Directionality Concepts for Overcurrent Relay Applications

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Abstract: Directional overcurrent protection IEEE device (67) refers to protection functions that utilize some angular relationship component of current or current and voltage to determine relay directionality. Electromechanical relays (EM) sense of directionality is accomplished by voltage polarizing, current polarizing, or both. Today, with microprocessor relays, there are several unique ways in which manufacturers have combined these phase relationships to provide the most secure and reliable operation for direction overcurrent elements. This paper will provide a brief discussion on past polarization methods on EM relays but will highlight newer, more reliable, directional functionality available in microprocessor relays. These methods include comparing sequence components (V_0 vs. I_0), (V_1 vs. I_1), (V_2 vs. I_2), and cross polarization methods utilizing V_{BC} for I_{AG} and I_{AB} faults as well as traveling wave relationships. Examples will be presented showing polarization methods for different system configurations.

Index Terms—Protective Relaying, sequence components, directional overcurrent relaying

I. INTRODUCTION

In most sub-transmission, and virtually all high voltage or higher networks, source current is supplied from more than one of the line terminals. This is why without directional supervision, non-directional relays are unable to distinguish if a fault is present in the forward or reverse looking direction. In these networked systems it is imperative, for coordination purposes that the relay responds differently depending on the physical location of the faulted equipment. Directional overcurrent relays depend on a concept called polarization, which is a term used in relaying to choose some reference phasor with which other phasors can be compared to in order to distinguish forward or reverse faults. This paper will draw on polarization methods used in EM, static, and microprocessor relays and draw conclusions on the benefits of each method in different system configurations and scenarios.

II. DIRECTIONAL RELAY OPERATING CONCEPTS

In order for directional relays to determine fault location they are designed to have their maximum sensitivity during fault conditions. It is well documented that during fault situations the current can significantly lag its typical operational unity power factor position by up to 90°. One way to compensate for this current shift and yet maintain the maximum torque angle (MTA) is to introduce a phase shift in the polarization quantity. MTA is a term that was prevalent in EM relays and still resides today but has slowly been outpaced with the term relay characteristic angle (RCA). An example of this is seen in Figure 1.

Directional relay connections are commonly identified in terms of the angular difference between the current flowing under normal balanced unity power factor flowing in the tripping direction and the polarizing or reference quantity in which is applied to the directional relay. The two categories of faults that need to be considered when implementing directionality are ground faults and phase faults. Within these two categories there are several different connection types. This paper will focus on the options available to both of these categories.

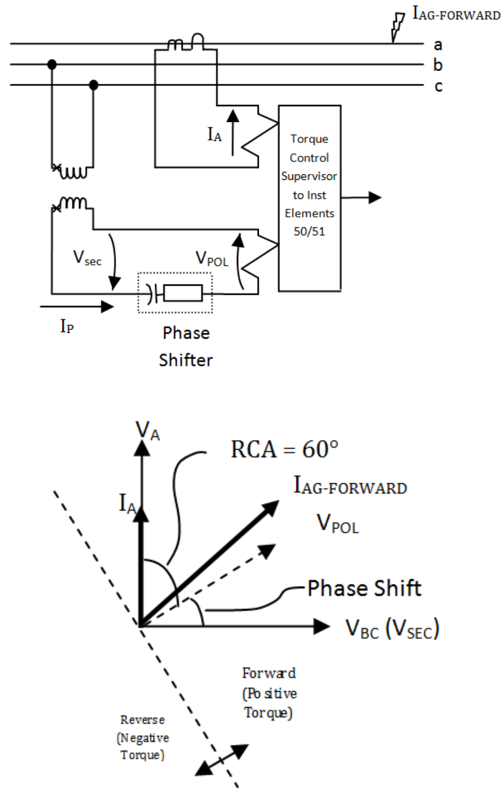


Figure 1: 90° Phase Quadrature I_A -V_{BC}

III. Polarization for Ground Relays

There have been many papers written on the subject of ground polarization sources and the advantages and disadvantages of the available options. This paper will simply highlight the three most commonly used sources of ground polarization. These would include zero-sequence current, zero sequence voltage, and negative sequence voltage. Each is used because of its reliability in correctly predicting the direction for a ground fault irrespective of the fault location. A quick overview of the operating principles as well as the potential issues that they inherently have during certain system configurations will be addressed. It should be recognized that the three methods mentioned above are not the only ways to polarize for ground relays. In fact some manufacturers will use different combinations of the above listed methods. Each manufacturer should be consulted for the specific way in which they use system impedances and measured current and/or voltage to determine directionality.

Self Polarization

Traditionally the directional element in EM relays was essentially a contact making wattmeter that held open the contact by a spring when in the de-energized state. This directional element supervised the tripping in the overcurrent relay. It is quite apparent that if directional relays were to only employ the wattmeter concept, angular differences between phase current and phase voltage of +90° through -90° would be considered a forward event, and everything else would be considered a reverse event. The problem with this concept is that it directly compares faulted phase currents and voltages more commonly called a directional power relay (32). If the fault were to be a close in fault the voltages may collapse to near zero. In order to resolve this issue, quadrature voltages were used as is observed in Figure 1. To this day there are still a number of relays that provide as an option this type of directional control in addition to variations of it.

Another way to overcome the low voltage polarizing magnitudes when using self polarization for close in ground faults is to have the relays implement a memory circuit for the voltage profile. This memory circuit method has been used successfully in electromechanical through microprocessor relays. EM relays use parallel LC circuitry that is designed to resonate at the 60Hz system frequency. Conversely, microprocessor relays implement digital filtering through an algorithm similar to (1). It should be noted that this is simply a generic equation to illustrate the premise of memory voltages and is not necessarily a method used by any one manufacturer. Memory filters, such as these are able to track the phasor changes of the system voltage and supply sufficient signal for sufficient time for the relay to make a directional decision once the fault ensues.

$$V_{MEM} = V_{IN} - a_1 V_{MEM} z^{-\alpha} \qquad (1)$$

Where:

α = Design constant

z = the unit delay operator

$0 < a_1 < 1$

In equation (1) above, it is observed that as the value of a_1 decreases the voltage mimics the characteristics of the system voltage. Conversely, as a_1 increases to a value unity, V_{MEM} decays at the rate of $N/2$. One also needs to consider that there is a transient response once the system voltage is reestablished. Many manufacturers compensate for this by setting the value of a_1 to a value very near zero when a line is being energized (i.e. when system voltage is at 0 and rising) and a value near unity once the line energization, transient dies out. The time required for this to take place is usually less than five cycles. An example of this is shown in Figure 2a and 2b below.

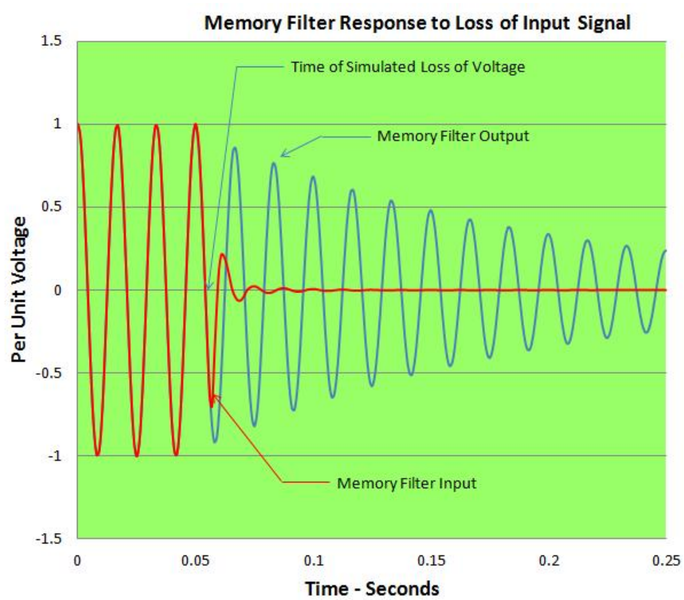


Figure 2a: Filter Response to Complete Loss of Signal

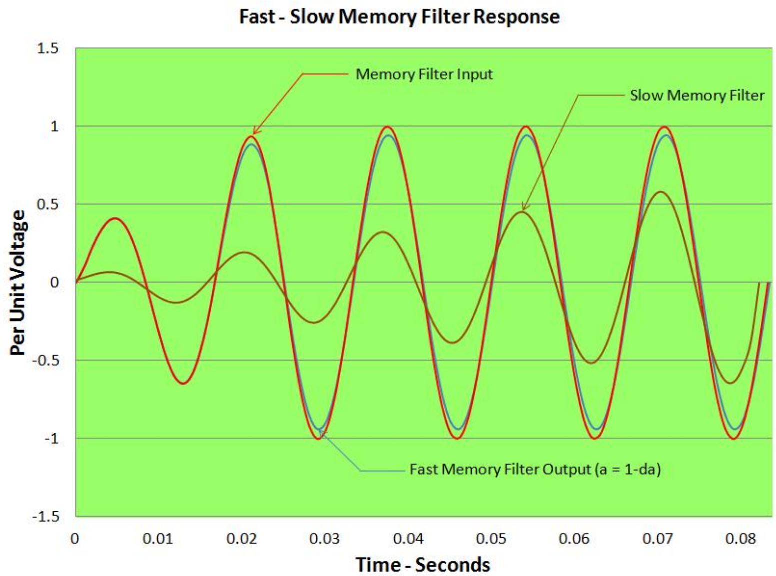


Figure 2b: Comparison of Fast & Slow Filter Response

Manufacturers utilize and formulate memory voltages many different ways. The principle is that on a sudden loss of the polarization voltage the angular difference is calculated based off of the memory voltage. The memory voltage is calculated using the positive phase voltage measured before the fault initiated, assuming that it was not affected by the fault.

