polarization method. The degree of expansion or contraction depends on the choice of polarizing signal, the source impedance and the fault type. Because of its dependency on source impedance, the dynamic behavior is more pronounced for a system having a larger source impedance.

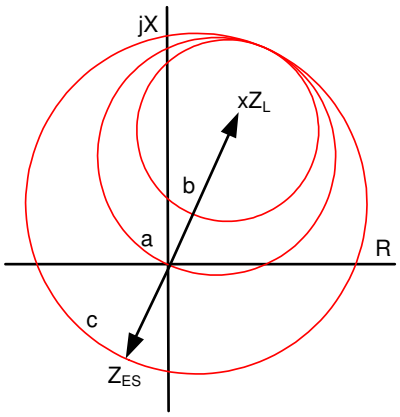

Figure 11 a) Static, b) Contraction during a reverse fault, c) Expansion during a forward fault

Polarization can also improve resistive coverage during load flow [3]. Figure 12 shows the expansion of a cross-polarized mho for load import and export. Note that the expansion of the characteristic is in the same direction as the shift in fault resistance.

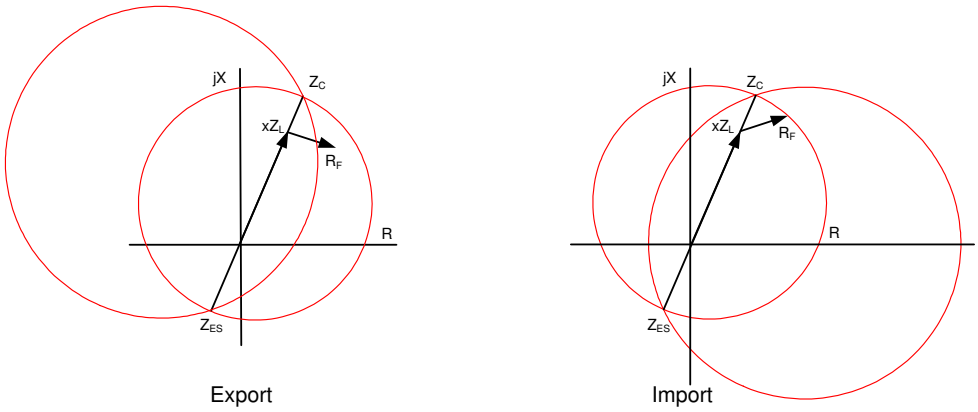

Figure 12 Expansion of the Cross-polarized Mho for Load

6. Zones of Protection

In Section 2 it was seen that 6 separate distance elements can provide detection for all possible fault types. Taken together these elements form a distance zone. Practically, a single zone cannot provide complete coverage of the transmission line because the reach of these elements cannot be set at 100 percent of the line length. This is due to several factors:

- Difficulty in estimation of the impedance of the transmission line especially the zero sequence component (Z_O) and mutual coupling component (Z_{OM}) in the case of parallel transmission lines.
- Infeed effects in the case of three ended lines.
- Transient overreach (See section 13)

- Measurement accuracy of the CTs, VTs and relays themselves

Placing 2 distance zones at each end of the line provides complete coverage.

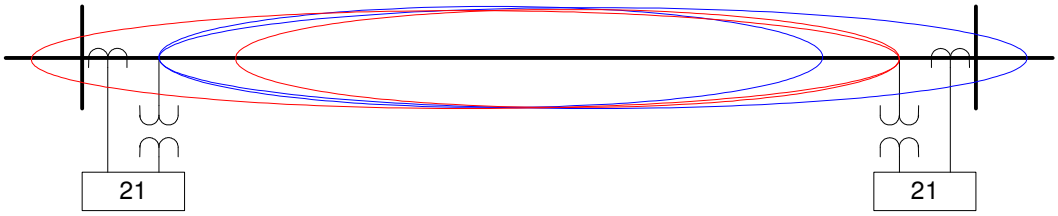

Figure 13 Step Distance Scheme

The first zone is set detect faults in the first 80-90% of the line (underreaching) and operates with no intentional time delay. The second zone is set at 120-130% of the line length (overreaching) and is delayed to allow remote relays to operate in the case that the fault is beyond the end of the protected line. This scheme is known as step distance and provides instantaneous fault clearance for 60-80% of the line. Teleprotection schemes utilize signals sent over a communications channel to bring this number up to 100%. In the past several teleprotection schemes have been employed:

- Direct under-reaching transfer trip (DUTT)
- Permissive under-reaching transfer trip (PUTT)
- Permissive over-reaching transfer trip (POTT)
- Directional comparison blocking (DCB)
- Directional comparison unblocking (DCUB)

The factors influencing the choice of scheme include type of communication channel and the configuration of the line. The development of these schemes was driven by the need to minimize the number of distance elements. This is not a limiting factor in modern distance relays. As such, some of the schemes are less relevant today.

7. Switched versus Non-switched Schemes

In step distance schemes, zones 1 and 2 may have an independent set of distance elements or they may have a single set of elements with reach settings that are switched from zone 1 and zone 2. In a switched scheme, a starting element is used to signal the beginning of the fault. The starting element could be an overcurrent element or an additional distance element. When the starting element picks up, the zone 1 reach and a time delay of zero are applied. If no fault is detected the reach and time delay are switched to the zone 2. The process could be extended to include any number of zones.

Switched schemes minimize the number of elements required. This reduced the cost and improved the reliability of electromechanical and solid state implementations. The same benefits are not realized in microprocessor-based devices. Switched schemes can have problems with evolving faults (e.g. an external fault on a parallel line developing into an internal fault). As a result, modern relays usually incorporate independent zones.

8. Mutual Coupling

When two transmission lines share the same tower or the same right-of-way there will be mutual inductive coupling between their conductors. Transposition of the lines minimizes the impact on the positive and negative sequence impedances. However, in the zero sequence path, mutual coupling manifests itself as a voltage drop equal to the zero sequence current in the adjacent line multiplied by the mutual inductance and as a consequence, produces an error in the apparent impedance measurement. This error is difficult to predict if the two transmission lines are members of different power systems.

In the case of parallel lines the measurement error can be calculated. A thorough analysis is given in [4]. The results show that, for single-ended infeeds, the relay will generally overreach. For double-ended infeeds, the relay can underreach or overreach depending on the distribution of the ground fault current.

Many modern relays can compensate for mutual coupling. The relay is typically supplied with the residual CT current from the adjacent line. A zero sequence compensation factor ($k_{OM}=Z_{1L}/3\cdot Z_{OM}$) is entered into the relay.

9. Homogeneity

A system is said to be homogeneous if all of its constituent impedances – in a given sequence domain - have the same angle as illustrated in Figure 14.

