Line Distance Protection Overreaching: a tutorial on how phase selectors, directional elements, and intentional delays make distance relays more secure

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***Abstract*— line distance protection relays are intricate devices that are made up of several different functions. This team of functions works together to form a device that strikes a balance between security and dependability. There are several conditions that forced the evolution of the impedance relay from a basic comparator. Phase selectors, directional elements, and build-in delays are some of the elements that are commonly found in modern distance relays. This paper is a tutorial on the different elements that make up a modern line distance relay. A review of the principles of the Mho characteristic, including its respective comparator will be presented. A description and review of the principles related to phase selectors and directional elements will be presented. In addition, the fault conditions that could lead to a relay mal operation if either of these elements is not present will be analyzed.**

I. INTRODUCTION

Line protection is without a doubt one of the most complex application areas in power systems protective relaying. Some of the variables that make Line protection complex include:

- Source impedance
- Variable system configuration
- Line length
- Fault resistivity

When compared to other application domains in power system protective relaying, line protection challenges engineers in part due to the possible ranges and variability of the factors mentioned above. These factors will in turn affect the available fault current, phase voltage profile, symmetrical components voltage profile, and apparent impedance seen by the relay.

Source impedance is defined as the impedance that is "behind" the line that's being protected. Figure 1 illustrates this definition. Note that per Ohm's law, the fault current for a particular incident in its most basic definition is a function of the system voltage (V), source impedance (Z_{source}), line impedance (Z_{line}), and fault location (n).

$$I_f = \frac{V}{Z_{source} + n * Z_{line}}$$

Equation 1.

It is well known that other factors such as fault type (phase-phase, phase-ground, phase-phase-ground, three phase) and fault resistance will influence the magnitude of fault current. However, for any given fault type, location, or fault resistance; the magnitude of fault current will be defined by the source impedance. It is important to also understand that small source impedance represents a stiff source (high fault currents), whereas a high source impedance represents a weak source (low fault currents). Source impedance is defined by the amount of generation connected and system configuration. The configuration of the system plays a role because the source impedance will be smaller if more lines and or transformers are in service. Note that the reactance of these elements will in turn add in parallel, thus reducing the resultant source impedance in the circuit. Intuitively it can be understood that more fault current will be available if more contributing sources are connected to the system. Also, fault currents will be larger if the impedance between those sources and the fault is smaller (based on system configuration). The availability of fault current affects the sensitivity of the protection relay since its fault detection or pickup level is typically set above the maximum load current that the line may experience.

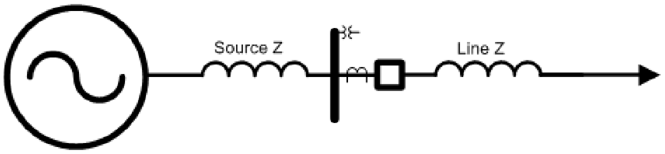

Fig 1. Source and Line Impedance

Another quantity that the source impedance affects is the voltage at the location of the relay. Equation 2 defines this point. It can be seen that the voltage drop across the source impedance will be defined by the fault current and the value of the source impedance. For a given current magnitude, a bigger source impedance will yield a bigger voltage drop whereas a smaller source impedance will yield a smaller voltage drop. Figures 2, 3, and 4 illustrate this relationship.

$$V_{relay} = V_{source} - \left(\frac{V_{source}}{Z_{source}+n*Z_{line}}\right) * Z_{source}$$