Today, newer microprocessor relays typically provide an option for the end user to set the time in which this memory voltage can be used. If the polarization quantity increases to a sufficient level for discriminating the fault direction, the measured voltage is applied in lieu of the memory quantity. It is also discarded if it is below the required voltage threshold for longer than the user settable memory time or if the fault current disappears while it is in use. It should also be realized that memory voltage is not present when reenergizing a line into a fault. To protect for this type of scenario close into fault logic is used where the relay will monitor the breaker close and initiate a high set non-directional element for a specific period of time.

$3I_0 – 3I_0$

Current polarization can be used at power transformer locations where reliable sources of zero sequence current can be obtained. Reliable in this sense means locations where direction of the polarizing quantity does not change direction based on the location of the faulted equipment. One such example is shown in Figure 3 below. This example clearly demonstrates the principles of the zero sequence polarization relay with the neutral of the transformer serving as a source of $3I_0$ polarizing quantity.

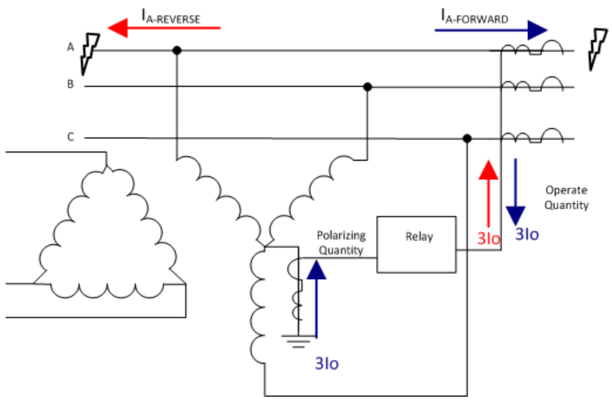


Figure 3: $3I_0$ Directional Relays Tapped Transformer

It is readily seen that a fault in the forward and reverse directions could produce similar magnitude faults; however, the angular difference between the polarizing and operating quantities will be 0° for $I_{A\text{-}FORWARD}$ and 180° for $I_{A\text{-}REVERSE}$. In either case, the $3I_0$ flows up the neutral of the wye connection. If a fault were to take place on the high side of the delta winding, no zero sequence current would flow up the neutral of the wye winding since it would be trapped in the delta. In this situation the polarizing current would be below the threshold value and the operate current would be flowing in the reverse direction, from that of a forward fault, resulting in no operation. A vector diagram of the operating characteristics for this relay is shown in Figure 4.

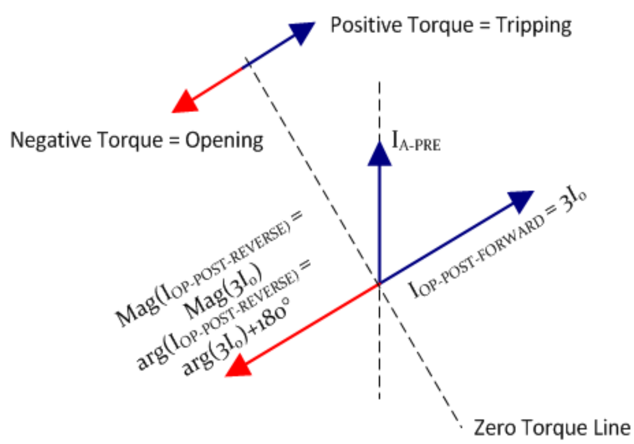


Figure 4: Current Directional Ground Relays

Figure 4 demonstrates that the operating current will shift during the fault by the angle of the line reactance. This allows for the opportunity for highly resistive reverse faults to lie within the directional characteristic of the relay. Manufactures deal with this scenario in different ways. One option that was available for EM relays was to use a voltage restraint element so that it would only allow the relay to pickup if the low voltage threshold was met. Newer microprocessor relays are able to set up maximum and minimum operating angles as well as initiating blocking of the directional element if the polarizing quantity is below the set threshold. This method has the benefit of increasing the directional security utilizing individual utility practices.

Acceptable Polarization Sources for $3I_0$

It is known that certain polarization sources and CT configurations give the appearance of providing dependable directional supervision during fault situations but there may be many reasons why they prove to be unusable. Table 1 illustrates transformer connections that do not reliably source polarizing current for ground faults. While only one three winding connection below is called out as being a poor source for polarization; great care must be taken when using any three winding wye-delta-wye or autotransformer connection with a delta tertiary. These transformer connections may have the appearance of having negative impedance in their equivalent circuit. The impedance of the transformer obviously is not truly negative; however, the values that are calculated in equations 2-4 below do accurately predict performance of the transformer and thus are used in modeling their winding impedances.

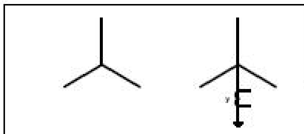
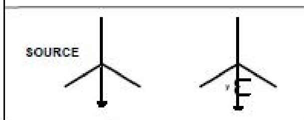
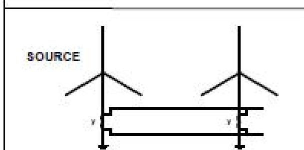
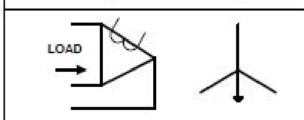
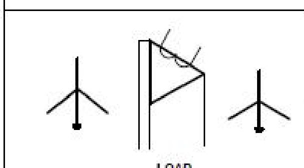
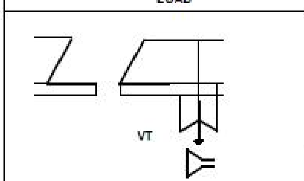
	NO Io PATH FOR COMPENSATING CURRENT
	SOURCE MAY BE OPEN
	SOURCE MAY BE OPEN
	MASKED BY LOAD
	MASKED BY LOAD (3 CT'S REQUIRED)
	NO ZERO-SEQUENCE VOLTAGE IN LINE-LINE QUANTITIES

Table 1: Current Directional Relays Tapped Transformer

$$Z_H = \tfrac{1}{2}(Z_{HT} + Z_{HL} - Z_{LT}) \quad (2)$$

$$Z_L = \tfrac{1}{2}(Z_{LT} + Z_{HL} - Z_{HT}) \quad (3)$$

$$Z_T = \tfrac{1}{2}(Z_{HT} + Z_{LT} - Z_{HL}) \quad (4)$$

Where:

$Z_{HT} = Z_H + Z_T$; $Z_{LT} = Z_L + Z_T$; $Z_{HL} = Z_H + Z_L$

Since usually the physical windings of a transformer are wound with low voltage, medium voltage, and high voltage starting at the core and working their way out it stands to reason that the low voltage through the high voltage windings impedance increases in a similar order. If we substitute the impedances for Z_H, Z_L, and Z_T, in equations 2, 3, and 4 above it is observed that Z_{HT} will be the largest and Z_L has the highest likelihood of becoming negative.

If we were to analyze the three winding or autotransformers a bit more it is possible to determine the requirements needed to determine their suitability for being used for polarization. In Figure 5 below, the per unit fault current being supplied through the high voltage side of the transformer is 1.0. It is the summation of the current that can flow within the tertiary ($1-K_0$) plus the current that flows from the low voltage winding K_0. For a single line to ground fault on the high voltage side K_0 per unit will flow in the low voltage side and $1-K_0$ within the tertiary. Converting these per unit values to amperes there will be $K_0(V_H/V_L)$ amps in the low voltage system and $(1-K_0)(V_H/V_T)$ amps in the tertiary. In order for these three winding or autotransformers to be reliable sources, the current must not change direction (i.e. consistently flow up the transformer neutral) for faults on either the high or low voltage sides of the transformer. This can only happen only if $K_0(V_H/V_L)$ is a value less than 1. For a more in depth explanation of each connection, refer to Reference [1] and [2].