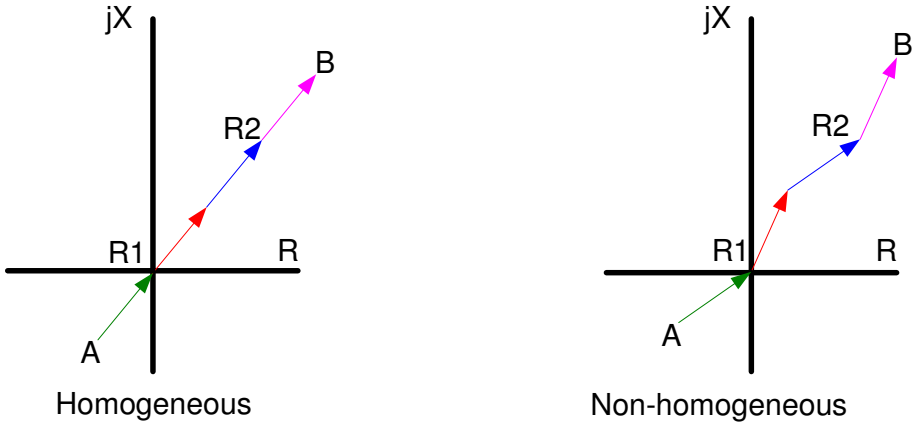

Figure 14 Power System Homogeneity

In the case of a ground fault in a homogeneous system inspection of Figure 2 shows that the zero sequence current measured at the relay will be in phase with the zero sequence fault current [5] A reactance characteristic formed from $I_R\cdot Z-V$ and jI_{0R} will lie in parallel with the fault resistance. The behavior of an element polarized with I_{2R} will be the same. As such the element will not have a tendency to overreach or underreach.

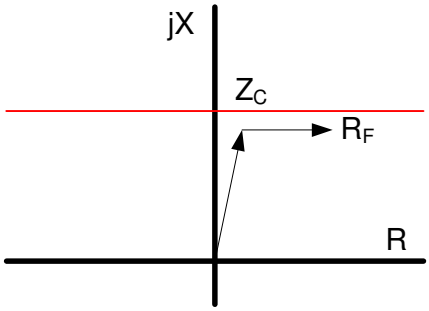

Figure 15 Fault Resistance and the Reactance Characteristic in a Homogeneous System

If the system is non-homogeneous neither I_{0R} nor I_{2R} may be in phase with I_F. Equations (23) can be used to calculate the angles between I_{0R}, I_{2R}, and I_F.

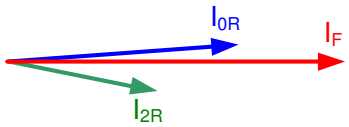

Figure 16 Polarizing current Phase Relationships in a Non-homogeneous System

In many distance relays these values are used to correct the error introduced by the non-homogeneity of the system.

$$\Theta_0 = ang\left(\frac{I_F}{I_{0R}}\right) = ang\left(\frac{Z_{0A} + Z_{0L} + Z_{0B}}{Z_{0B} + (1-m)\cdot Z_{0L}}\right) \quad (23a)$$

$$\Theta_2 = ang\left(\frac{I_F}{I_{2F}}\right) = ang\left(\frac{Z_{1A} + Z_{1L} + Z_{1B}}{Z_{1B} + (1-m)\cdot Z_{1L}}\right) \quad (23b)$$

The choice of best polarizing signal and correcting angle both depend on system parameters and intended reach of the zone. If the system configuration is static, the selection is straightforward. In highly non-homogenous and dynamic systems where the correction for non-homogeneity is not feasible, conservative reach and/or correction angle settings should be considered.

10. Phase Selection

As was mentioned earlier, six distance elements are required to detect all possible fault types. The phase elements are intended for detection of phase-phase, double-phase-ground and three-phase faults. The ground elements are intended for detection of ground faults and will also operate for three phase faults. However, a ground element can operate for a double-phase-ground fault that is outside of its characteristic (see appendix A2 for a sample calculation). As well phase elements can operate for ground faults close to the relay location. Although this fault occurs within the zone, it would result in an incorrect three-pole trip in a single pole tripping application.

Since the distance elements cannot be relied upon to determine the fault type, phase selection schemes have been developed. One commonly applied method is to monitor the angle between the zero and negative sequence currents. From symmetrical component theory we know that:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_0 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (24)$$

In an unloaded system, a ground fault will produce current in one phase only. Substituting the phase currents into (24) it is evident that for an AG fault, I_2 and I_0 are in phase, for a BG fault I_2 lags I_0 by 120° and for a CG fault I_2 leads I_0 by 120°.

Similarly, for an AB fault $I_B = -I_A$ and from (24) I_2 lags I_1 by 60°. Continuing this exercise for other fault types yields the phase relationships shown in Figure 17

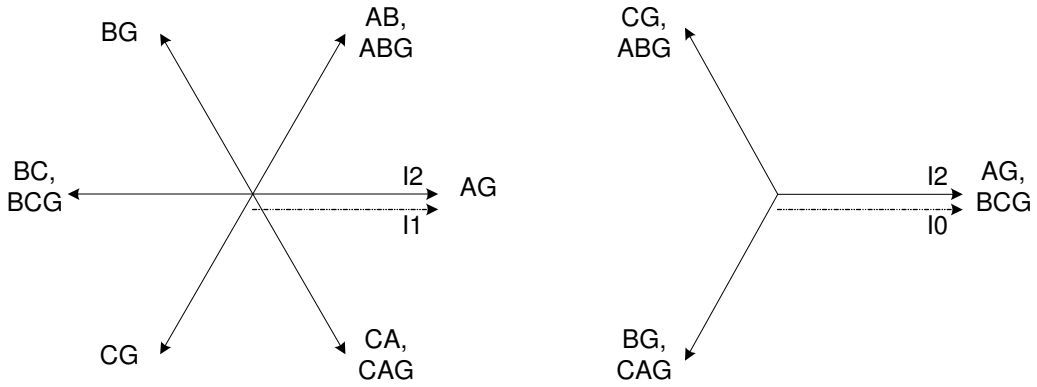

Figure 17 Sequence Component Relationships for Various Fault Types

In practical phase selectors, the prefault current is subtracted from the fault current to remove the effect of loading.

The phase selector can be adversely affected by simultaneous faults at different locations in the system, one of which could appear in the forward direction and the other in the reverse direction. It can also have problems with faults at weak terminals or terminals with strong zero-sequence sources where the zero sequence current masks the fault current. Voltage-based phase selectors have been developed to address such issues [6].

11. Implementation methods and generations of technology

11.1. Electromechanical

Electromechanical distance elements are designed around the induction cup [7]. This device is similar in operation to an induction motor. On the stator, the operate winding and restraint winding are physically oriented at 90 degrees from a polarization winding.

The rotor is composed of a stationary core and a rotating cup.

