Comparing Ground Directional Element Performance Using Field Data

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INTRODUCTION

Relay Engineers are faced with several options when determining how to polarize directional ground overcurrent elements. This paper presents differences between negative-sequence and zero-sequence polarization techniques, with emphasis on selecting the correct polarization method.

Several actual system faults are analyzed using event reports extracted from various microprocessor-based relays. These event reports, along with some mathematical analysis, demonstrate how the directional elements behave during a fault with a voltage neutral shift, how a zero-sequence voltage polarized element can be affected by mutual coupling with a parallel line, and how selection of the proper polarizing method can be dependent upon system operating conditions.

The event reports used in this paper are field data supplied by utilities using microprocessor relays.

REVIEW OF GROUND DIRECTIONAL ELEMENT POLARIZING

For single-phase to ground faults, you expect the phase-to-ground voltage to collapse, the magnitude of the faulted phase current to increase, and the angle of the faulted phase current to increase in the lagging direction with respect to the faulted phase voltage. We can use this to polarize a directional element.

In residual or ground overcurrent relays, the current is extracted from the three-phase currents and the resultant residual current is given by:

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

Because the residual current is caused by an unbalance in any phase, a reference quantity is needed to obtain a correct directional response. There are several methods of determining the direction of fault current for a ground fault. The most common reference quantities are zero-sequence voltage, and zero-sequence current. Negative-sequence voltage and current quantities are also used for directional polarizing.

Microprocessor-based relays measure voltages and currents to create phasor quantities. These quantities are used to calculate torque-like products. The value of the torque product indicates the direction of current flow: For a forward fault, the sign of the torque is positive; and for a reverse fault, the sign is negative.

Zero-Sequence Voltage Polarization (32V)

Zero-sequence polarization direction elements measure the angle between the zero-sequence voltage (V_0) and the residual current ($3I_0$). V_0 is the phasor sum of the individual phase voltages and is zero for balanced conditions. The residual voltage is displaced from the residual current by the characteristic angle of the source and line impedances (Z_{0S} + $m \cdot Z_{0L}$). The sequence networks for a single-phase to ground are shown in Figure 1. E_{1S} and E_{1R} are sources at the local and remote ends with Z_{1R} and Z_{1S}, the respective source impedances, and m is the per unit line distance to the fault. The angle between V_0 and I_0 is unaffected by fault resistance R_F.

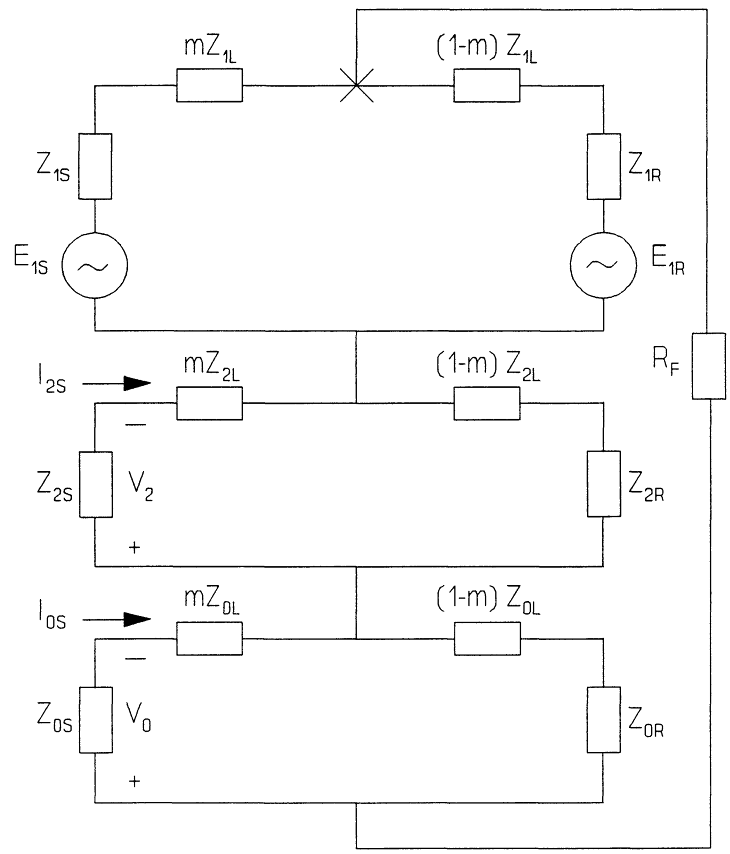

Figure 1: Sequence Networks for Single-Phase to Ground Fault

In most cases, the impedance is predominantly reactive. Therefore, the maximum torque (32VT) is developed when the residual current lags the negative residual voltage by this angle (called the maximum torque angle or MTA) and is expressed as:

$$32VT = |V_0| \cdot |I_R| \cdot [\cos(\angle -V_0 - (\angle I_R + MTA))] \qquad \text{Equation 2}$$

where 32VT is positive for a forward fault. The negative sign of the V_0 angle is best described graphically. Figure 2 shows balanced three-phase voltages.

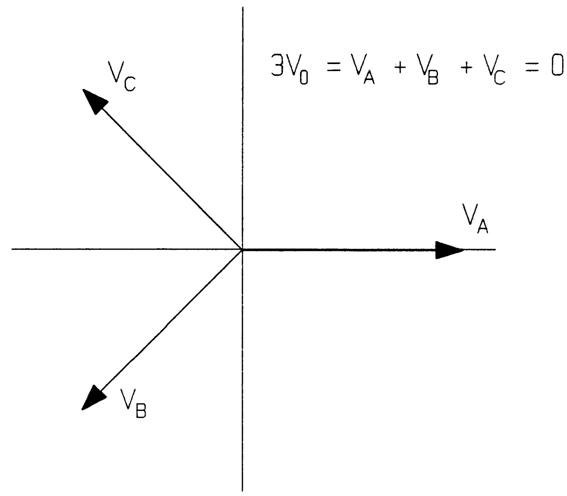

Figure 2: Pre-Fault Balanced Voltages

Assuming no fault resistance and a forward A-phase to ground fault, Figure 3, the A-phase voltage depresses, and A-phase current increases and lags the faulted phase voltage by the characteristic angle of the source and line impedances.