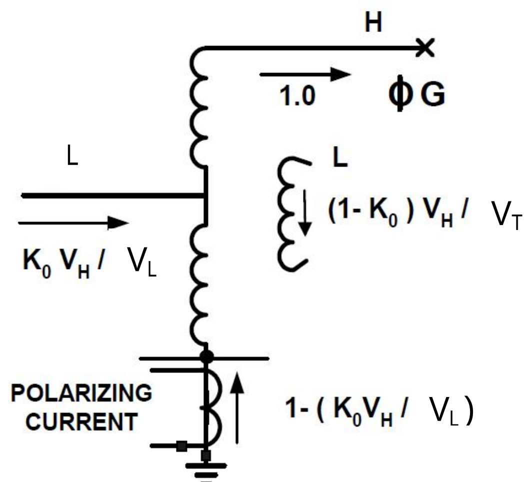


Figure 5: Requirements for Reliable Polarization in Three Winding Transformers

$3V_0 - 3I_0$

Zero Sequence voltage polarization ($3V_0$) is an alternative to the current polarization method described previously for directional ground relays; however, it mimics many of the characteristics previously shown in Figure 4. It has long been the method selection of choice for polarizing ground relays because the $3V_0$ voltage values were typically easily measurable from the broken delta PT connection from wye grounded – delta potential transformers and $3I_0$ from the residual CT connections which were already being brought into the relays. Figure 6a and 6b below show the typical system connections as well as the phasor diagrams respectively needed to provide directionality for zero sequence voltage polarization.

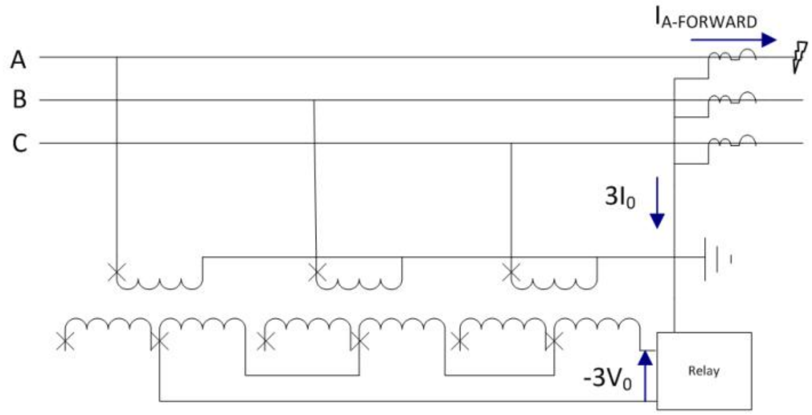


Figure 6a: $3V_0$ Directional Relays Connections

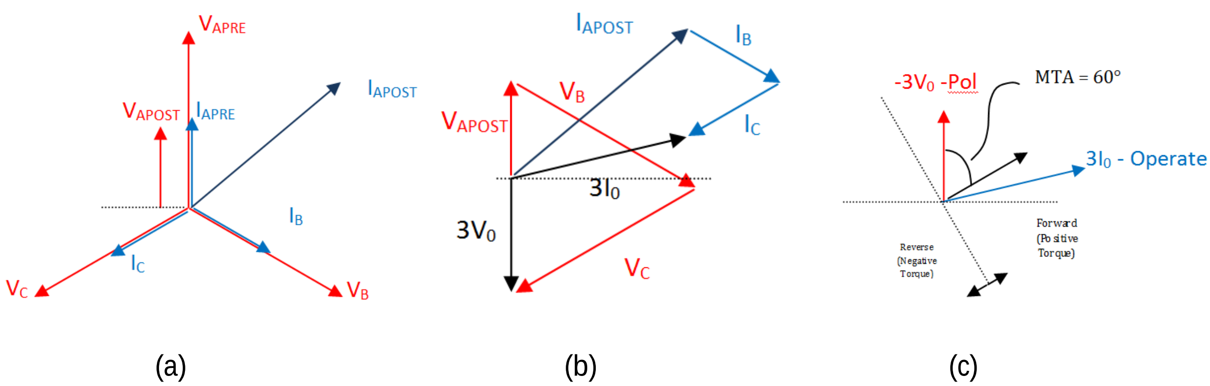


Figure 6b: $3V_0$ Phasor Diagram

$3I_0$ typically lags $3V_0$ anywhere from 30° - 88° so the RCA is set for 60°. This will be the point in which the relay will be the most definitive on a forward fault. This 60° value was something used within EM relays. This value of course is completely arbitrary now with microprocessor relays and can be adjusted to match system configurations and expected angular displacement during faulted situations.

Many of the characteristics of $3V_0$ polarizing are highlighted here.

1. $3V_0$ at the source is a function of system Z_0
2. Zero sequence voltage is maximum at relay location and minimum at fault –Illustrated in Figure 7.
3. $3V_0$ magnitude is a function of source impedance as well as distance to fault impedance
4. Need for voltage transformers connected in open delta arrangement
5. Can serve as polarizing source for delta-delta transformers.
6. Must add potential transformers to gain directionality if they don't already exist

It can be seen from below that the magnitude of $3V_0$ voltage at the relay location is a function of the zero sequence impedance of the line and it increases in value as the fault moves closer to the relay location. It can be deduced that using $3V_0$ for distant faults may not produce a large enough magnitude to determine the phase angle while faults closer to the relay location $3V_0$ would be an excellent choice in determining directionality for ground faults.

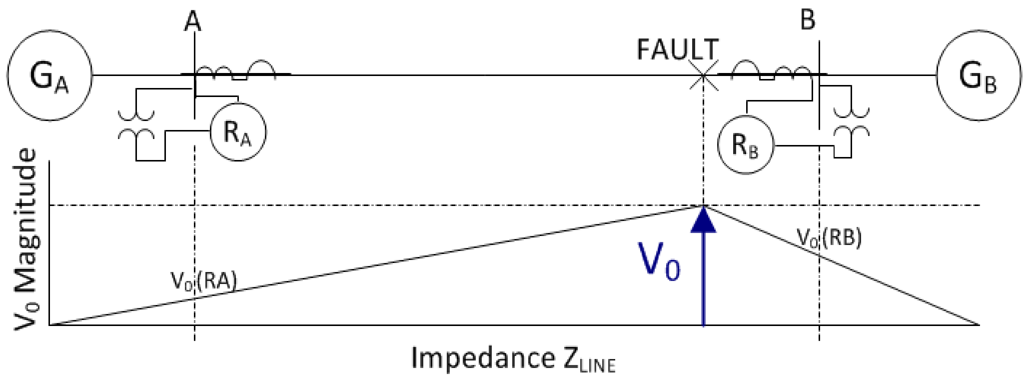


Figure 7: V_0 Profile for Single Line to Ground Fault

Dual Polarization

Many EM and virtually all microprocessor directional relays are designed so that either current only, voltage only, or the combination of both can be used to polarize the relay. This proves to be advantageous for several reasons. Firstly, the relay may still be able determine direction with either polarizing source disconnected. When EM relays had a larger market exposure the ability to use dual polarized relays required utilities to only stock and install one relay rather than creating an either, or, or both scenario. The largest benefit may be that maximum sensitivity can be observed. As shown previously, $3I_0$ polarizing quantities generally dominate for lines with larger zero sequence impedance (i.e. further away faults) and $3V_0$ will dominate when faults approach the relay location.

Negative Sequence Voltage Polarization

Negative sequence voltage polarizing methods have been around for many years and have a proven record of operating reliably if the system is capable of supplying sufficient negative sequence current during faults. This form of directional sensing was, and still is, available in EM relays but has found increased popularity in microprocessor relays because of their ease in breaking down phase quantities into their respective symmetrical components. It has increased in popularity for a number of reasons. These reasons include:

1. Immunity to single line to ground faults on mutually coupled lines
2. No additional added hardware cost in current microprocessor relays if already using zero sequence voltage
3. Ease of functional testing
4. Allows for system connections where zero sequence current is not always available
5. If the source behind the relay is strong; magnitude of available negative sequence voltage at the relay will be stronger than the zero sequence voltage

Much like the current and current-voltage polarization methods, negative sequence relays use angular relationships of the phase quantities provided to the relay. The amount of negative sequence that is normally present in a healthy networked system is very low, this allows for the threshold that is set in the relay to be quite sensitive. Because of this, the magnitude needed to operate for directionality simply needs to be large enough to determine the angular displacements to reliably make determinations. Figure 8 below shows the phasor diagrams needed to provide directionality for negative sequence voltage polarization for an I_{AG} fault. It should be apparent that the phasors shown look very similar to those seen from the zero sequence voltage polarization with the distinct advantages shown above.