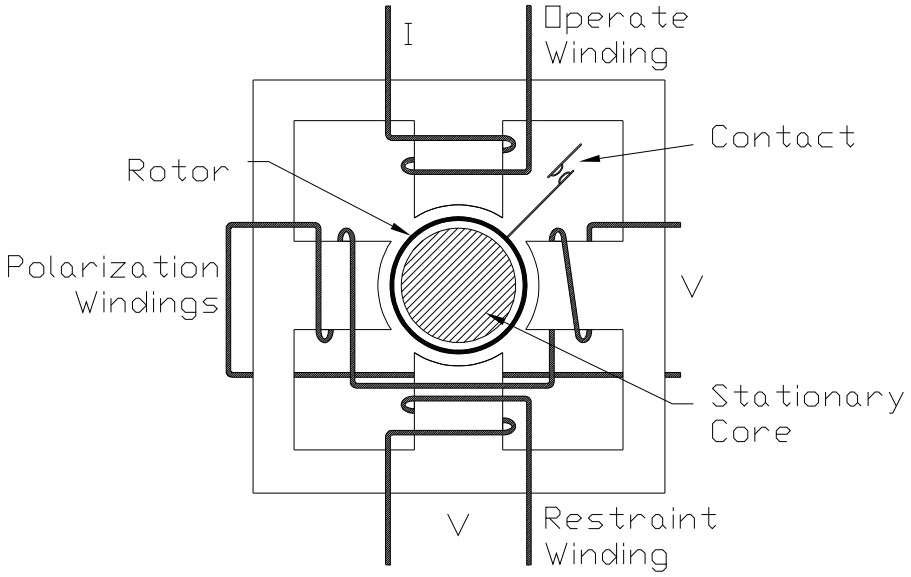

Figure 18 Induction Cup

The torque produced by the induction cup is:

$$T = V \cdot I \cdot \cos(\varphi - \theta) - \frac{V^2}{Z_C} \tag{25}$$

Where φ is the angle between V and I. At the balance point of the relay T=0 and:

$$V \cdot I \cdot \cos(\varphi - \theta) = \frac{V^2}{Z_C} \tag{26}$$

and:

$$\frac{V}{I} = Z_C \cdot \cos(\varphi - \theta) \tag{27}$$

11.2. Solid State

Solid-state distance relays are designed around the op amp. Op amp circuits can be designed to implement filter, summation, and comparison functions to name a few. In one solid-state implementation the signals $I \cdot Z_C - V$ and V_{POL} are derived through a series of these op amp circuits. These signals are then converted to square waves. The input to the D flip-flop is latched on a positive or negative transition of the polarizing signal. The output of the latch is Exclusive ORed with the polarizing signal. The resultant output is a logic 1 when V_{POL} leads $I \cdot Z_C - V$ by 0-180 degrees.

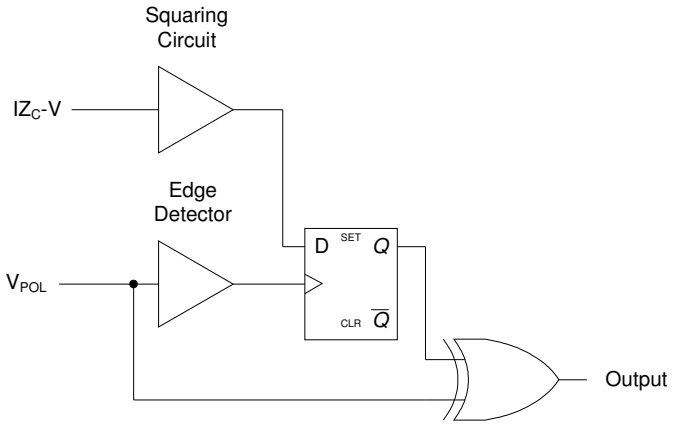

Figure 19 Solid-State Phase Comparator

11.3. Microprocessor

In a microprocessor based relay, the voltages and currents signals are reduced to a level that is suitable for processing using solid-state devices. Prior to sampling they are passed through an anti-aliasing filter. This filter ensures that any high frequency components in the waveforms are not folded back during the phasor estimation process. After the signals are sampled they are converted to digital values and passed to the microprocessor.

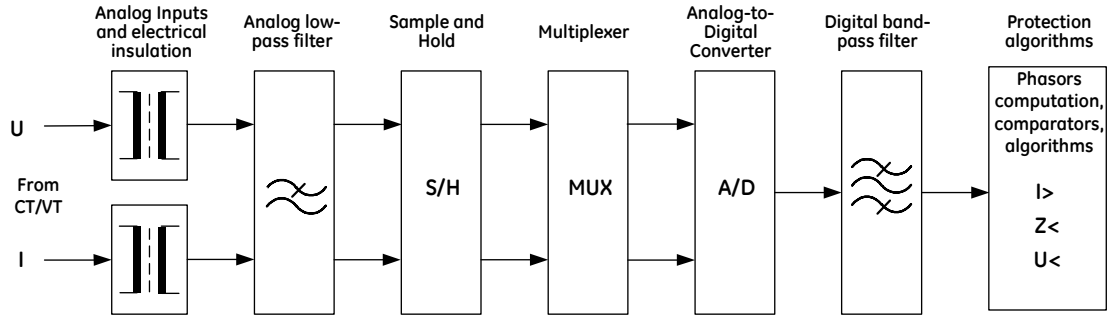

Figure 20 Microprocessor-Based Distance Relay

The microprocessor is responsible for converting the time-domain representations of the voltages and currents into phasor values. A Discrete Fourier Transform (DFT) is typically used for this purpose. If the time domain signal has a DC component it will "leak" into the fundamental. Figure 21 shows a fault current with DC offset plotted

against its phasor magnitude (unfiltered). Note that the magnitude is overestimated for a brief period. Over estimation of the current can cause transient over-reach when used within a distance element.

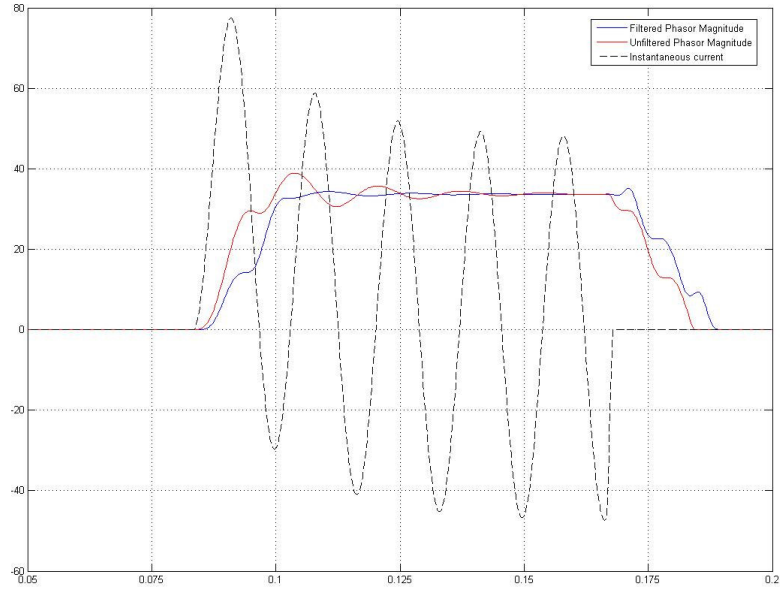

Figure 21 Impact of DC Components on DFT Calculation

For this reason a digital filter is often used to remove the DC component prior to the DFT calculation. Figure 22 shows the frequency response of such a filter. Note that the signal is heavily attenuated as the frequency approaches zero.