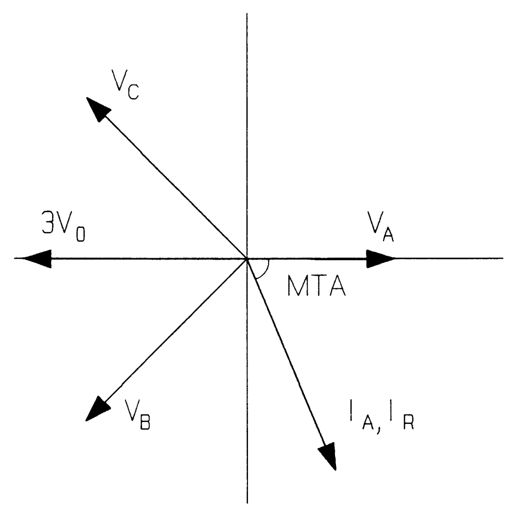

Figure 3: A-phase to Ground Fault

V_0 is actually the opposite direction of the faulted phase voltage. As seen in Figure 4, to correctly compare V_0 with I_0, the sign of the V_0 angle is reversed (thus, the negative sign).

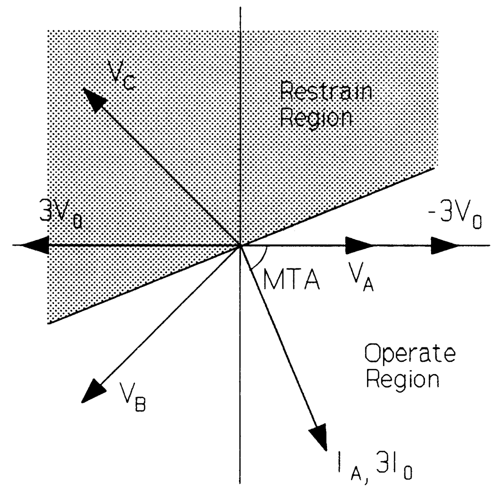

Figure 4: Zero-Sequence Phasors for a Single-Phase to Ground Fault

Directional elements also require minimum torque thresholds. This ensures that there is adequate signal to make a secure directional decision. A zero length vector makes a poor candidate for angle reference.

Zero-Sequence Current Polarization (32I)

If the residual voltage is insufficient to polarize the relay, you may polarize from the neutral current of a local power transformer with a grounded neutral. For a forward fault, the neutral current from the transformer and the circuit residual current are in phase, whereas the residual current in the circuit reverses for a reverse fault. Therefore, the maximum torque (32IT) is developed when the residual current and the polarizing current (I_{pol}) are in phase and is expressed as:

$$32IT = |I_{pol}| \cdot |I_R| \cdot \cos(\angle I_{pol} - \angle I_R) \qquad \text{Equation 3}$$

It is beyond the scope of this paper to address all of the concerns of applying a current polarizing element, but much care should be taken to verify that the polarizing current flows from the ground to the system for all ground faults. If the current does not flow in the same direction for all ground faults, this method of polarizing cannot be used. One polarizing current source is an autotransformer, which is sometimes unreliable when the direction of the polarizing current is examined for different fault locations [5].

Figures 5 and 6 illustrate a forward and reverse fault using a zero-sequence current polarized element extracted from the neutral of wye-grounded transformer.

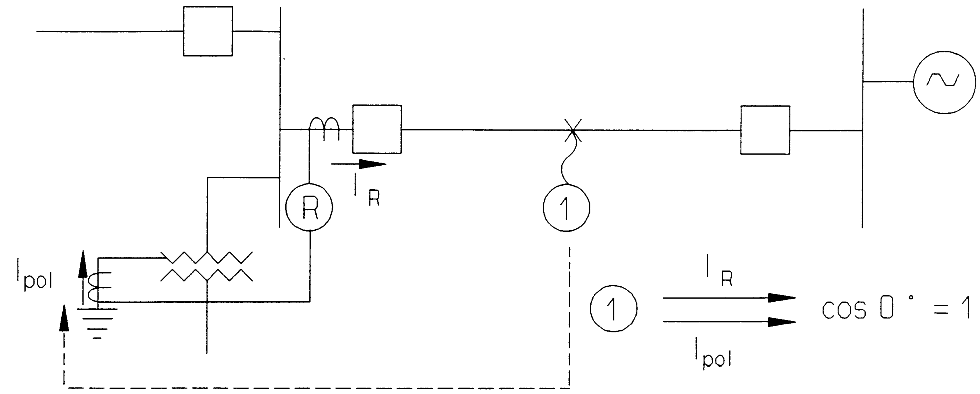

Figure 5: Current Polarization for Forward Fault

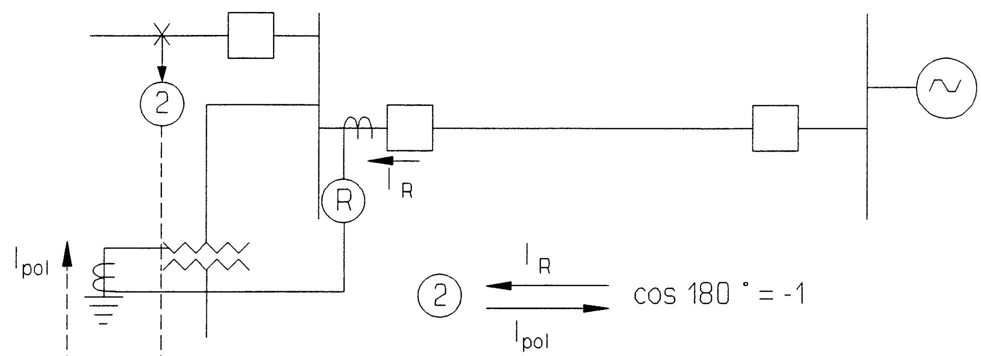

Figure 6: Current Polarization for Reverse Fault

Dual Polarization (32V or 32I)

Sometimes the amount of residual voltage is too low for certain system conditions, or the polarizing current is eliminated by the subject transformer being out of service. In these cases, dual polarization may be applied where either the zero-sequence voltage polarized element or the zero-sequence current polarized element provides the directional decision.