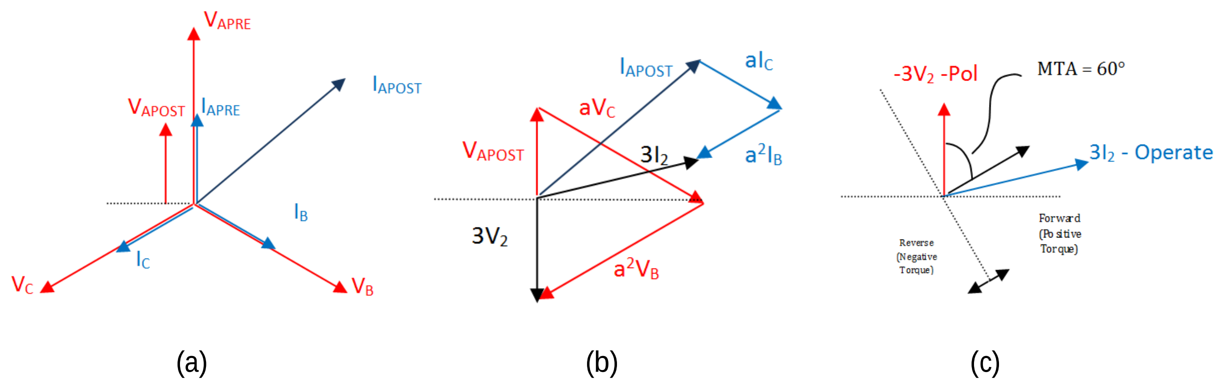


Figure 8: V_2 Phasors for Single Line to Ground Fault

Zero Sequence Components vs. Negative Sequence Components

In order to choose the most appropriate ground polarization method an analysis needs to be done on the system sequence components that are available to determine whether zero sequence or negative sequence voltage will be dominant at the relay. It was shown above that the largest zero and negative sequence voltages appear at the fault point because they are the source of these voltages. However, the voltages that must be evaluated are those at the relay location because this is where the directional determination takes place. Figure 9 shows the generic connection diagram for a single line to ground fault.

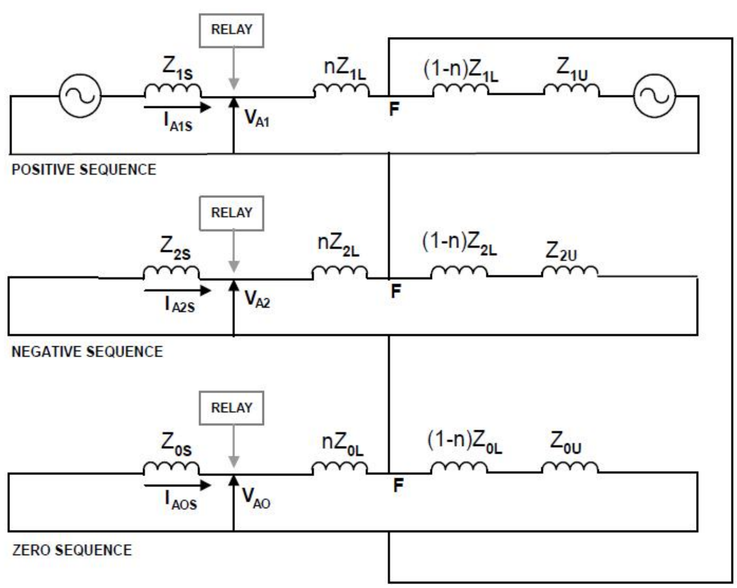


Figure 9: Generic System Impedance Connection Single Line to Ground Fault

From the diagram, we can gain a perspective of the zero sequence to negative sequence voltages present at the relay location for a generic system where the system and line zero and negative sequence impedances are not equal. The per unit voltages at the relay location can be found from equations 6 and 7. The zero sequence voltage at the relay location for an I_{AG} fault is found in equation 5 by using the voltage divider principle for the zero sequence voltage at the fault point.

$$\mathrm{V}_{a0r} = V_{a0f}\left(\frac{Z_{0S}}{Z_{0S} + nZ_{0L}}\right) \quad (5)$$

Simplifying:

$$\mathrm{V}_{a0r} = V_{a0f}\left(\frac{1}{1 + nZ_{0L} / Z_{0S}}\right) \quad (6)$$

A very similar thing can be done for the negative sequence resulting in the following:

$$\mathrm{V}_{a2r} = V_{a2f}\left(\frac{1}{1 + nZ_{2L} / Z_{2S}}\right) \quad (7)$$

Taking the ratio of equations 6 and 7 above, setting $Z_1 = Z_2$, and realizing that $V_{a0f}/V_{a2f} = Z_0/Z_2$ gives an completely generalized expression for the polarization voltage level in relation to the relay location anywhere on the line. For a single line to ground fault this expression produces equation 8. Because Z_{1L} is significantly lower than Z_{0L} and Z_{1S} is usually larger than Z_{0S}, equation 8 tends to be a value less than 1. This equates to the negative sequence voltage being a more dominant factor for long transmission lines.

$$\frac{\mathrm{V}_{a0r}}{V_{a2r}} = \frac{Z_0}{Z_1}\left(\frac{1 + nZ_{1L} / Z_{1S}}{1 + nZ_{0L} / Z_{0S}}\right) \quad (8)$$

IV. GROUND POLARIZATION PROBLEMS

As mentioned previously there is no one method that works for all ground fault situations and system configurations. One must always evaluate the specific system configuration on a case by case basis. Highlighted below are many of the common problems that have been experienced when using directional relays throughout the years. [2]

Mutual Coupling

Mutual coupling can occur for transmission lines on the same tower or within the same right of way. It is well known that the positive and negative sequence impedances of transmission lines are of equal magnitude. This results in very little mutual impedances for these quantities. Typically these values are less than 10% of the self impedances. However, the zero sequence mutual impedance can be as large as 50-70% of the self impedance of the line itself. This large mutual impedance could result in incorrect operation if care is not taken.

An example of mutual coupling using zero sequence polarization is shown in Figure 10 below. In this example a I_{AG} fault occurs on line CD very near breaker 3. It can be seen that the $3I_0$ current that flows from C to D imposes a zero sequence voltage on the parallel line AB causing the current to flow up the neutral of the transformer at A and down the neutral at B. The polarizing and operate quantities on line AB are aligned to operate on zero sequence directional ground relays at both A and B.

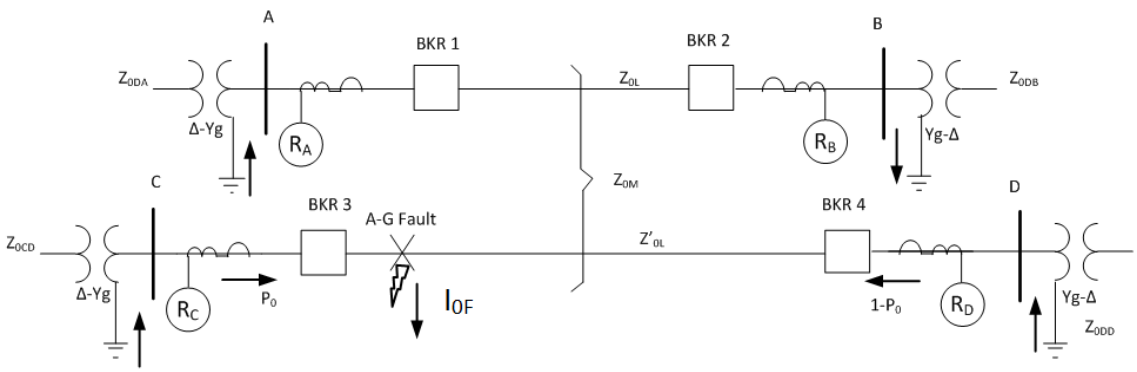


Figure 10: Zero Sequence Mutual Coupling

With P_0 being the per unit fault contribution from breaker C to the fault and n representing the percentage of line length from bus A to where the fault is taking place on the adjacent CD line. It can be seen from this diagram and is derived in [1] that the amount of mutual fault current produced for this line is as shown in equation 9. As the fault is applied along the line from breaker C to D, the mutual current that will be induced in line AB, will decrease as one approaches the fault from bus C because P_0 dominates in the above equation, become 0 right when $n+P_0=1$, then increase after this point. It should be noted that mutually coupled lines that terminate at both line terminals on the same bus are not prone to incorrect operation of the directional ground element that is zero sequence polarized.

$$I_{0M} = \frac{[(1-(n+P_0))]I_0 Z_{0M}}{Z_{0DC} + Z_{0L} + Z_{0DD}} \qquad (9)$$

Different Polarization Sources on Opposite Ends of Line

With the introduction of the microprocessor relay, being able to choose a best case polarization method: negative sequence, zero sequence voltage, or zero sequence current has been a possibility from a manufacturers perspective. Some manufactures have taken different approaches on this flexibility: some have given the option to utilities to use all three methods and allow the relay to make a determination on which to use, based off of the strength of the polarizing values available, while others have provided the option for all three, but leave it up to the utility to choose either current, voltage, dual or negative sequence. From a utility perspective it may be tempting to allow the relay to make the choice on directionality based off of the negative and zero sequence values but there is the possibility of causing mis-operations by polarizing different ends of a line with different methods such as this.