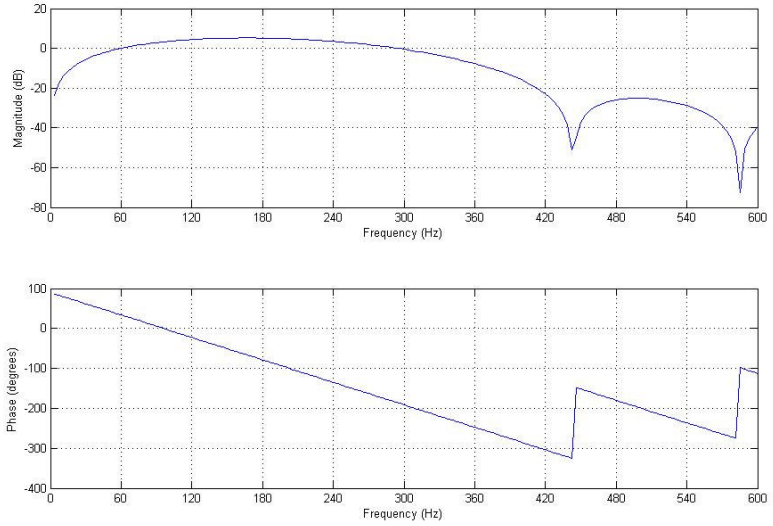

Figure 22 DC Offset Filter Frequency Response

Once the phasors have been calculated, the operating signal $I \cdot Z_C - V$ and V_{POL} are calculated. Subtracting the angles between these signals and comparing the result to the limit angle produces a mho characteristic in its most basic form. Similar procedures are used to implement reactance lines, directional elements, phase selectors, and the like.

Some modern implementations of distance functions operate in time-domain. This means samples of currents and voltages are processed without extensive filtering such as using the DFT in order to extract all possible information in the input signals. The traditional approach of extracting phasors and manipulating phasors is no longer a must as the new microprocessor-based platforms became powerful enough to mimic any known technology in the time domain.

12. Mho and Quadrilateral characteristics

A reactance line implemented using a single comparator cannot be used on its own to protect a transmission line since it would operate for load or for reverse faults. In a practical distance relay the reactance line comparator is combined with right and left blinders, and a directional element to form a quadrilateral characteristic.

Similarly a comprehensive Mho element may include Mho comparator plus several auxiliary comparators.

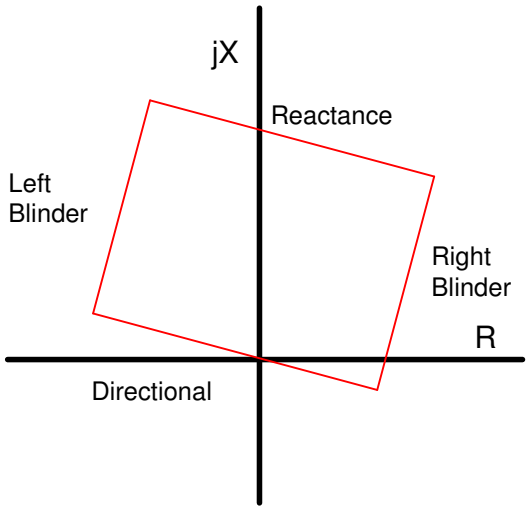

Figure 23 Basic Quadrilateral Characteristic

Tables 1 through 4 list the comparators that make up the phase and ground distance elements in a modern distance relay. For a particular element the values of V and I are replaced with those listed in Table 1.

Table 2 Mho Phase Distance Functions*

Characteristics	Comparator Inputs	
Variable mho	$I \cdot Z_C - V$	V_{1M}
Reactance	$I \cdot Z_C - V$	$I \cdot Z_C$
Directional	$I \cdot Z_D$	V_{1M}

Table 3 Mho Ground Distance Functions*

Characteristics	Comparator Inputs	
Variable mho	$I \cdot Z_C - V$	V_{1M}
Reactance	$I \cdot Z_C - V$	$I_0 \cdot Z_C$
Directional	$I_0 \cdot Z_D$	V_{1M}
Directional	$I_2 \cdot Z_D$	V_{1M}
Phase selection (removed during open pole conditions)	I_0	I_2
Zero-sequence (removed for open pole conditions)	$I_0 \cdot Z_D$	$-V_0$

Table 4 Quadrilateral Phase Distance Functions*

Characteristics	Comparator Inputs	
Reactance	$I \cdot Z_C - V$	$I \cdot Z_C$
Directional	$I \cdot Z_D$	V_{1M}
Right Blinder	$I \cdot Z_R - V$	$I \cdot Z_R$
Left Blinder	$I \cdot Z_L - V$	$I \cdot Z_L$

Table 5 Quadrilateral Ground Distance Functions*

Characteristics	Comparator Inputs	
Reactance	$I \cdot Z_C - V$	$j \cdot I_0 \cdot Z_N$ or $j \cdot I_2 \cdot Z_N$
Directional	$I_0 \cdot Z_D$	V_{1M}
Directional	$I_2 \cdot Z_D$	V_{1M}
Right Blinder	$I \cdot Z_R - V$	$I \cdot Z_R$

Left Blinder	$I \cdot Z_L - V$	$I \cdot Z_L$
Phase selection	I_0	I_2
Zero-sequence (removed during open pole conditions)	$I_0 \cdot Z_D$	$-V_0$

$^*Z_C$ Characteristic Impedance (Reach∠RCA) of the Mho or Quadrilateral function
Z_D $1\angle \alpha$ where α is the characteristic angle of the directional element
Z_N $1\angle \phi$ where ϕ is the non-homogeneity angle of the system
$V1_M$ Memorized positive sequence voltage

13. Challenges for the Distance Element

Capacitive voltage transformers are the principal source of the voltage signal for distance relays applied in HV and EHV systems. They provide a cost effective way of obtaining the voltage signal. However they create significant problems for the relay. A CVT under line fault conditions (i.e. when the voltage drops and there is no possibility of exceeding the knee point of the step-down transformer) can be represented by the equivalent linear circuit as shown in Figure 24 [8]. The circuit of Figure 24 can be simplified to that shown in Figure 25. The second circuit sufficiently models the dynamics of the CVT.