Negative-Sequence Polarization (32Q)

Negative-sequence polarization is an excellent method of polarizing directional elements. Negative-sequence voltage and current are used in place of zero-sequence voltage and current. This is particularly useful at stations with unreliable I_{pol} sources, zero-sequence mutual coupling, or when only 3-wire voltages are available. Negative-sequence quantities, once difficult and expensive to obtain, are now easily developed in newer microprocessor-based designs. This torque product (32QT) is expressed as:

$$32QT = |V_2| \cdot |I_2| \cdot [\cos(\angle -V_2 - (\angle I_2 + MTA))] \qquad \text{Equation 4}$$

Again, positive values indicate a forward fault, negative values indicate a reverse fault. Figure 7 shows the phasors for the negative-sequence directional element.

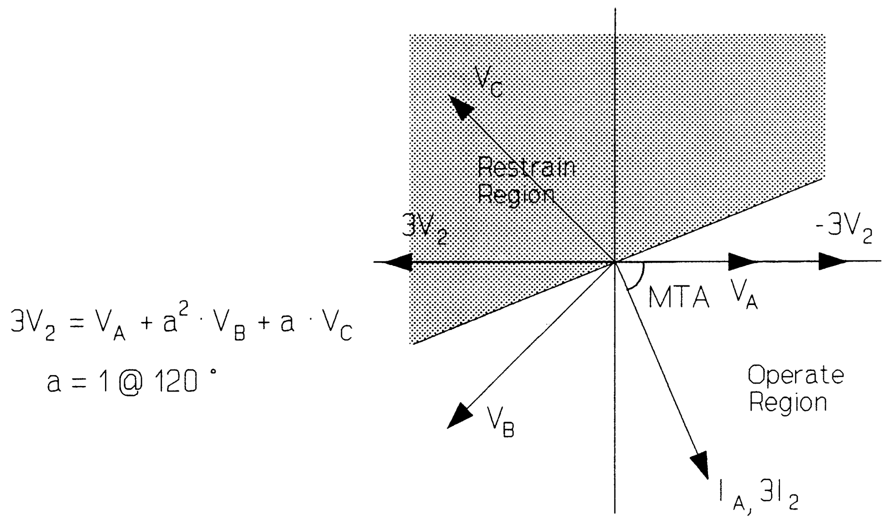

Figure 7: Negative-Sequence Element Phasors for a Single-Phase to Ground Fault

Negative-sequence polarization may be preferred for several reasons:

1. The magnitude of V_2 at the relay may be larger than that of V_0, resulting in a more positive operation of the directional element. Examine system studies to determine the amount of available V_2 and V_0.

2. Negative-sequence directional elements are not affected by zero-sequence mutual coupling due to parallel lines and are less affected by the effects of vt neutral shift.

3. Negative-sequence elements do not require an additional ct to extract a polarizing current.

4. Only 2 vts are required versus 3, which are required for zero-sequence voltage polarization.

One possible drawback to applying negative-sequence polarization is that the source may produce inadequate negative-sequence voltage for relay minimum sensitivity levels. This is overcome with a new approach of using negative-sequence impedance [2].

RELAY EVENT REPORTS

Most microprocessor-based relays produce and save event reports when faults or other triggering events occur. The particular event reports discussed in this paper report voltages, currents, relay elements, and contact I/O in an easy-to-use 11-cycle format. The first four cycles of the report are pre-fault and the remaining data are fault or post-fault data. The following is included:

1. Date and time of the fault or disturbance.
2. Pre-fault, fault and post-fault voltages and currents.
3. Relay input and output status.
4. Relay element status.
5. Calculated fault location in miles or kilometers.
6. Relay settings at the time of the fault or disturbance.

The voltage and current data are scaled into primary quantities for the event report. Scaling is accomplished using the current and voltage transformer ratios entered in the relay settings. Because the samples are taken every quarter-cycle, the adjacent data have the 90° relationship required to create phasor diagrams. Therefore, with respect to the present output, the previous value was taken one quarter-cycle earlier and leads the present value by 90°.

The values shown in the event reports represent the voltages and currents as phasors:

The PRESENT value of the output is the X-component of the phasor.
The PREVIOUS value of the output is the Y-component of the phasor.

On Cartesian coordinates, the lower row (more recent value) is plotted as the X-component and the upper row (older value) is plotted as the Y-component. To convert the Cartesian coordinate to polar coordinates, use the simple equations:

Magnitude = $(X^2 + Y^2)^{1/2}$

Angle = Arctan (Y/X)

Analyzing event reports extracted from SEL relays is enhanced by using VIEW, a software program developed by Rick Bart of Montana Power Company. VIEW accepts event reports, calculates the phasor data, and graphically represents the phase and sequence phasors and oscillographic plot. Outputs produced by VIEW are used in the paper to illustrate system events.

SYSTEM EXAMPLES

Example I

Figure 8 shows a one-line diagram in which a 138 kV line is protected by impedance relays for phase faults and has a dual-polarized electromechanical ground directional overcurrent relay (67N) for ground fault protection. In addition, a multi-function phase distance/ground directional overcurrent relay (11-67N) was added for fault location purposes only.

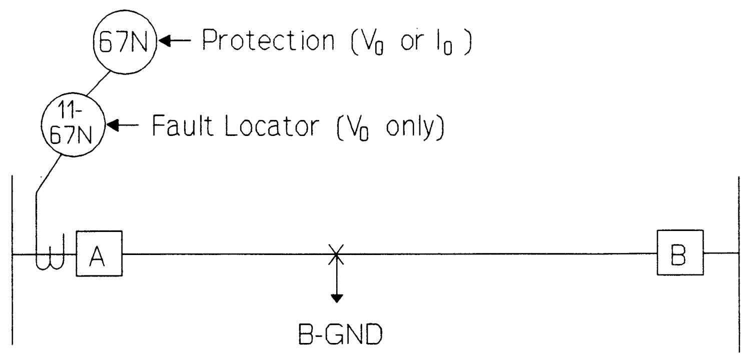

Figure 8: Example I - One Line Diagram

Elements of the multi-function relay are set to reach beyond the remote terminals for all fault types and the ground directional overcurrent element is set for zero-sequence voltage polarization.