An example was presented by Walter Elmore and Elmo Price in a well known paper "Polarization Fundamentals" that describes the potential consequences that could arise from polarizing opposite ends of a transmission line with different polarization sources. In this paper, the example that was presented demonstrated under certain system configurations and impedances it is possible for mis-operation to occur when choosing mismatching sources. The lesson learned from this was that both ends of the line need to be polarized using the same polarization method, whether that be current, voltage, dual or negative sequence. For further information on this subject it is suggest the reader look into "Polarization Fundamentals". [2]

System Unbalances

One of the main principles behind directional relaying is the utilization of symmetrical components to create the angular relationship between the operating and polarizing quantities. If the system were to have significant amounts of unbalance, which could be caused by un-transposed transmission lines, or any other discontinuities between the three phases and ground, the current that flows during normal balanced load conditions will see negative and zero sequence current.

It has been observed in some unique cases that during single line to ground remote faults the amount of system impedance unbalance has been significant enough to cause a voltage reversal resulting in improper operation of the directional sensing unit. There are three different scenarios demonstrated in Figure 11 below. These phasor plots demonstrate that both zero and negative sequence polarization would distinguish a forward fault for a completely balanced system (11a), only negative sequence would be able to distinguish a forward fault if phases B and C phase angles were shifted by less than 5° (11b), and only zero sequence would be able to distinguish a forward fault if phases B & C were shifted by a similar amount as that seen in Figure 11b.

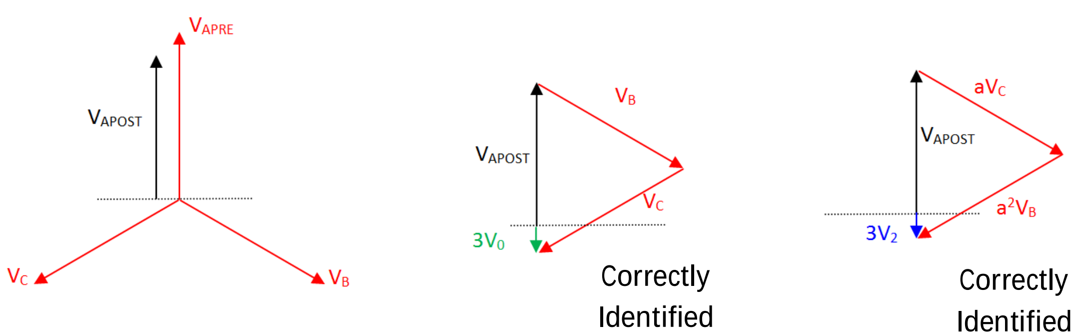


Figure 11a: Balanced System Zero & Negative Sequence Determination

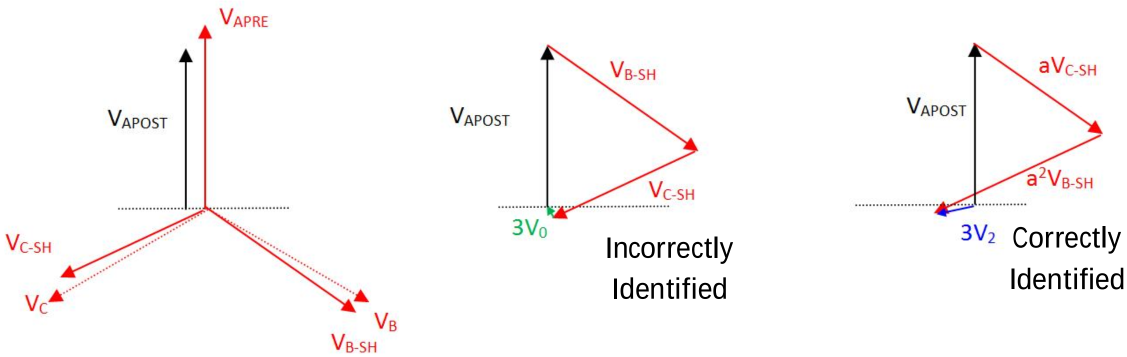


Figure 11b: Unbalanced System Negative Sequence Determination

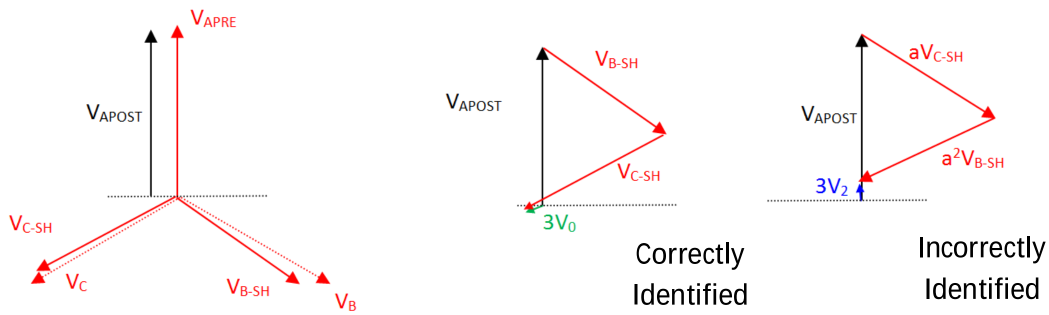


Figure 11c: Unbalanced System Zero Sequence Determination

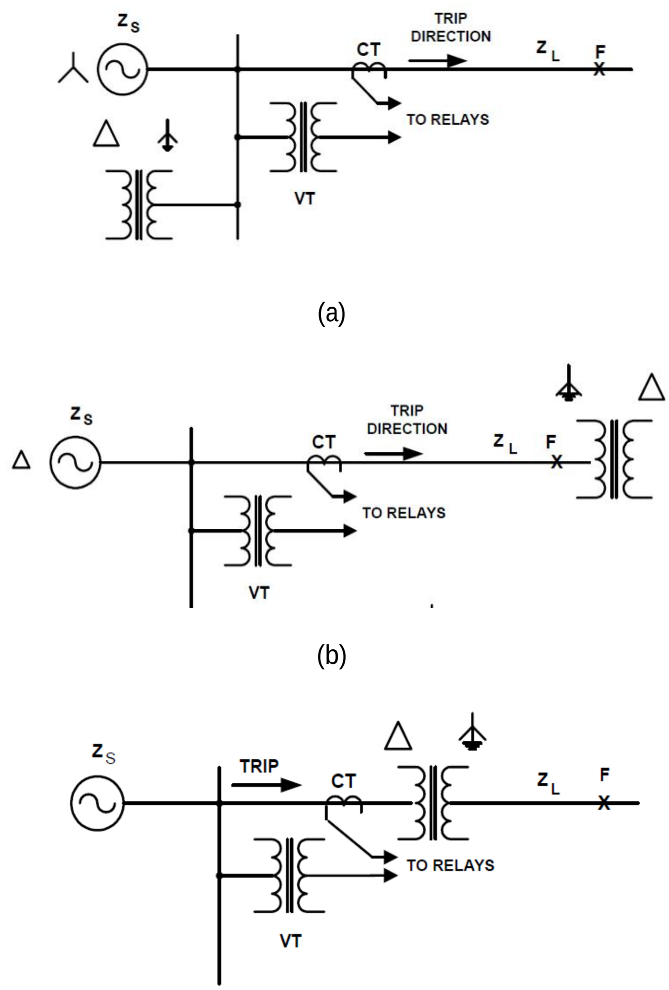
From the above examples it is noticeable that the phase angles of the shift in 11b and 11c are the same. The only appreciable difference is that for negative sequence determination, phase C is depressed along with the faulted phase, and with zero sequence determination, both phases B and C are slightly depressed. This is to highlight that good system modeling as well as investigation into what the appropriate polarization source should be for the system configuration is important on a case by case basis.