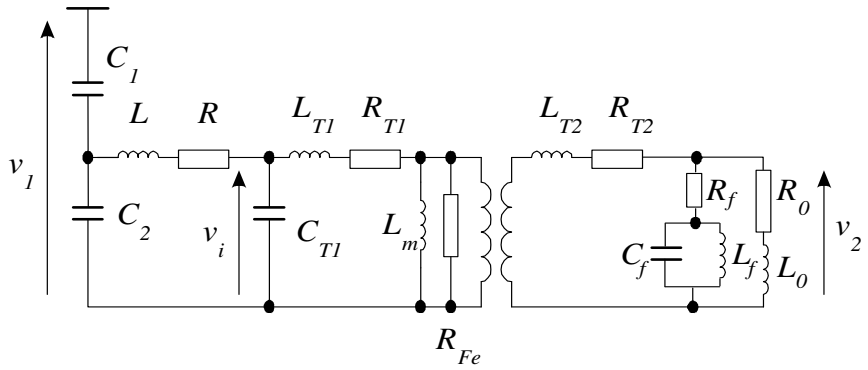

Figure 24 Equivalent circuit diagram of a CVT

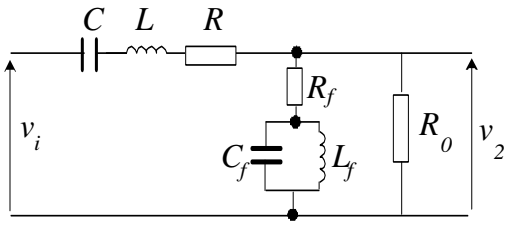

Figure 25 Simplified model of a CVT

The parameters in the circuit of Figure 22 are:

C sum of the stack capacitances

L inductance of a tuning reactor and a step down transformer

R equivalent resistance of a tuning reactor and a step down transformer

R_0 burden resistance

L_f parameters of the anti-resonance circuit

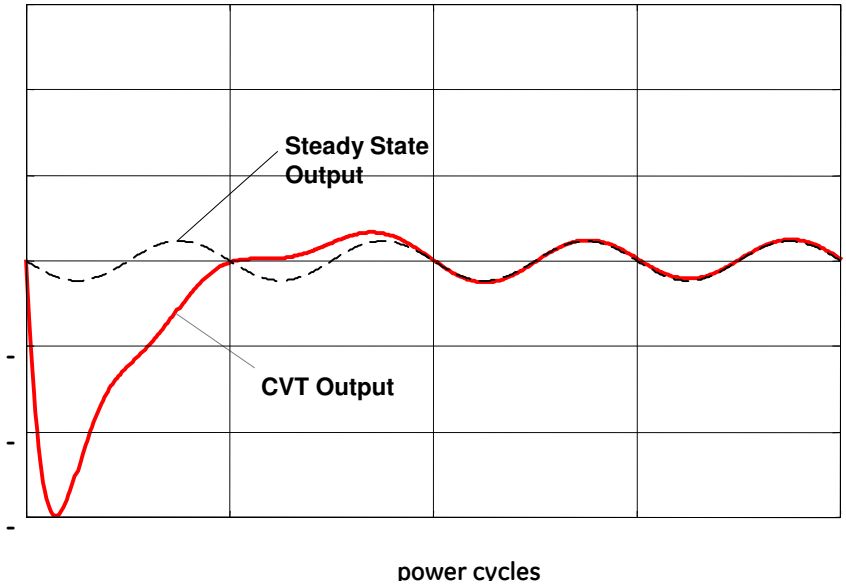

Figure 26 CVT Transient Response

The transient response of the CVT is a function of the stack capacitances, ferroresonance circuits, burden, and fault incidence angle. It can be composed of several large decaying exponential components as will as decaying sinusoids. Initially these components can be significantly larger than the steady-state which represents the "true" value of the voltage. This voltage is a key term in the operating signal of the distance element ($I \cdot Z_C - V$).

The problem is aggravated when the source-impedance ratio (SIR) is also high. For these systems the voltage at the relay during a fault is approximately:

$$V_{FAULT} = \frac{V_{NOMINAL}}{1 + SIR} \tag{28}$$

For high SIRs the voltage signal becomes very small. The CVT transient, however is independent of SIR.

A large transient superimposed onto a small operating signal creates two problems for the distance element:

1. During external fault the voltage magnitude is underestimated and the phase angle can shift by 360 degrees, the effects of which can be seen in Figure 27. In order to prevent a mis-operation relay designers often introduce intentional

delays (security counts) into the distance element. These delays necessarily impact the speed of operation for internal faults.

2. For faults near the reach point, the relay voltage for internal and external faults may differ by as little as a few tenths of a percent, making internal faults indistinguishable until the transient dies out.

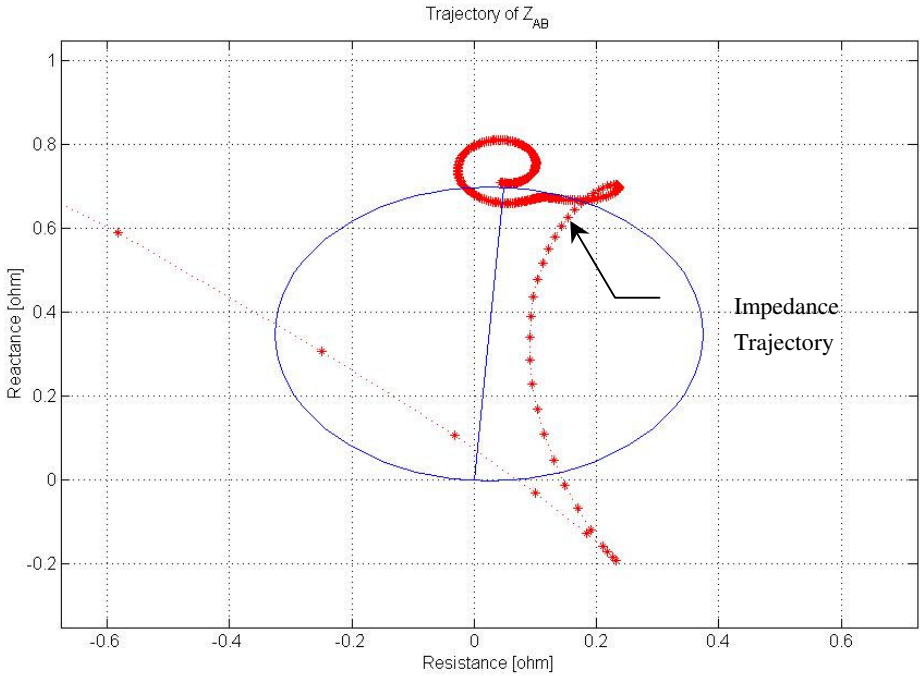

Figure 27 External Fault with CVT Transient

Taken together these issues can dramatically impact the speed of the relay. Modern microprocessor based relays often incorporate techniques to deal with CVT transients [8].