A ground fault (B-phase to ground) occurred on the line which was correctly detected by the dual-polarized relay. The fault locator, however, did not pick up for the initial fault and triggered an event report only when a Zone 3 phase-phase element picked up as the breaker opened. The fault locator indicated a negative distance to fault, which was investigated.

Since the event report was triggered after all of the currents and voltages dropped out, the fault location is based on invalid data, and is therefore, discarded. Also, since the fault had already occurred prior to the event report being triggered, the portion of the event report which is usually the "pre-fault" data (the first 4 cycles), is, in fact, the "fault" data. A portion of the event report is shown in Figure 9. The question is: why didn't the ground directional element of **11-67N** pick up at fault inception?

Example 138 kV Line   Date: 7/10/92   Time: 16:26:02.729

		Currents (amps)				Voltages (kV)			Relays	Outputs	Inputs
									52265L	TCAAAAA	DPBD5E
	IPOL	IR	IA	IB	IC	VA	VB	VC	011710	PL1234L	TTTC2T
									P3PNNP		A
Rows 1&2	0	1369	-107	1743	-245	-60.3	-15.6	75.9	M.....	..*....	......
	0	-939	76	-1145	120	49.0	-78.7	17.3	M.....	..*....	......
	0	-1364	113	-1730	245	60.1	15.6	-75.8	M.....	..*....	......
	0	937	-76	1139	-113	-48.8	78.6	-17.4	M.....	..*....	......
	6	1362	-113	1724	-252	-60.2	-15.4	75.9	M.....	..*....	......
	-6	-936	76	-1133	120	48.7	-78.6	17.4	M.....	..*....	......
	-6	-1361	120	-1730	245	60.3	15.3	-75.8	M.....	..*....	......
	6	937	-82	1139	-120	-48.7	78.7	-17.5	M.....	..*....	......
	6	1361	-120	1730	-252	-60.1	-15.2	75.8	M.....	..*....	......
	0	-942	76	-1139	120	48.3	-79.0	17.5	M.....	..*....	......
	-13	-1372	113	-1711	233	59.4	15.2	-76.5	M.....	..*....	......
	0	963	-69	1133	-101	-44.4	79.3	-18.1	M.....	..*....	......
	6	1468	-101	1711	-145	-59.1	-15.3	86.0	M.....	..*....	......
	0	-1004	82	-1139	50	32.9	-79.7	6.0	M.....	..*....	......
	0	-1648	57	-1756	50	56.7	18.2	-87.3	M.....	..*....	......
	0	941	-63	1032	-19	-12.5	69.4	3.1	M.3...	..*....	......
	0	1249	-19	1277	-6	-53.0	-23.6	75.3	M.....	..*....	......

Event   : 3AB   Location   :-26.15 mi -5.20   ohms sec
Duration: 0.25   Flt Current: 1642.1

Figure 9: Event Report Triggered for Example I Fault

Two quarter-cycle samples (rows 1 & 2) from the relay event report are used as the y and x coordinates of the fault phasor quantities in question. By analyzing the phasor quantities, the torques for the respective directional elements are calculated. A MathCad program worksheet is shown in Appendix I. The torque of the zero-sequence voltage element (Equation 2) is given by:

$$VT = |V_0| \cdot |I_R| \cdot [\cos(\angle -V_0 - (\angle I_R + MTA))]$$

where T is positive for a forward fault. If we substitute the primary phasor quantities from Figure 9 into this equation and scale for the ct and vt ratios (CTR & VTR), the torque is:

$$VT = -13.685$$

Therefore, the zero-sequence voltage polarized directional element indicates a fault in the reverse direction. According to the data, the element responded correctly (did not operate).

If this analysis is done for the negative-sequence element (Equation 4), we see the following:

$$QT = |V_2| \cdot |I_2| \cdot [\cos(\angle -V_2 - (\angle I_2 + MTA))]$$
$$QT = 3.844$$

Therefore, the negative-sequence directional element indicates a fault in the forward direction.

The VIEW program, Figure 10, illustrates the phasors of the voltages and currents referenced to V_B.