Equation 2. Positive sequence voltage at the relay

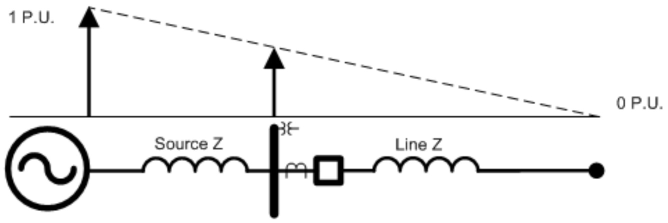

Fig 2. Voltage profile from source to fault location

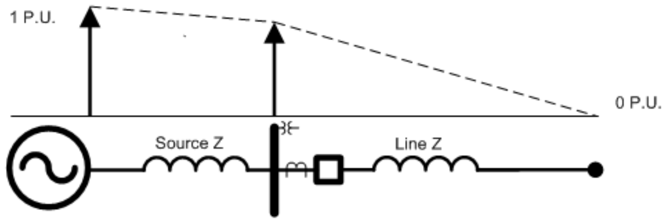

Fig 3. Voltage profile for a small source impedance

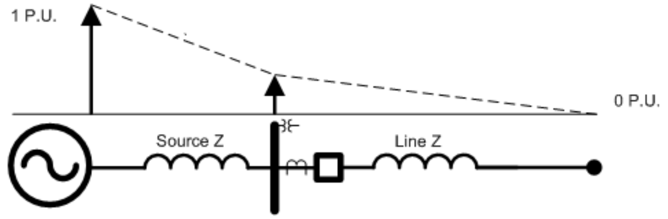

Fig 4. Voltage profile for a large source impedance

Note that Figure 3 displays a larger voltage magnitude at the location of the relay compared to Figure 4. The above mentioned relationship is true for positive sequence voltage. Note that the voltage profile of negative and zero sequence voltages is different. Since the zero and negative sequence voltages at the source are zero, the formulas for those voltages at the relay are as follows:

$$V2_{relay} = 0 - \left(I2_f\right) * Z2_{source}$$

Equation 3. Negative sequence voltage at the relay

$$V0_{relay} = 0 - \left(I0_f\right) * Z0_{source}$$

Equation 4. Zero sequence voltage at the relay

Equations 3 and 4 display a relationship where the larger the source impedance, the larger the zero and negative sequence voltages will be. This relationship is very important to consider since the magnitude of voltage will affect the torque and thus the speed of operation of the distance element as explained later in this paper. Also, there are certain phase selection methods that are dependent on the magnitude of the sequence component voltages. Those methods will too be affected by the value of source impedance since the aforementioned voltages will vary accordingly. The discussion above regarding source impedance will be central to this paper due to the impact that this factor has in the available fault currents and relay voltages.

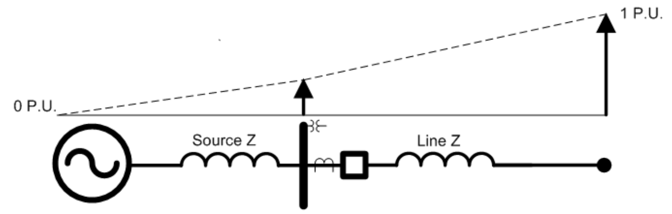

Fig 5. Zero and Negative sequence voltage profile for a small source impedance

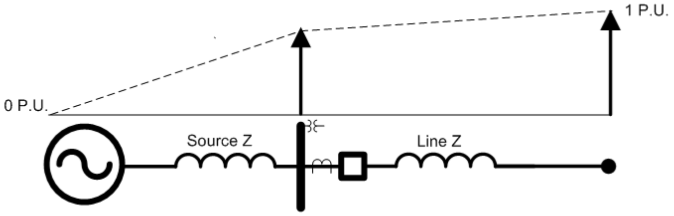

Fig 6. Zero and Negative sequence voltage profile for a large source impedance

As previously described, the configuration of the system will definitely affect the conditions that need to be considered to protect a line. From a source impedance perspective, having more lines and transformers in service will reduce it thus making the available fault current larger. Another aspect of system configuration that makes an impact is the availability of grounding sources. Based on system configuration, the availability of ground currents may vary. One way the configuration of the power system affects the protection of lines is illustrate in Figure 7. Note that in the configuration shown on the left of the figure there are 2 lines in service that provide power to the load. The figure on the right displays a single line. Equation 5 demonstrates why the configuration on the left represents a lower source impedance assuming the impedance on Line A and Line B is the same.