False Residuals

False zero sequence current that is generated in the CT secondary that is not present on the primary system is defined as a false residual. This situation can happen for a number of reasons. The scenarios in which this may take place include CT saturation, unbalanced burdens, sequential pole action, and switching of tapped load on transmission lines. In the last two cases the false residual can be produced when one or more phases of the three phase system is opened at a slightly different speed then the remaining phases. If the time difference between the unequal phase openings is too large, and the relaying is fast enough, mis-operation may occur.

V. Polarization for Phase Relays

There are several different connection types that have been used throughout the years for phase relays. These include 90°, 60° Type 1, 60° Type 2, and 30°. To expand on the variation of connection possibilities and the potential mis-operations that could occur for different system configurations references will be made to the exhaustive work made by W.K. Sonnemann. [3] In his analysis he studied all four connection types mentioned above for the three different system configurations shown in Figure 12 and for ten different fault types being: A-G, B-G, C-G, AB-G, BC-G, CA-G, AB, BC, CA, and ABC faults. As a manner of completeness Table 2 below is also presented to show the different connections used for the operating and polarization quantities that were used in the analysis.



(a)

(b)

(c)

Figure 12: System Configurations Evaluated by Sonnemann

Connection Type	Phase A		Phase B		Phase C	
	Polarize	Operate	Polarize	Operate	Polarize	Operate
90°	V_{BC}	I_A	V_{CA}	I_B	V_{AB}	I_C
60° Type 1	V_{AC}	$I_A - I_B$	V_{BA}	$I_B - I_C$	V_{CB}	$I_C - I_A$
60° Type 2	$-V_{CN}$	I_A	$-V_{AN}$	I_B	$-V_{BN}$	I_C
30°	V_{AC}	I_A	V_{BA}	I_B	V_{CB}	I_C

Table 2: Connections Evaluated for Phase Faults

The three system configurations shown above can accurately represent any real life system when broken down to their fundamental components. It is quite obvious that with the multitude of fault types, system configurations, and relay connection possibilities the evaluation of correct operation given the systems Z_{S0}, Z_{S1}, Z_{L0}, and Z_{L1} was an arduous task. However, the results from the evaluation were as follows.

1. Shifting the RCA to 45° leading for the 90° connection appeared to have the best results for the systems given and given system and line impedances (it was later suggested that 30° current leading polarizing voltage was more suitable)
2. Each connection has its merits but has the possibility to mis-operate in extreme cases
3. The 30° connection was found to not be a well suited connection type for system configurations b and c

Since the findings determined that the 90° was most versatile connection in most situations, and there are theoretically the possibility for mis-operation for this connection, a review of the possible faults types, system configurations that led to these events have been added below.

1. Relay B for a Phase BCG Fault in system a above
2. Relay C for a AG Fault in system b above
3. Relay B for a AB Fault in system c above

Phase Polarization Types

There are essentially four common ways in which to polarize phase relays. These include self polarization, discussed earlier, quadrature polarization, sometimes referred to as cross polarization, positive sequence polarization, and negative sequence polarization. As with ground directionality each has their merits. A brief discussion of quadrature, positive sequence, and negative sequence is presented below.

Quadrature Polarization

Quadrature Polarization compares un-faulted phase voltages V_{BC} to faulted phase currents I_{AN} to determine directionality. To account for the fact that fault current is highly lagging the voltage the relay angle is shifted. This is done to compensate for the expected angular shift and to make the relays torque angle be at a maximum during a fault situation. This compensation is accomplished by shifting the voltage, as shown previously in Figure 1.

Given this schematic it is possible to derive the phasor diagram that relates I_A, V_{SEC}, and V_{POL}. Figure 13 illustrates the response for the single line to ground fault in both a forward and reverse looking direction. It also illustrates the effect of the phase shift inserted into the voltage polarizing V_{POL} is approximately in phase with the secondary phase current when it lags the unity power factor angle by the design angle.

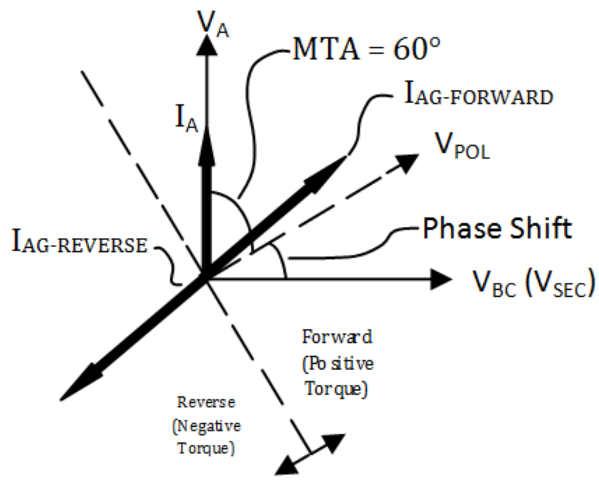


Figure 13: Vector Diagram Cross Polarization I_{AG}

Unlike for ground faults, cross polarization for phase faults effects one of the voltages that makes up the polarizing quantity. An analysis of how this affects the phasor relationships during this scenario is shown in Figure 14 for an I_{AB} fault.

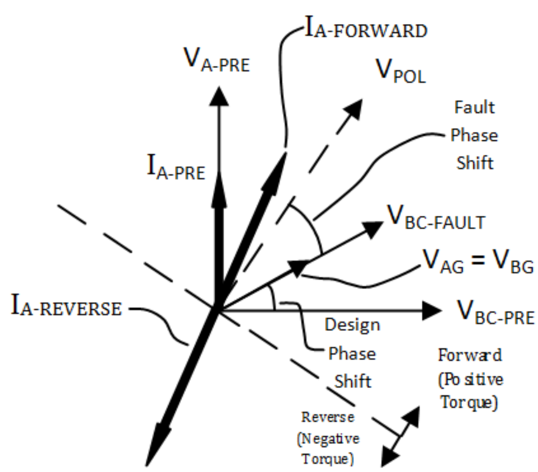


Figure 14: Vector Diagram Cross Polarization I_{AB}

The main observation to take away when comparing an I_{AG} fault to an I_{AB} fault is that the current I_A phasor as well as the polarizing voltage shifts by 30° in the counterclockwise direction. The same shift would take place between I_B and its polarizing quantity V_{CA}. Since the current and cross polarized voltage are the two vectors that are used to sense directionality and they both shift in the same direction and by the same amount there is no loss of reliability for the cross polarized unit to operate for forward or reverse faults.

There are some drawbacks to cross polarized relays. In fact, early generation of phase relays have been known to operate under some ground fault conditions such as two phase to ground faults. Typically this scenario has been overcome by using the microprocessors to perform zero sequence blocking when two phase to ground faults are recognized. This solution is a method that some manufacturers have implemented but may not be universal to all. Checking individual manufacturer practice is necessary to determine how phase elements determine that two phase to ground faults are truly ground faults and not phase faults.

Positive Sequence Polarization

The 90° connection discussed by Sonneman took into account balanced phase faults which very well may not be the case in real life fault situation. To determine its discrimination an example is provided below to determine if this connection is able to properly distinguish directionality for a forward three phase forward fault and for a reverse single line to ground fault where the infeed affect from bus B is predominately zero sequence. The three phase fault below is initiated at 80% of the line length from Line AB and the impedance values are displayed in per unit.

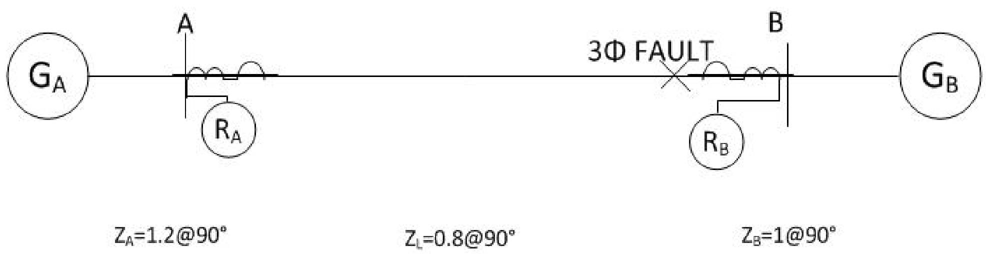


Figure 15: Symmetrical 3Φ Fault Line AB

I_A = 0.54@0°	V_{POLA} = 0.69@0°
I_B = 0.54@-120°	V_{POLB} =0.69@-120°
I_C = 0.54@-240°	V_{POLC}= 0.69@-240°

Relay A Currents and Polarizing Voltage

I_A = 0.86@0°	V_{POLA} = 0.46@0°
I_B = 0.86@-120°	V_{POLB} = 0.46@-120°
I_C = 0.86@-240°	V_{POLC} = 0.46@-240°

Relay B Currents and Polarizing Voltage

The symmetrical three phase fault in line AB is correctly identified as a forward fault by both relays at buses A & B. Now let's investigate if a reverse B phase single line to ground fault would be correctly identified if a fault were initiated behind the bus at relay A.