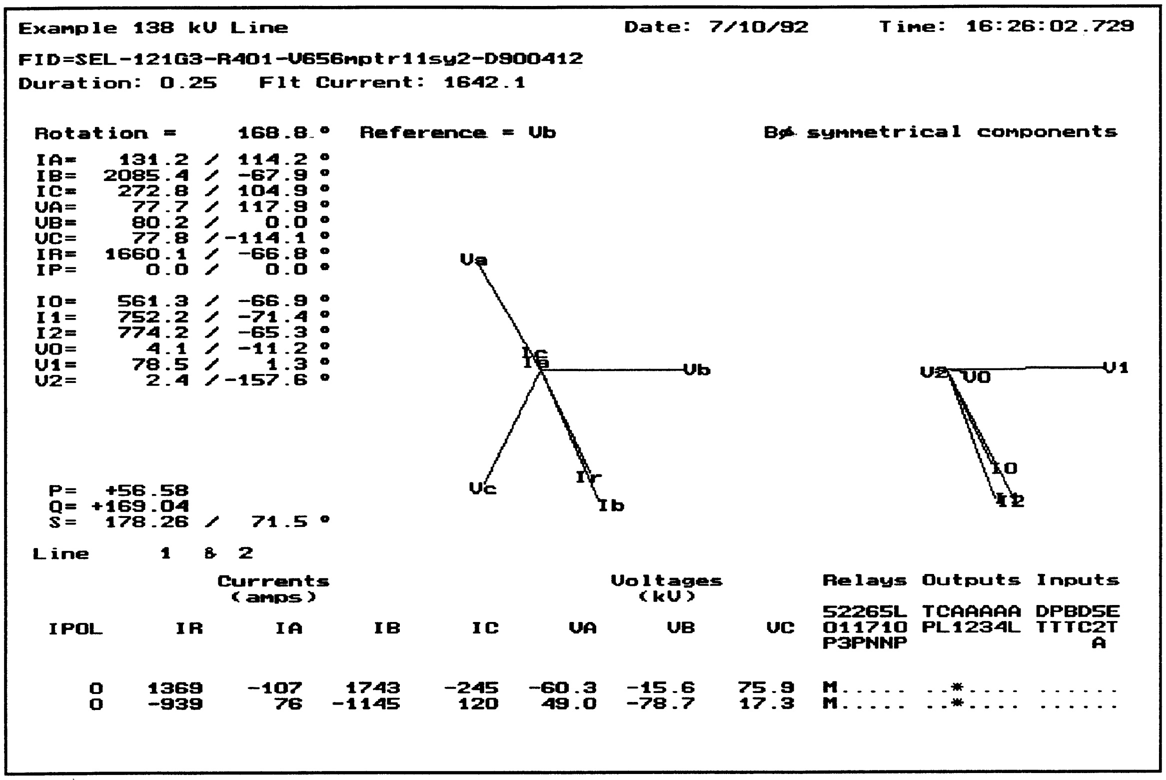

Figure 10: Example I - Phasors as illustrated in VIEW Program

If we examine the phasor quantities more closely, the faulted phase (B-phase) voltage magnitude is greater than the non-faulted phase voltages (80.2 kV vs. 77.8 kV). This indicates that the neutral reference of the phase voltages is shifted from the center position. Consequently, the reason the zero-sequence voltage polarized element sensed a reverse fault is due to a neutral shift of the input voltages to the relay. This is probably the result of ungrounded or multiple grounds on the supplying vts. Also, the dual-polarized relay that operated correctly did so due to its current polarized directional element.

Besides the magnitude of the phase voltages, another characteristic of neutral shift is that the angle between the non-faulted phase voltages (V_B and V_C) increases. For an actual ground fault, this angle decreases. Figure 11 illustrates the phase and sequence voltages and currents. Since the phasors V_2 and V_0 are nearly in opposite directions, we see that the zero-sequence voltage polarized element responds the opposite of the negative-sequence polarized element.

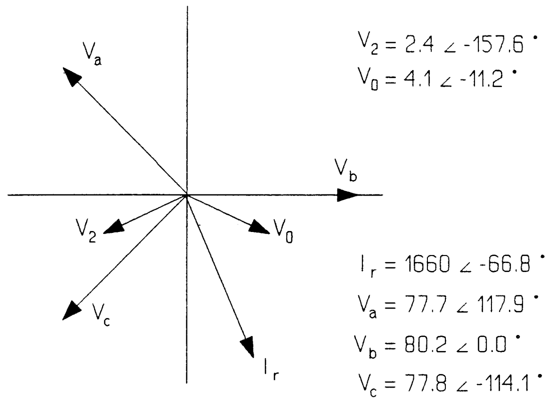

Figure 11: Phase and Sequence V and I

A graphical representation of the neutral shift is shown in Figure 12.

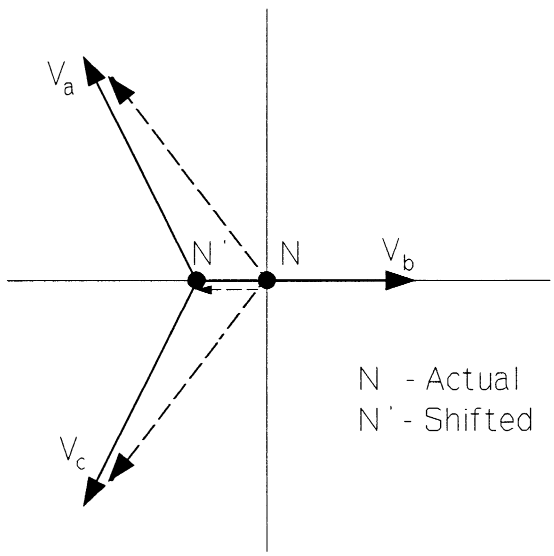

Figure 12: Neutral; Actual and Shifted

Lessons learned:

1. Even when relays are applied as fault locators, set the relays as if to trip. In this example, the relays were set correctly and would have produced the correct results if not for the vt neutral shift.

2. Negative-sequence polarization is relatively immune to neutral shift compared to zero-sequence voltage polarization.

3. Check for ungrounded or multiple grounded vts!

Example II

In Example II, ground directional overcurrent relaying is applied in a directional comparison blocking scheme on two 345 kV lines. A quick review of a DCB scheme is illustrated in Figure 13. If a local overreaching element (forward Zone 2) senses a fault and if a block signal from a remote element (reverse Zone 3) is not received, the local breaker is tripped.

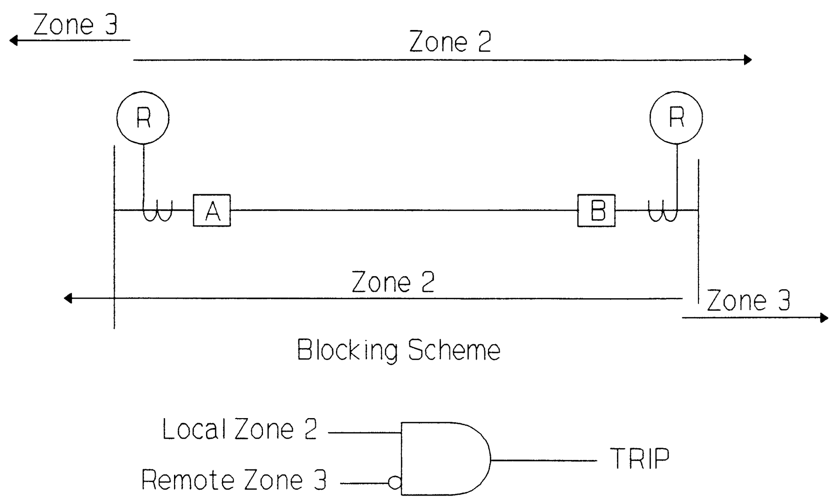

Figure 13: One-Line and Logic Diagrams for a Directional Comparison Blocking (DCB) Scheme

In this example, two lines terminate at a power plant bus at one end (Breakers P1 and P2) and run parallel for some distance before terminating at two separate locations (Breakers A & B). See Figure 14. Only the relays at the power plant had accessible event reports for analyzing the faults and performance of the ground directional elements. The application is unique in that the tripping relays at the power plant bus are set for negative-sequence polarization (32Q) and the blocking and tripping relays at the remote ends are discrete zero-sequence voltage polarized (32V) relays.