14. Distance functions looking through power transformers

Certain applications require that a distance relay reaches correctly through a power transformer – backup distance on a generator being the classic example. A Delta/Wye connection introduces a discontinuity into the zero sequence circuit, hence ground distance elements cannot be applied. The phase distance elements utilize phase-phase voltages and currents in accordance with Table 1. However these quantities are modified by the transformer connection. For instance, when looking through a Delta/Wye connection the high side phase-neutral voltage becomes a phase-phase quantity. The result is that the distance element will not reach correctly for all fault types. The solution for electromechanical relays was to re-wire the CT and VT secondary currents in order to undo the transformation introduced by the power transformer. In a microprocessor-based the same the current and voltage transformations can be applied digitally. For instance for a DY1 connection the following operations are necessary to correct the voltages and currents.

Table 6 Operations required for a DY1 Transformation

Element	Current	Voltage
AB	$I_{AB} = \sqrt{3} \cdot I_A$	$V_{AB} = {(V_{AB} - V_{CA})}/{\sqrt{3}}$
BC	$I_{BC} = \sqrt{3} \cdot I_B$	$V_{BC} = {(V_{BC} - V_{AB})}/{\sqrt{3}}$
CA	$I_{CA} = \sqrt{3} \cdot I_C$	$V_{CA} = {(V_{CA} - V_{BC})}/{\sqrt{3}}$

15. Applications on series compensated lines

Series capacitor banks are installed on transmission lines in order to increase the maximum transmittable power. The capacitive reactance X_C can be 50-70% of the line reactance X_L. An MOV and bypass devices are typically connected in parallel with the capacitor to protect the capacitor during faults. The series capacitor essentially violates a fundamental principle upon which distance protection is built; namely that the apparent impedance varies proportionally with the distance to the fault. Under normal operation of the power system the capacitor presents a large, lumped, negative reactance reducing the total reactance of the line.

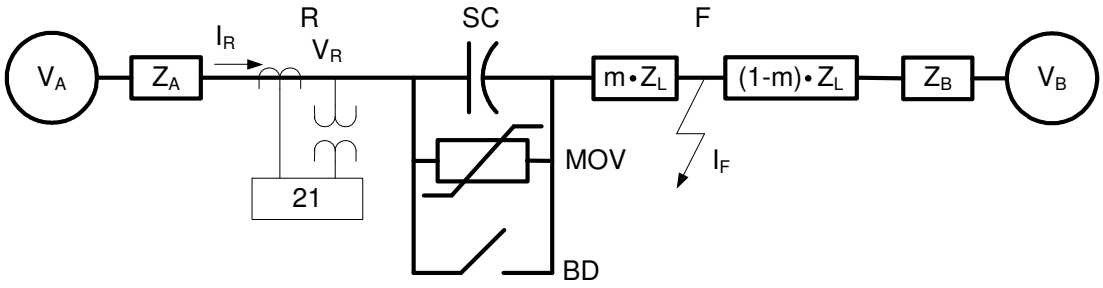

Figure 28 Series Compensated Transmission Line

During a fault and depending on the fault current magnitude both the MOV and the bypass device will conduct some, or all of the fault current thereby modifying the impedance that the bank presents to the system.

For low magnitude external faults, only a small amount of the fault current may be shunted. In this case the fault loop becomes a series RLC network. Because of the relative magnitudes of X_C and X_L the resonant frequency can be as little as 10 Hz below the nominal system frequency. Figure 29 shows the resulting apparent impedance during a low current fault.

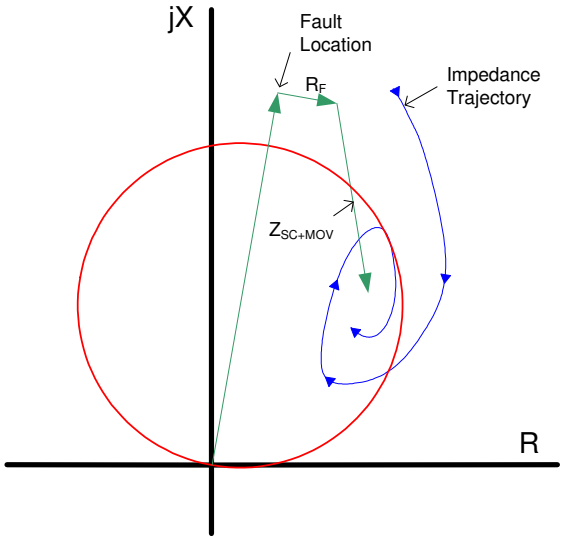

Figure 29 Overreach for a Low Magnitude Fault

Voltage and/or current inversion may lead to false direction discrimination by directional elements. A detailed analysis of these phenomena is given in [9] and may be summarized as follows:

- In the circuit of Figure 30, the impedances Z_A and Z_B are determined by the location of the VT in relation to the capacitor and the location of the fault.
- A current inversion will occur in particular sequence network if $Z_A + Z_B$ is capacitive.
- A voltage inversion will occur in particular sequence network if Z_A and Z_B have opposite signs (one capacitive, the other inductive).

An inversion will cause the apparent impedance to appear in the wrong quadrant potentially resulting in either a failure to operate on a forward in-zone fault as well as mis-operation on a reverse fault. Both distance and overcurrent directional elements can be affected. The use of memory-polarized comparators will prevent a mis-operation in such cases.

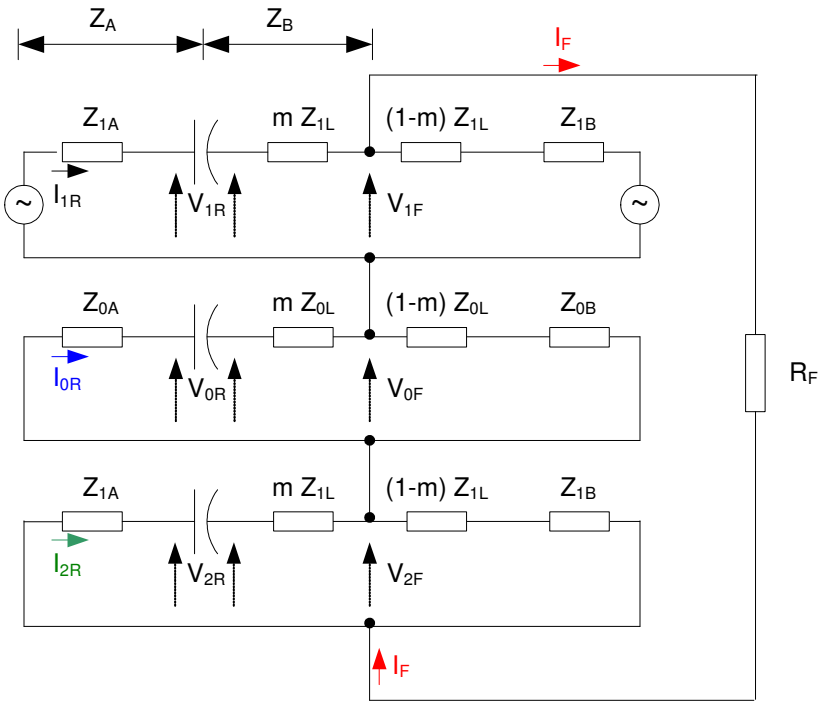

Figure 30 Network equivalent diagram for single-line-to-ground faults

16. Single Pole Tripping

Single pole tripping can improve the stability of the power system since, by opening only the faulted phase, synchronization is maintained through the healthy phases. Proper phase selection is important since the distance elements cannot be relied upon to determine the fault type as was noted in section 10.