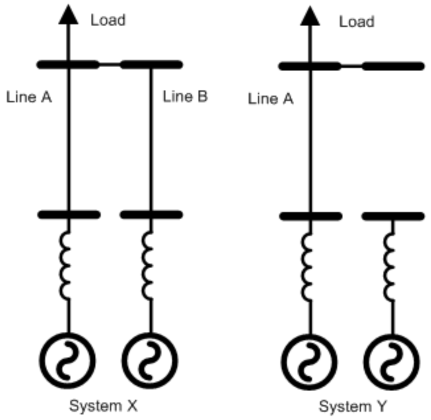

Fig 7. Voltage profile for a large source impedance

$$I_{f\ at\ loadX} = \left(\frac{V_{source}}{(ZlineA^{-1} + ZlineB^{-1})^{-1}}\right)$$

Equation 5. fault current at load for System X

$$I_{f\ at\ loadX} = \left(\frac{V_{source}}{ZlineA}\right)$$

Equation 6. fault current at load for System y

Intuitively, fault location impacts the fault current since the impedance that limits the fault current is depended on fault location per Equation 1. A fault closer to the start of the line will have higher magnitudes of current than a fault further down the line. Likewise, fault resistance will decrease the fault current since it further limits the flow of current per Ohm's law.

Protection of lines and feeders at lower voltage levels is typically accomplished by using overcurrent relays. In the case of higher voltages however, the available fault current is typically very high, thus high speed operation is often required. It is due to this reason that distance relays are typically employed to protect lines in high voltage networks. A distance relay is a device that measures the ratio of voltage and current (i.e. impedance). This impedance will be representative of the impedance in front of the relay. If a fault occurs inside the protected line, the distance relay will measure impedance smaller than the impedance of the line and it will trip. This action is accomplished by comparing the measured impedance with the set impedance threshold often referred to as the reach.

$$Z_{measured} = \left(\frac{V_{relay}}{I_{relay}}\right) = \frac{I_{relay} * Z_{line} * n}{I_{relay}} = Z_{line} * n$$

Equation 6. Impedance at the relay

Distance relays do not exactly measure impedance and compare it to a set value for their operation. They rather compare 2 quantities that are representative of the impedance that the relay could measure per Equation 6. In the case of the Mho element, two quantities known as the "operating" and the "polarizing" quantity are compared. These quantities are vectors as displayed in Figure 8. Whenever the angle between these 2 vectors (angle "D") is more than 90 degrees, the comparator will operate triggering the operation of the distance relay. Equation 7 documents this relationship.

$$90° \le \frac{If * Zreach - Vrelay}{Vpol} \le -90°$$

$If = Measured\ fault\ current$
$Zreach = Relay\ reach\ setting$
$Vrelay = Measured\ voltage\ at\ the\ relay$
$Vpol = Polarizing\ voltage$

Equation 7. Mho operates the above condition is met

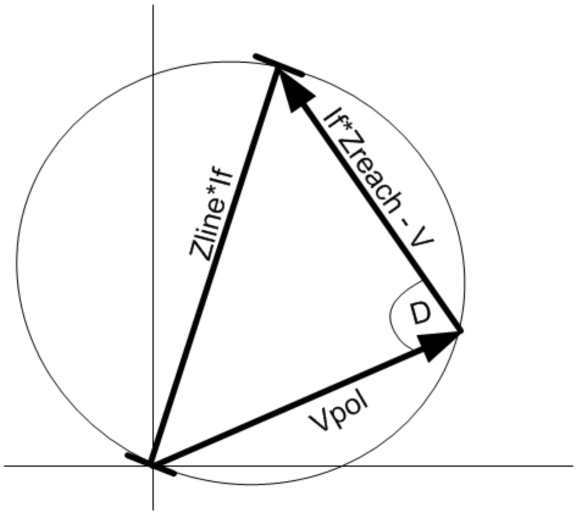

Fig 6. Basic Mho characteristic

The comparator in the Mho elements will provide fast operation for faults that result in the condition outlined in Equation 7. Note however, that there are certain conditions as outlined later in this paper that may cause this comparator to operate for faults beyond the reach it is supposed to cover.