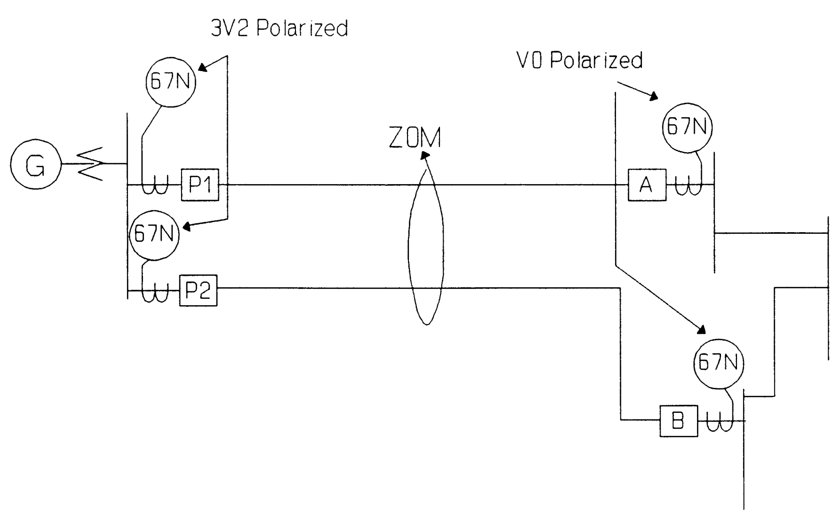

Figure 14: Example II - Pre-Fault Conditions

A B-phase to ground fault occurred on line P2-B near breaker B which resulted in correct tripping of the faulted line, but also resulted in an incorrect trip of the parallel line. Why did the non-faulted line trip incorrectly?

Using the relay event reports at the P1 & P2 breakers, we calculate the torques for the negative-sequence (QT) and zero-sequence voltage (VT) directional elements. Although negative-sequence polarization is selected, observing the zero-sequence voltage polarized element helps to determine what happened at the remote (BKR A) end. The calculations are based on the torque formulas previously stated. In this example, we examine:

1. Initial Fault Inception
2. Fault after the B breaker opens

Bold indicates the elements that are enabled at the P1 and P2 breakers.

Initial Fault Inception:

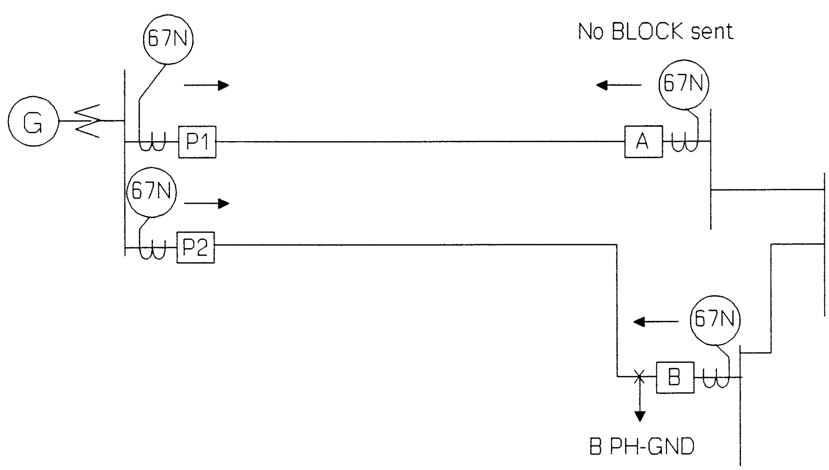

Figure 15: Example II - Initial Fault Inception

At fault inception, the negative-sequence directional element at P1 (**32QT**) senses a forward fault, which is delayed 0.75 cycles to allow arrival of the block signal from the remote terminal (BKR A). However, the block signal is never received, resulting in a trip at P1. BKR A tripped by its local 67N relay sensing a forward fault and no block received from BKR P1. In Figure 15, the arrows indicate the direction of the current as calculated from the directional overcurrent elements and confirmed by targets from the BKR A relay.

The 32V element at P1 produces a negative torque (reverse fault), opposite the 32Q element. This is probably due to mutual coupling caused by the parallel line configuration. It also explains why breakers P1 & A tripped: the BKR A relay determines the fault is in the forward direction thus tripping its own breaker and squelching the block signal to the remote (P1) breaker.

Example 345 kV Line (rows 21 & 22)

	Currents (amps)				Voltages (kV)			Relays	Outputs	Inputs
								565565 071071 PPPNNN	TCAAAAA PL1234L	DPBD5E TTTC2T A
IPOL	IR	IA	IB	IC	VA	VB	VC			
0	-936	462	-1306	-103	181.5	-7.6	-173.5	...11.	*......	......
0	71	-235	382	-59	-88.2	193.8	-106.4	...11.	*......	......

P1-A Line:	**32QT** = 0.658	Negative-sequence element--forward
	32VT = -2.593	Zero-sequence voltage element--reverse (Forward for BKR A relay)
P2-B Line:	**32QT** = 6.79	Negative-sequence element--forward
	32VT = 0.581	Zero-sequence voltage element--forward

Fault After B opens:

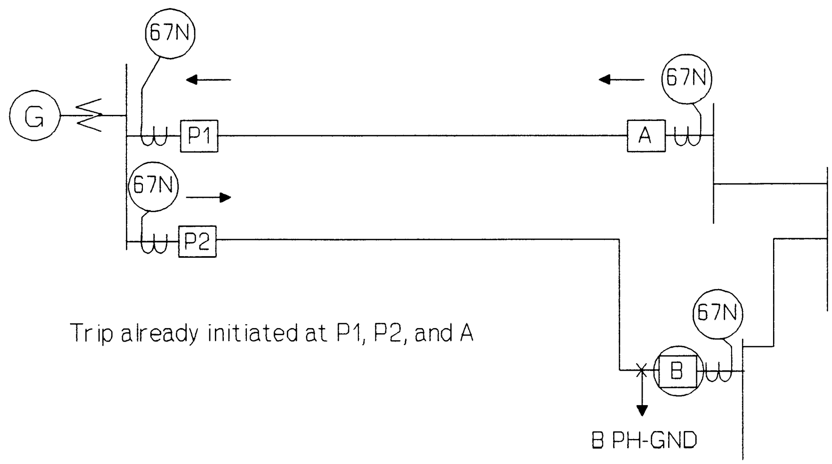

Figure 16: Example II - Fault Conditions After BKR B Opens

Example 345 kV Line (rows 33 & 34)

	Currents (amps)				Voltages (kV)			Relays	Outputs	Inputs
								565565 071071 PPPNNN	TCAAAAA PL1234L	DPBD5E TTTC2T A
IPOL	IR	IA	IB	IC	VA	VB	VC			
0	-1555	-103	-1335	-125	181.7	-4.1	-177.1	...11.	*......	......
0	166	-257	183	242	-95.6	196.4	-102.4	...11.	*......	......