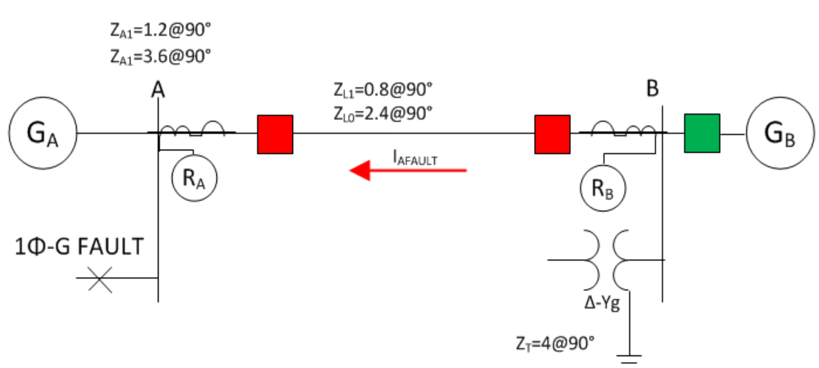


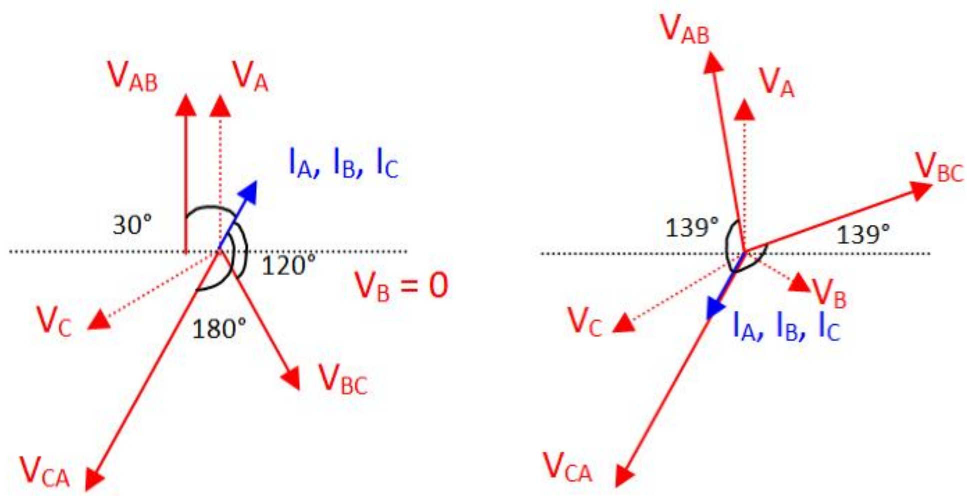
Figure 16: SLG B Phase Fault Behind Bus A

I_A = 0.295@60°	V_{POLA} = 0.577@300°
I_B = 0.295@60°	V_{POLB} =1@240°
I_C = 0.295@60°	V_{POLC}= 0.577@90°

Relay A Currents and Polarizing Voltage

I_A = 0.045@-120°	V_{POLA} = 0.764@19.05°
I_B = 0.045@-120°	V_{POLB} = 1@240°
I_C = 0.045@-120°	V_{POLC} = 0.675@100.95°

Relay B Currents and Polarizing Voltage



Bus A

Bus B

Figure 17: Phasor Diagrams of Polarization for SLG B Phase Behind Bus A

With the operating current and polarizing angular displacements above one can observe that with the 90° connection the C phase directional relay at bus A will perceive that the fault is forward when it is intended to recognize the fault as a reverse event. The directional relays on phases A and C at bus B will perceive the faults to be in the reverse looking direction. The conclusion that can be taken away from this example is that quadrature polarization reliable predicts forward or reverse multiphase faults but can mis-operate for out of zone single phase to ground faults that are predominately zero sequence in nature if the pickup of the overcurrent element and the magnitude of the polarizing quantities are sufficient to produce enough torque to allow tripping.

One solution to insure security for directional phase relays for this out of zone single line to ground scenario is to implement positive sequence directional elements. If positive sequence directional elements were used in the same system as shown in Figure 16 above the phase relays would securely and accurately identify the directionality at bus A to be in the reverse direction and at bus B to be in the forward direction. This happens because no positive sequence current (I_1) exists at A for a reverse single line to ground fault, thus no torque will be produced which will prevent operation. Using positive sequence elements with memory voltages, where V_{MEM} takes the place of V_1 is also a reliable choice for close in three phase faults.

Negative Sequence Polarization

Negative sequence polarization for phase faults retains many of the advantages inherent for ground faults that were presented earlier; however, their use in mutually coupled circuits as it pertains to phase faults is not required as it was in ground relaying. The remaining advantages will not be readdressed here but the principle behind comparing the negative sequence voltage and current for phase to phase faults is illustrated for a BC fault in the phasor plots in Figure 18 below. It can be seen from this plat that $-3V_2$ is compared to $3I_2$ to make the directional determination.

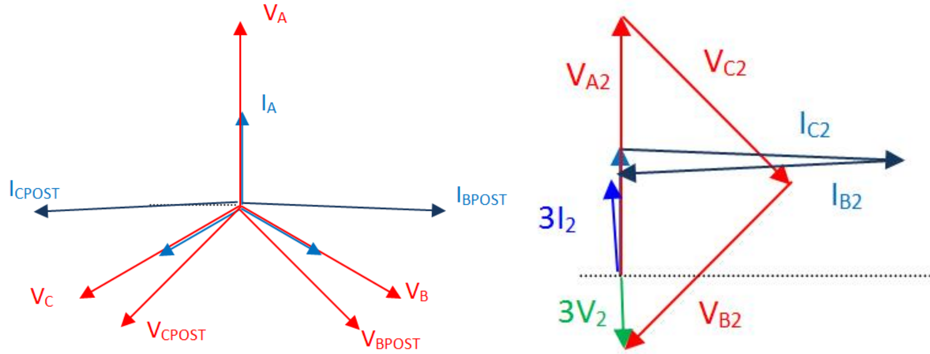


Figure 18: Vector Diagram Negative Sequence Polarization I_{CB}

VI. TRAVELING WAVE DIRECTIONALITY

The use of traveling wave relays to determine directionality is not a new concept but its application has seen limited exposure. The reason for this is that it primarily has only been used in special relay applications where more traditional relays have had difficulty providing the speed and the discrimination between forward and reverse looking faults. One example of this is for lines that incorporate series capacitors.

One of the first traveling wave relays detected faults and determined directionality using the incremental changes in voltage (Δv) and current (Δi) at the relay location that were generated at the initiation of an event. It was determined that directionality was indicative of the relationship of the incremental voltage and currents that propagated to the relay locations on both ends of the line. At this point the information from the relays at opposite ends of the line was shared over a communication channel. For internal or forward fault the polarities were different between the incremental voltage and current and for an external or reverse fault the polarities were different only on one end. Figure 19 demonstrates this principle at one of the line terminals for faults that ensue on different times of the voltage wave. For a more inclusive overview of what the relay must see, and transmit via a communication channel, to the other line terminal for a simple two terminal AB line configuration refer to Table 3.