The comparator presented in Equation 7 outlines the general concept of a Mho characteristic. There are typically 6 measuring loops in a distance relay to provide proper and accurate protection for all fault types. Table 1 displays the comparator equations for each of these loops. Note that there are variations on this from manufacturer to manufacturer, especially in the polarizing quantity where multiple options exist, some of which include:

Self-polarized: the operating and polarizing quantities are derived from the same phases corresponding to the loop, e.g. I_a and V_a for the AG loop.

Cross-polarized: the operating quantity is derived from the phase corresponding to the loop, the polarizing quantity is obtained by using the quadrature voltage to the loop, e.g. I_a and V_{bc} for the AG loop.

Positive sequence-polarized: the operating quantity is derived from the phase corresponding to the loop, the polarizing quantity is obtained by using the positive sequence voltage corresponding to the loop, e.g. I_a and $V1_a$ for the AG loop.

Table 1 displays a summary of the necessary operating and polarizing quantities for each loop of a positive sequence polarized Mho characteristic. This is very important to take into consideration since when a fault occurs one, or multiple loops may operate. The operation of multiple loops is not a desirable condition for the most part since the accuracy of the measurement is better on certain loops based on the fault type. It is desired that only the lop that corresponds to the faults operates, e.g. loop AG for a phase-ground fault between phase A and ground. Certain fault types result in the pickup of multiple loops such as the case of phase-phase-ground faults. For this cases, the operation of the phase-phase loop will result in a more accurate operation as it will be outlined later on this paper.

Loop	**Operating**	**Polarizing**
AB	$I_{ab} * Zreach - V_{ab}$	$V1_{ab}$
BC	$I_{bc} * Zreach - V_{bc}$	$V1_{bc}$
CA	$I_{ca} * Zreach - V_{ca}$	$V1_{ca}$
AG	$(I_a + k_n * I_0)Zreach - V_a$	$V1_a$
BG	$(I_b + k_n * I_0)Zreach - V_b$	$V1_b$
CG	$(I_c + k_n * I_0)Zreach - V_c$	$V1_c$

Table 1. Summary of loops, operating, and polarizing quantities for a positive sequence polarized Mho characteristic

II. LINE DISTANCE OVERREACHING

The fundamental setting of a distance relay is the reach. This parameter represents the impedance threshold that the relay is supposed to use. If the impedance seen by the relay is less than this value the condition outlined in Equation 7 will be met and the relay will operate. In the application of distance/impedance relays the term overreaching refers to a relay operation that occurred for a fault that was beyond the set reach of the relay. Since the fault was beyond the set reach of the relay and it operated, the condition is referred to as an “overreach”. Figure 9 illustrates this point where a relay with a reach setting of 80% of the line impedance operates for a fault beyond the line it is protecting. Another condition that is considered as overreaching occurs when the distance relay operates for a fault behind it. Both of these operations will in turn be considered mal operations since the relay did not perform as expected.

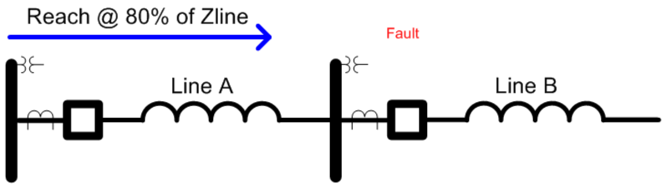

Fig 9. Distance relay overreaching for a fault beyond its set reach

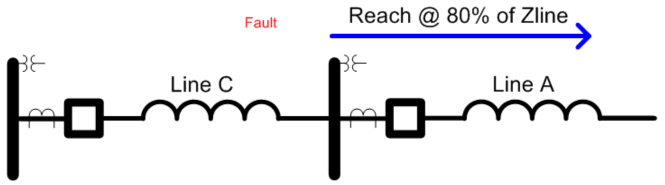

Fig 10. Distance relay overreaching for a fault behind it

Now that overreaching is defined a discussion regarding the conditions that cause it can be started. Some of the conditions that could potentially cause overreaching include:

- Mho dynamic expansion
- Fault resistance

The Mho characteristic is not fixed since its polarizing voltage is equipped with a memory action. This means that the voltage used to evaluate the condition outlined in Equation 7 is not exactly the same voltage that the relay is measuring post fault inception but rather a voltage that is saved in memory for a few milliseconds. This in turn results in the characteristic displayed in Figure 11 where despite the fact that the Mho characteristic is considered as an inherently directional characteristic (it only operates in the forward direction if set that way) it could potentially operate for a reverse fault. This in fact is the case since a fault behind the origin of the X-R plane shown in Figure 11 could still satisfy the condition provided in Equation 7. Note that this dynamic expansion is dependent on the source impedance. The larger the source impedance, the larger the expansion of the Mho circle and vice versa. The reason for this phenomenon is that the expansion of the Mho characteristic is proportional to the source impedance times the fault current.

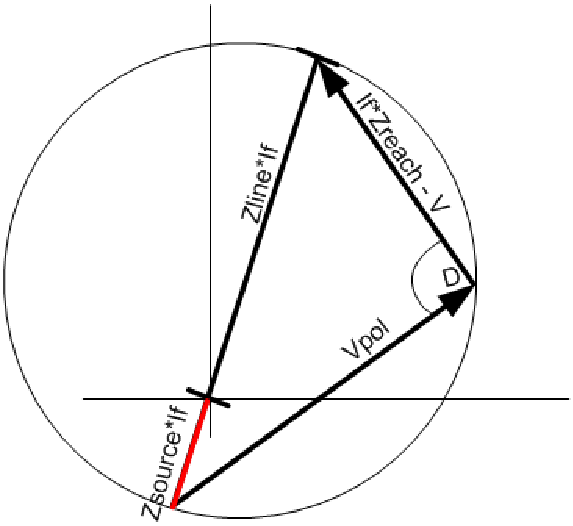

Fig 11. Mho characteristic expansion due to memory polarizing voltage

The other condition that was mentioned was fault resistance. Note that fault resistance on certain types of faults could shift the apparent impedance and make the distance relay trip. Figure 12 illustrates this point where the BG loop overreaches for a phase-phase-ground fault (BCG). In this particular case, the Z1 reach is set at 80 % of the line impedance. The fault occurred at 90% of the line. The graph shows how the apparent impedance varies based on different values of fault resistance. Note how the apparent impedance measured in the BG loop varies from 90% (the correct value at 0 fault resistance) to a value that encroached on the reach of Z1.

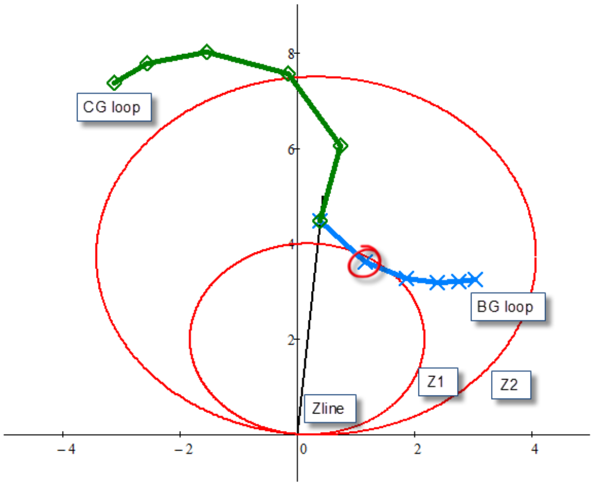

Fig 12. Overreaching due to fault resistance

III. MITIGATING THE RISK OF OVERREACHING

Two distinct conditions that cause overreaching were described in the section above. This section will describe elements that have been successfully applied to minimize the risk of overreaching for the above mentioned conditions.

A. Directional Element

As previously discussed; Mho characteristics use a memory feature in their polarizing quantity to ensure that sufficient voltage is available during close in faults. As such, an expansion of the circle will occur. This expansion will in turn enable the operation of the comparator for close in reverse faults. To combat this issue, a directional element can be used to supervise the operation of the impedance element. Figure 13 illustrates this point where the red line effectively “cuts” the Mho characteristic to only enable its operation for forward fault. From a design perspective the logic is illustrated in Figure 14. The addition of a supervisory directional element results in a more secure distance element. It also results in additional settings and considerations for the end user. The settings typically include a maximum torque angle, width of the sector, and a type. Table 2 summarizes a list of the directional elements that are commonly applied for both phase-phase and phase-ground loops.