P1-A Line:	**32QT** = -0.152	Negative-sequence element--reverse
	32VT = -4.627	Zero-sequence element--reverse (Forward for BKR A relay)
P2-B Line:	**32QT** = 6.263	Negative-sequence element--forward
	32VT = 1.888	Zero-sequence element--forward

After BKR B tripped (correctly), the directional element (32QT) reversed. However, the trip signal had already been applied to the breaker (BKR P1). Thus, the non-faulted parallel line tripped for an out-of-section fault due to the misbehavior of the ground directional element at BKR A.

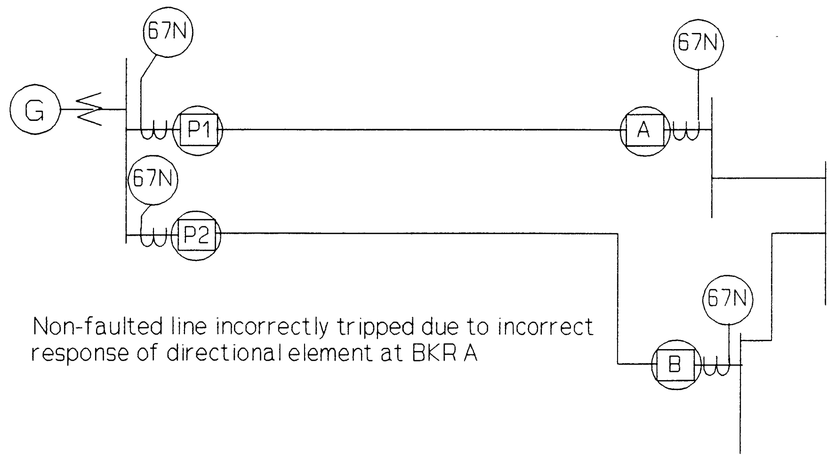

Figure 17: Example II - Post-Fault Conditions

The elements at the P1 end are shown in a time-line of the event in Figure 18. **67N** picks up after **32QF** and **50N** assert. **67N** drops out after **32Q** reverses (**32QR** asserts). **32V** was picked up in the reverse direction (**32VR** asserted) from fault inception.

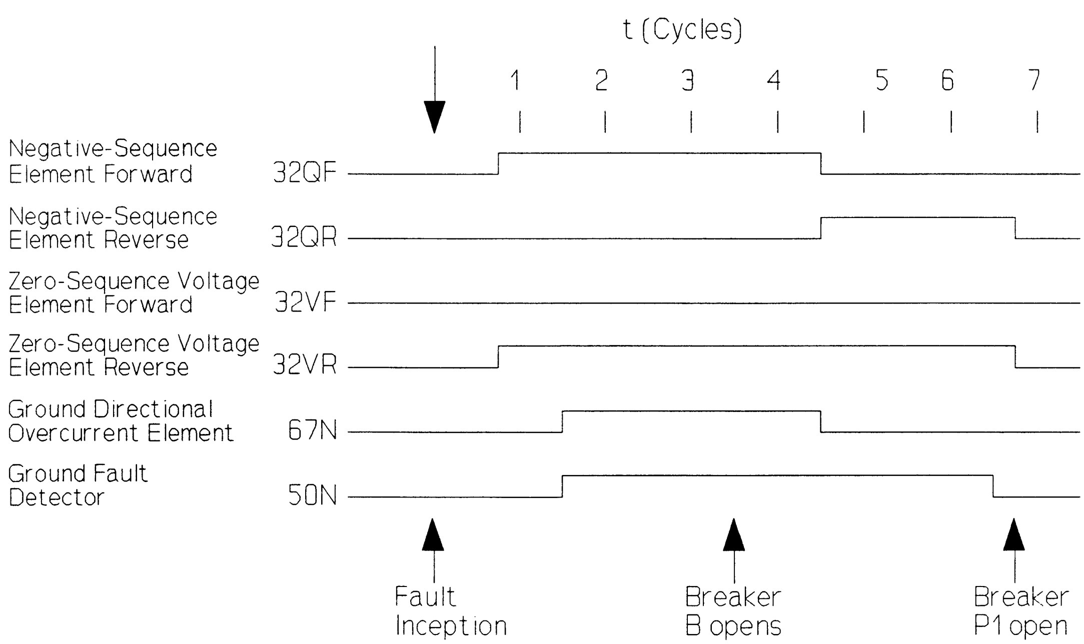

Figure 18: Time-Line of Elements at P1 end of P1-A Line

Lessons learned:

Since directional elements polarized by negative-sequence are immune to zero-sequence mutual coupling affects, negative-sequence polarization is recommended for all parallel line applications.

Example III

Figure 19 shows a subtransmission line protected by ground directional overcurrent relaying.

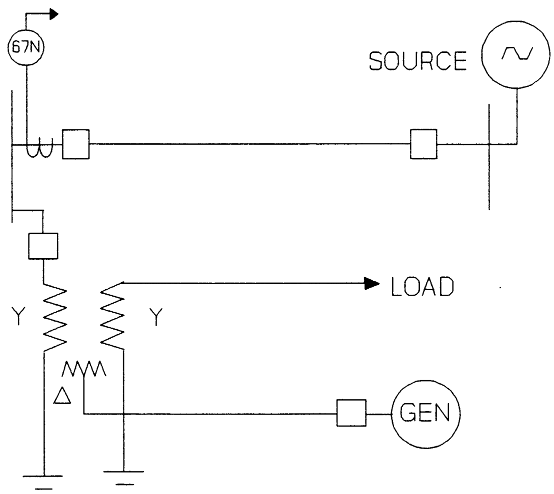

Figure 19: Example III - One-Line Diagram

The ground directional overcurrent element (**67N**) is set for negative-sequence polarization. Under normal operating conditions, the relay has a source of positive-sequence and negative-sequence current (generator **GEN**) and a source of zero-sequence current (the wye-grounded transformer). In this example, the generator is out of service. (See Figure 20.)