Once the faulted phase has been isolated, it is important to block selected elements that could mis-operate for the unbalance created by the open pole. For instance, an open pole on phase A requires blocking of the A, AB, and CA distance elements plus any zero or negative sequence directional elements. The remaining elements (B, C and BC) are required in the case the fault evolves to include other phases.

Positive sequence memory polarization provides the greatest security during open pole conditions [10].

17. Summary

In this paper we reviewed some basic principles of distance protection. This includes fundamentals of measuring distance to fault based on electrical signals from one end of the circuit; the principles of amplitude and phase comparators to implement a distance relay; and various technologies used to build distance relays.

A number of application aspects have been discussed including shaping of the impedance characteristic, the impact of fault resistance, different methods of polarizing distance functions, the need for phase selection, switchable vs. non-switchable schemes, distance function looking through power transformers or series compensated lines.

Factors impacting performance of distance elements including CVTs and SIR have been discussed as well.

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Biographies

Bogdan Kasztenny holds the position of Protection and System Engineering Manager for the protective relaying business of General Electric. Prior to joining GE, Dr. Kasztenny conducted research and taught protection and control at Wroclaw University of Technology, Texas A&M University, and Southern Illinois University. Between 2000 and 2004 Bogdan was heavily involved in the development of the Universal Relay™ series of protective relays. He authored more than 160 papers, is the inventor of several patents, Senior Member of the IEEE, and the Main Committee of the PSRC. Dr. Kasztenny is a registered professional engineer in the province of Ontario. In 1997, he was awarded a prestigious Senior Fulbright Fellowship. In 2004 Bogdan received GE's Thomas Edison Award for innovation.

Dale Finney began his career with Ontario Hydro where he worked as a protection and control engineer. Since 1999, he has been employed as an applications engineer with GE in Markham Ontario. His areas of interest include generator protection, line protection, and substation automation. Dale has a Bachelor of Engineering degree from Lakehead University and a Master of Engineering degree from the University of Toronto. He is a registered professional engineer in the province of Ontario, a member of the PSRC, and a senior member of the IEEE.

Appendix

The following calculations were carried out using Mathcad for the circuit of Figure 1.

$a := e^{120i \cdot deg}$ $\quad A := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix}$

Source Voltages

$VS1 := 1.0 \cdot e^{0i \cdot deg}$ $\quad VS2 := 1.0 \cdot e^{-30i \cdot deg}$

Relay Settings

$Reach := 0.85 \cdot .2$ $\quad RCA := 71 \cdot deg$ $\quad ZC := Reach \cdot e^{RCA \cdot i}$

Static Mho Characteristic (for plotting)

$q := 0 .. 200$ $\quad \phi_q := \frac{\pi \cdot q}{100}$ $\quad Mho_q := \frac{Reach}{2} \cdot \left(e^{j \cdot RCA} + e^{j \cdot \phi_q} \right)$

Fault Location

$m := 0.8$

System Impedances

$ZS11 := .4 \cdot e^{90i \cdot deg}$ $\quad ZS21 := ZS11$ $\quad ZL1 := .2 \cdot e^{71i \cdot deg}$ $\quad ZL11 := m \cdot ZL1$ $\quad ZL21 := (1 - m) \cdot ZL1$

$ZS10 := .125 \cdot e^{89i \cdot deg}$ $\quad ZS20 := ZS10$ $\quad ZL0 := .64 \cdot e^{67i \cdot deg}$ $\quad ZL10 := m \cdot ZL0$ $\quad ZL20 := (1 - m) \cdot ZL0$

$ZS12 := ZS11$ $\quad ZS22 := ZS12$ $\quad ZL2 := ZL1$ $\quad ZL12 := m \cdot ZL2$ $\quad ZL22 := (1 - m) \cdot ZL2$

$k0 := \frac{ZL0}{ZL1} - 1$

Fault Impedance

$RF := 0.05 \cdot Re(|ZS11 + ZL11|)$ $\quad RG := 2 \cdot RF$

Load

$IL := \frac{VS1 - VS2}{ZS11 + ZL1 + ZS21}$

$VS1 \cdot \overline{IL} = 0.512 + 0.102i$

Prefault (memorized) Voltages

$\begin{pmatrix} Vam \\ Vbm \\ Vcm \end{pmatrix} := \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} \cdot (VS1 - IL \cdot ZS11)$

Thevenin Equivalents

$$VTH := VS1 - IL\cdot(ZS11 + ZL11)$$

$$Z1TH := \frac{(ZS11 + ZL11)\cdot(ZS21 + ZL21)}{ZS11 + ZL11 + ZS21 + ZL21}$$

$$Z0TH := \frac{(ZS10 + ZL10)\cdot(ZS20 + ZL20)}{ZS10 + ZL10 + ZS20 + ZL20}$$

$$Z2TH := Z1TH$$

A1. The Impact of Fault during a Phase-Ground Fault

$$IF1 := \frac{VTH}{Z1TH + Z2TH + Z0TH + 3\cdot RF} \qquad IF2 := IF1 \qquad IF0 := IF1$$

$$IR1 := IF1\cdot\frac{ZS21 + ZL21}{ZS11 + ZL11 + ZS21 + ZL21} + IL$$

$$IR2 := IF2\cdot\frac{ZS22 + ZL22}{ZS12 + ZL12 + ZS22 + ZL22}$$

$$IR0 := IF0\cdot\frac{ZS20 + ZL20}{ZS10 + ZL10 + ZS20 + ZL20}$$

$$VR1 := VS1 - IR1\cdot ZS11 \qquad VR2 := -IR2\cdot ZS12 \qquad VR0 := -IR0\cdot ZS10$$