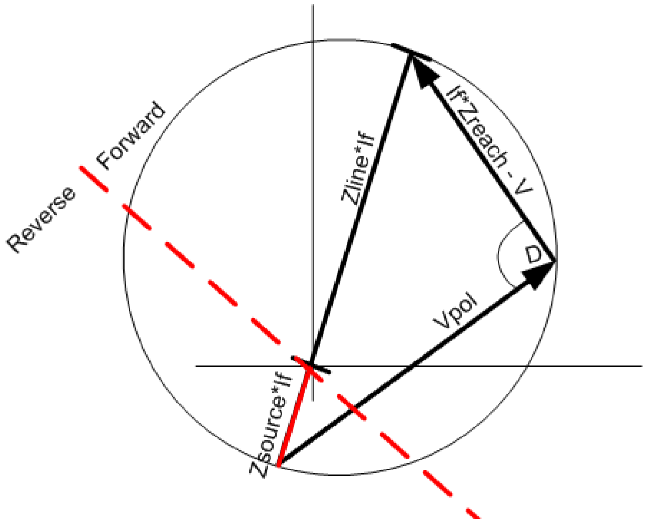

Fig 13. Directional element in Mho characteristic

Fig 14. Supervision of distance element

Application	**Description**	**Quantities**	**Maximum Torque angle (inductive load)**
Phase loops	Quadrature	I_a vs. V_{bc}	I_a in phase with V_{bc}
Phase loops	Positive sequence	I_1 vs. V_1	I_1 lags V_1 by 90 degrees
Ground loops	Negative sequence	I_2 vs. V_2	I_2 lags $-V_2$ by 90 degrees
Ground loops	Zero sequence voltage	I_0 vs. V_0	I_0 lags $-V_0$ by 90 degrees

Table 2. Summary of some commonly used directional elements and their application

B. Phase Selector

The selection of the correct impedance loop for a fault is critical for the correct operation of the impedance element. Figure 12 displayed the changes in the apparent impedance sensed by the BG and CG loops for a BCG fault. Figure 15 displays a contrast, where now the BC loop measured apparent impedance is more accurate for the same conditions (fault at 90% of the line). Note how the trajectory of the apparent impedance is parallel to the X axis as the fault resistance is increased (as it is expected since only resistance is being added). In the event of this fault, the BG loop would have overreached, however, the BC loop measured the correct apparent impedance. Based on this analysis the selection of the phase-phase loop for a phase-phase-ground fault is desirable.

A Phase selector is a function that accurately defines the fault type and only enables the operation of the preferred loop. There are several methods that manufacturers have employed in the pass to select right the faulted phases. Some of them are explained herein. Note that in addition to serving as a mitigating mechanism for overreaching, the information from the phase selector is used to open the proper pole in single pole tripping applications thus its accuracy is very important.

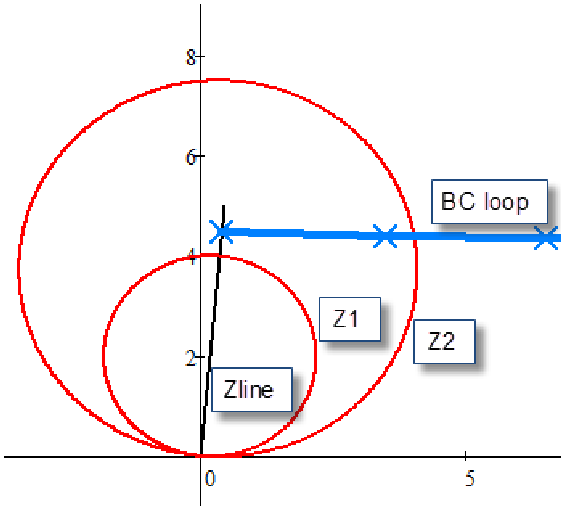

Fig 15. BC loop for a BCG fault with varying fault resistance

1) Torque base phase selection

This method utilizes the torque calculation of all loops. Note that the polarizing quantity for all 6 loops is positive sequence voltage. Having the same polarizing quantity for all loops is very important since in this way a comparison between the different torques is possible. The loop that yields the most torque is in turn selected and allowed to operate.