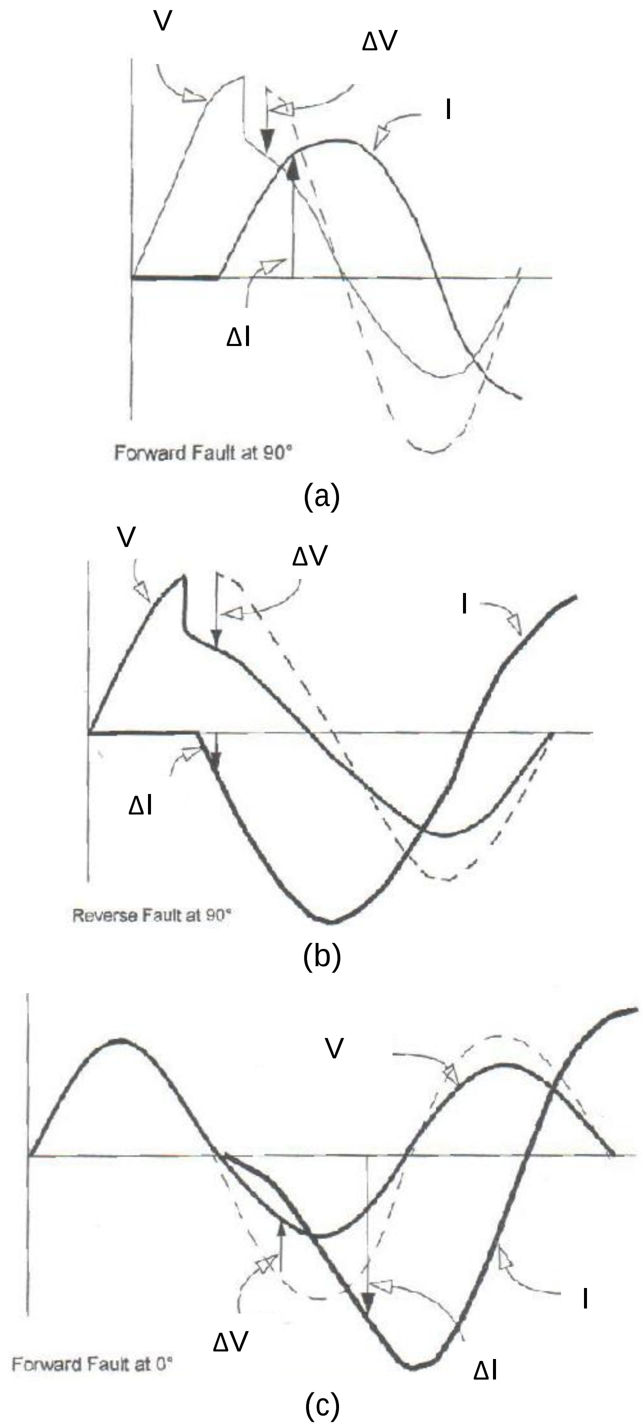


Figure 19: Incremental Change Traveling Wave Discrimination [4]

Type of Fault	V_{FAULT} (t)	TERMINAL			
		1		2	
		Δv	Δi	Δv	Δi
Internal	POSITIVE ($t=t_{FAULT}$)	POSITIVE	NEGATIVE	POSITIVE	NEGATIVE
	NEGATIVE ($t=t_{FAULT}$)	NEGATIVE	POSITIVE	NEGATIVE	POSITIVE
Behind Terminal 1	POSITIVE ($t=t_{FAULT}$)	NEGATIVE	NEGATIVE	POSITIVE	NEGATIVE
	NEGATIVE ($t=t_{FAULT}$)	POSITIVE	POSITIVE	NEGATIVE	POSITIVE
Behind Terminal 2	POSITIVE ($t=t_{FAULT}$)	POSITIVE	NEGATIVE	NEGATIVE	NEGATIVE
	NEGATIVE ($t=t_{FAULT}$)	NEGATIVE	POSITIVE	POSITIVE	POSITIVE

Table 3: Incremental Change Directional Both Line Terminals [5]

While determining directionality via traveling waves is more non-traditional than the other methods presented earlier for phase and ground faults, it is still a valid method all the same. When they were first implemented in the later part of the 1970's the cost for a communication channel would have been prohibitive if they were only being used for directionality; however, with the drastic improvement in communication infrastructure, this typically no longer is the case. The benefit to this technology is that it provides many of the inherent advantages of negative sequence polarization with the additional speed in directional determination for many high end transmission applications. Below are some of the advantages and disadvantages of using this type of relay for detection and discrimination for ground and phase faults.

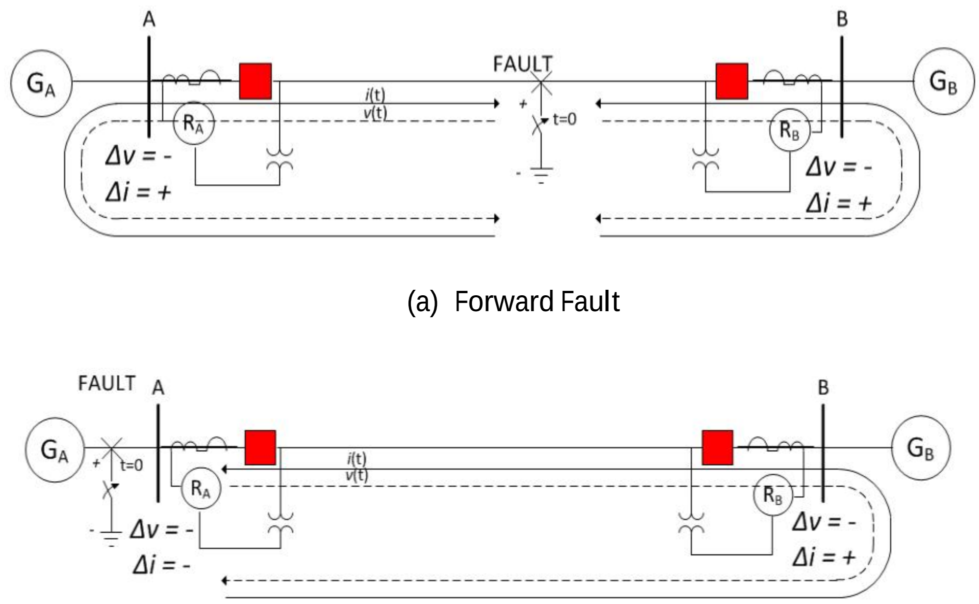
Advantages

1. Unaffected by current transformer Saturation
2. Ultra high speed (2-5 ms)
3. Suitable for mutually coupled lines
4. Suitable for series compensated lines

Disadvantages

1. Requires a communication channel
2. Requires additional hardware
3. High end solution that only be justified by critical assets
4. Line PT's must be used to avoid mis-operation during switch transients

An example of this method is shown in Figure 20 below. It clearly demonstrates how the principle of the incremental voltage and current are processed by the local relays and transmitted to the remote line terminal to make directional determination.



(a) Forward Fault

(b) Reverse Fault behind Bus A

Figure 20: Voltage-Current Direction Forward-Reverse Faults

VII. CONCLUSIONS

In conclusion, this paper has attempted to cover the most common and important concepts when choosing the polarization source for directional protective relaying. Many of the polarization concepts have been presented through examples and phasor plots with advantages and disadvantages as well as pitfalls that could cause directionality to be compromised.

It was found that the ground directional relaying polarization needs to be determined on a case by case basis. Zero sequence voltage polarization by itself or complemented with zero sequence current can correctly determined directionality if an adequate source of zero sequence is available under all system conditions. When system configurations include lines on the same structure or within the same right of way zero sequence voltage and current is not reliable. In the cases where significant amounts of mutually coupling exist or where zero sequence sources don't exist the use of negative sequence polarization should be utilized.

When selected polarization method for phase relays it was found by Sonnemann that the 90° connection where the current leads the polarization source by 30° to be the most reliable for all types of balanced phase faults except for the three different system scenarios shown previously. An example was presented where the 90° connection could potentially mis-operate for out of zone single line to ground faults that were predominately zero sequence in nature. In the investigation it was determined that positive sequence polarization could reliably distinguish these reverse single line to ground faults and still possess the same desirable characteristics as the 90° connection for multiphase faults. A third option for phase relays is negative sequence polarization. It maintains many of the same advantages as was observed for ground polarization but is not required to detecting phase faults on mutually coupled lines and thus is used less frequently.

Traveling wave relays have successfully been deployed for high end relay applications where ultra high speeds have been required. They are able to operate dependably for both phase and ground faults, without the need for a zero sequence source, and without the need for special current or voltage transformer hardware. While traveling waves have yet to be implemented in a relay for the sole purpose to determine directionality, the concept has been proven and is a viable option as another means for reliable polarization.

The polarization concepts presented for both ground and phase protection have been examined in detail with examples showing where misapplication with given system conditions may cause mis-operation of the directional element. By applying the appropriate polarization method for the given system configuration there the reader should feel confident that their system will be able to reliable discriminate between forward and reverse fault events.

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[4] W.A. Elmore, Pilot Protective Relaying, Marcel Dekker, Inc., 2000.

[5] Ultra High Speed Line Protection type RALZB, ABB, November 1988 Edition 3.

VIII. Biographies

Michael Fleck received his BSEE degree in 2005 from Rose-Hulman Institute of Technology in Terre Haute, Indiana and a MSEE with a concentration in Power Systems in 2010 from Arizona State University in Tempe, Arizona. He began his career with Hoosier Energy REC, Inc. in Bloomington, Indiana and had a variety of responsibilities that ranged from physical substation design, SCADA implementation, path profile analysis, and ultimately protective relaying. In 2010 he moved to Ann Arbor, Michigan and took the position of Substation Project Engineer at HDR Engineering. In this position he was responsible for designing and reviewing protective control schemes for projects ranging from 115 through 500kV. In 2011 he joined ABB as Regional Technical Manager for the Great Lakes Region in support of product sales and applications. Michael is a registered professional engineer and a member of IEEE. He is also a member of PSRC. Michael's email address is michael.fleck@us.abb.com