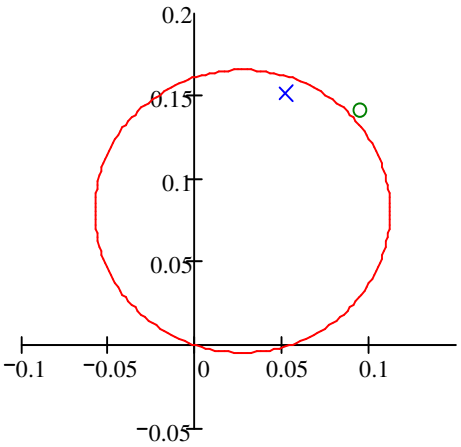
Fault Current and Relay Quantities

$$\begin{pmatrix} IFa \\ IFb \\ IFc \end{pmatrix} := A\cdot\begin{pmatrix} IF0 \\ IF1 \\ IF2 \end{pmatrix} \qquad \begin{pmatrix} IRa \\ IRb \\ IRc \end{pmatrix} := A\cdot\begin{pmatrix} IR0 \\ IR1 \\ IR2 \end{pmatrix} \qquad \begin{pmatrix} VRa \\ VRb \\ VRc \end{pmatrix} := A\cdot\begin{pmatrix} VR0 \\ VR1 \\ VR2 \end{pmatrix}$$

$$|IRa| = 1.813 \qquad \arg(IRa) = -74.476\,\text{deg} \qquad |VRa| = 0.453 \qquad \arg(VRa) = -24.941\,\text{deg}$$

Apparent Impedance

$$Zapp := \frac{VRa}{IRa + k0 \cdot IR0}$$



x is the fault location
o is the apparent impedance

Operating signal

$Sop := (IRa + k0 \cdot IR0) \cdot ZC - VRa$ $Spolsp := VRa$ $Spolmp := Vam$

Angles of operating and polarizing signals

$\arg(Sop) - \arg(Spolsp) = 98.273deg$ Self Polarized does not operate

$\arg(Sop) - \arg(Spolmp) = 85.387deg$ Memory Polarized operates

A2. Overreaching of Ground Element for a Double-Phase-Ground fault

Relay Settings

$Reach := 0.75 \cdot .2$ $\quad RCA := 71 \cdot deg$ $\quad ZC := Reach \cdot e^{RCA \cdot i}$

Static Impedance Line (for plotting)

$q := 1 .. 200$ $\quad X_q := (q - 100 + j \cdot Reach) \cdot e^{j \cdot (RCA - 90 \cdot deg)}$

$$IF1 := \frac{VTH}{Z1TH + \frac{RF}{2} + \frac{\left(Z2TH + \frac{RF}{2}\right) \cdot \left(Z0TH + \frac{RF}{2} + 3 \cdot RG\right)}{Z2TH + Z0TH + RF + 3 \cdot RG}}$$

$$IF2 := -IF1 \cdot \frac{Z0TH + \frac{RF}{2} + 3 \cdot RG}{Z2TH + Z0TH + RF + 3RG} \qquad IF0 := -IF1 \cdot \frac{Z2TH + \frac{RF}{2}}{Z2TH + Z0TH + RF + 3RG}$$

$$IR1 := IF1 \cdot \frac{ZS21 + ZL21}{ZS11 + ZL11 + ZS21 + ZL21} + IL$$

$$IR2 := IF2 \cdot \frac{ZS22 + ZL22}{ZS12 + ZL12 + ZS22 + ZL22}$$

$$IR0 := IF0 \cdot \frac{ZS20 + ZL20}{ZS10 + ZL10 + ZS20 + ZL20}$$

$VR1 := VS1 - IR1 \cdot ZS11$ $\quad VR2 := -IR2 \cdot ZS12$ $\quad VR0 := -IR0 \cdot ZS10$

Fault Current and Relay Quantities

$$\begin{pmatrix} IFa \\ IFb \\ IFc \end{pmatrix} := A \cdot \begin{pmatrix} IF0 \\ IF1 \\ IF2 \end{pmatrix} \qquad \begin{pmatrix} IRa \\ IRb \\ IRc \end{pmatrix} := A \cdot \begin{pmatrix} IR0 \\ IR1 \\ IR2 \end{pmatrix} \qquad \begin{pmatrix} VRa \\ VRb \\ VRc \end{pmatrix} := A \cdot \begin{pmatrix} VR0 \\ VR1 \\ VR2 \end{pmatrix}$$

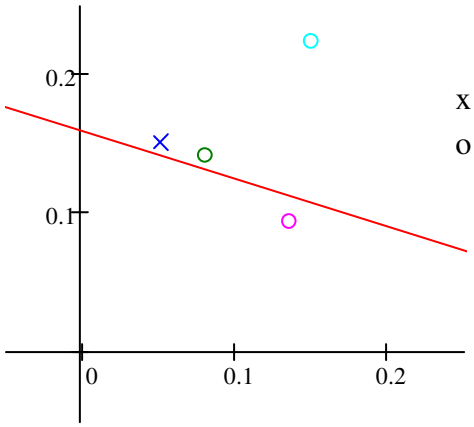
$\lvert IRa \rvert = 0.648$	$\arg(IRa) = -26.786deg$	$\lvert VRa \rvert = 0.842$	$\arg(VRa) = -19.17deg$
$\lvert IRb \rvert = 2.132$	$\arg(IRb) = 169.32deg$	$\lvert VRb \rvert = 0.436$	$\arg(VRb) = -170.364deg$
$\lvert IRc \rvert = 1.343$	$\arg(IRc) = 39.693deg$	$\lvert VRc \rvert = 0.476$	$\arg(VRc) = 120.966deg$

Apparent Impedance

$$Zbc := \frac{VRb - VRc}{IRb - IRc} \qquad Zb := \frac{VRb}{IRb + k0 \cdot IR0} \qquad Zc := \frac{VRc}{IRc + k0 \cdot IR0}$$

$|Zbc| = 0.163$ $|Zb| = 0.166$ $|Zc| = 0.27$

$\arg(Zbc) = 60.548\text{deg}$ $\arg(Zb) = 35.122\text{deg}$ $\arg(Zc) = 56.191\text{deg}$



x is the fault location
o are the apparent impedances

Operating signal

$Sopb := (IRb + k0 \cdot IR0) \cdot ZC - VRb$

$Sopc := (IRc + k0 \cdot IR0) \cdot ZC - VRc$

$Sopbc := (IRb - IRc) \cdot ZC - (VRb - VRc)$

Polarizing signal

$Spolb := (IRb + k0 \cdot IR0) \cdot ZC$

$Spolc := (IRc + k0 \cdot IR0) \cdot ZC$

$Spolbc := (IRb - IRc) \cdot ZC$

Angles of operating and polarizing signals

$\arg(Sopb) - \arg(Spolb) = 80.695\text{deg}$ B overreaches

$\arg(Sopc) - \arg(Spolc) = -211.906\text{deg}$ C does not operate

$\arg(Sopbc) - \arg(Spolbc) = 109.004\text{deg}$ BC does not operate

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