2) Delta based phase selection

This method measures the change in the phase voltages and currents. It then performs a comparison to determine which were the phase voltages and currents that changed the most. The faulted loop is determined based on this comparison.

3) Impedance based phase selection

This method relies on the operation of a self-polarized impedance element. If more than one loop operates the fault is deemed as a phase-phase-ground fault and only the phase-phase loops are allowed to operate. In this method, all loops in the impedance element are free to operate. It is only upon the identification of a phase-phase-ground fault that the phase selector proceeds to block the phase-ground loops. This philosophy results in a more dependable element. Note that the impedance element used for phase selection must be set with a reach sufficiently longer to ensure proper operation, otherwise phase selection will fail.

4) Symmetrical component based phase selection

This method utilizes symmetrical component quantities to determine the faulted phases. There are a few variations on this method; however, all of them rely on the angle measurement between the zero sequence, negative sequence, and positive sequence quantities. One example is a phase selector that selects the right phase-phase loop by measuring the angle between the positive and negative sequence voltage. Another example is a phase-ground phase selector that uses the measured angle between the negative sequence voltage and the zero sequence current to determine the right faulted loop. On both of these examples the loop is selected based on the sector in which the sequence quantities fall as displayed in Figure 14.

C.Coordination between above mentioned elements and the operation of the impedance element

Both phase selectors and directional elements must operate before the Mho characteristic comparator for them to serve their purpose as expected. There is a risk of overreaching if the output of the Mho comparator outpaces either of these elements. This potential problem is tackled in several ways.

1)Delay the operation of the impedance element
This technique involves adding a small time delay to the operation of the impedance element to ensure the directional element and phase selector has reached their decisions. This way, secure operation of the impedance element is ensured, however it adds a delay to the operation of the impedance element which may not be desirable.

2)Block the operation of the impedance element
In this case the operation of the impedance element is supervised by the phase selector and directional element. Operation of the impedance element is always enabled; however, if the directional element detects the fault to be reverse it will block its operation. Similarly, the phase selector will block the operation of the unwanted loops. This technique is biased towards dependability since correct operation is depended on the coordination between the impedance unit, phase selector, and directional element.

3)Enabling the operation of the impedance element
In this case, the operation of the impedance element is only enabled if the phase selector and the directional element operate. There is no coordination needed with this method, however, if no phase selection is reached for example, the impedance element won’t operate despite the fact that the comparator may have asserted.

IV. CONCLUSIONS

Without a doubt impedance relays are one of the most popular alternatives to provide protection to lines. The operation of these devices is complex and intricate, and as discussed, there are several conditions for which their performance may be affected. Overreaching is a considerable problem as unjustified outages create inefficiency, unplanned costs, and threaten the stability of the power system. This paper presented several conditions that cause overreaching and how phase selectors and directional elements work together with the distance element to ensure correct and secure operation. It is important for end users to understand that an impedance relay includes a phase selector and a directional element, this way proper settings based on the application can be furnished. A comprehensive understanding of the behavior of these functions is needed when analysis faults since the operation of the distance relay may have been influenced by either of these elements.

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2) *“A Brief Overview of Polarized Mho Characteristic in Steady-State“*, Luis G. Perez

V. BIOGRAPHY

Alejandro Schnakofsky graduated from Florida International University in Miami, FL with a BS in Electrical Engineering. During his studies he conducted research in the field of digital relays and the concept of multi object protection systems. In 2002 Alejandro joined Bussiere Communications were he engineered, deployed and tested Ethernet networks. In 2005 he joined ABB Inc. where he has contributed in a variety of roles from Application Engineering to Management in the Distribution Automation and Substation Automation Products groups. In his current role as Application and Support Manager for North America Alejandro is in charge of the portfolio of products and application support services offered in the region. He is a member of IEEE and has authored several technical papers regarding protection, automation, and control in electrical substations.