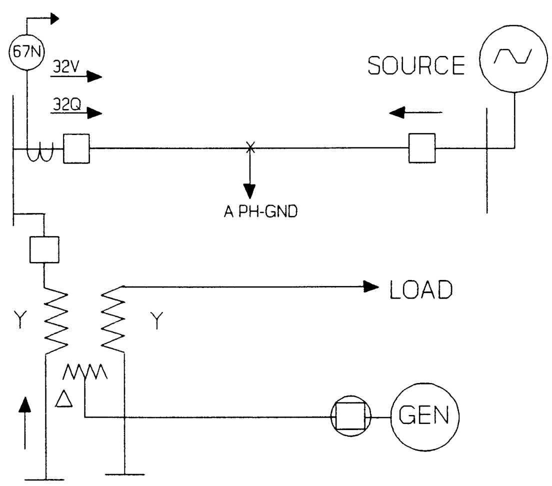

Figure 20: Example III - Initial Fault Conditions

Example 24 kV Line Date: 1/13/92 Time: 10:29:00.383

		Currents (amps)				Voltages (kV)			Relays	Outputs	Inputs
									52265L	TCAAAAA	DPBD5E
	IPOL	IR	IA	IB	IC	VA	VB	VC	011710	PL1234L	TTTC2T
									P3PNNP		A
	0	-11	24	-11	-23	-11.2	12.7	-1.3	......	....	....*.
	0	-6	-5	23	-25	-8.2	-5.9	14.0	......	....	....*.
	0	14	-22	12	24	11.0	-12.7	1.4	......	....	....*.
	0	13	8	-21	27	8.2	5.8	-14.0	......	....	....*.
	0	-22	19	-15	-26	-10.7	12.6	-1.5	......	....	....*.
	0	-33	-15	16	-34	-8.0	-5.9	13.9	......	....	....*.
	0	34	-15	19	30	10.1	-12.4	1.7	......	....	....*.
	0	51	22	-10	39	8.1	5.9	-13.9	......	....	....*.
	0	-37	14	-20	-31	-9.7	12.2	-1.8	......	....	....*.
	0	-62	-25	7	-44	-8.0	-5.9	13.8	......	....	....*.
	0	43	-12	22	32	9.1	-12.1	1.9	......	....	....*.
	0	104	40	6	58	7.4	6.1	-13.6	......	....	....*.
	0	-55	4	-25	-35	-7.5	11.6	-2.4	......	....	....*.
	0	-196	-76	-34	-87	-6.0	-6.6	13.2	L.....	....	....*.
Rows	0	22	-10	12	20	5.0	-10.8	3.2	L.....	....	....*.
15 & 16	0	305	115	68	122	4.5	7.0	-12.7	M..1P.	*.*.*..	....*.
	0	34	26	7	0	-2.9	10.1	-3.9	M..1P.	*.*.*..	....*.
	0	-353	-126	-86	-142	-4.1	-7.2	12.6	M..1P.	*.*.*..	....*.
	0	-53	-33	-13	-7	2.2	-9.9	4.1	M..1P.	*.*.*..	....*.
	0	352	120	88	143	4.0	7.2	-12.6	M.....	*......	....*.
	0	61	34	16	11	-2.3	9.9	-4.1	M..3..	*.*....	....*.
	0	-356	-120	-91	-146	-3.6	-7.3	12.4	M..3..	*.*....	....*.
	0	-75	-37	-21	-17	2.3	-9.9	4.1	M..3..	*.*....	....*.
Rows	0	362	122	93	148	3.2	7.5	-12.3	M..3..	*.*....	....*.
24 & 25	0	82	38	24	20	-2.1	9.8	-4.1	M..3..	*.*....	....*.
	0	-363	-122	-94	-147	-3.1	-7.5	12.3	M..3..	*.*....	....*.
	0	-79	-36	-24	-20	2.1	-9.8	4.1	M..3..	*.*....	....*.
	0	363	122	94	147	3.1	7.5	-12.3	M..3..	*.*....	....*.
	0	78	35	24	20	-2.1	9.8	-4.1	M..3..	*.*....	....*.
	0	-363	-122	-94	-146	-3.1	-7.4	12.3	M..3..	*.*....	......
	0	-74	-34	-22	-18	2.1	-9.7	4.1	M..3..	*.*....	......
	0	356	120	92	145	3.0	7.2	-12.5	M..3..	*.*....	......
	0	59	29	16	14	-2.2	9.7	-4.1	M..3..	*.*....	......
	0	-278	-94	-71	-113	-2.2	-5.9	14.2	M..3..	*.*....	......
	0	-36	-18	-9	-9	1.3	-11.3	1.8	M..3..	*.*....	......
	0	116	40	30	46	1.2	4.7	-15.4	...3..	*.*....	......

The Zone 1 directional element is set to detect faults in the forward direction, the Zone 3 element is set for the reverse direction. A forward A-phase to ground fault occurred on the protected line. The relay initially senses a forward fault, then switches direction and detects a reverse fault. There were no other operations on the system. Why did this happen and what can we learn from this event?

First, we examine the directional torque equations. At fault inception (rows 15 & 16), the negative- and zero-sequence elements pick up in the forward direction (positive torque values). The relay correctly sensed a forward fault and produced a trip output to the breaker.

Rows 15 & 16: 32QT = 1.48 (forward fault)
32VT = 69.44 (forward fault)

However, since the generator is out of service, there is no positive-sequence or negative-sequence source behind the relay. Consequently, the V_2 produced by the fault causes only a small amount of I_2 to flow (limited primarily by the high impedance of motor loads on the feeder). Since the only source is the back EMF created by the motors on the feeder, it is too weak to provide an adequate directional source. It is simply good fortune that the directional element happened to see forward initially.

About one and one-half cycles later, the negative-sequence element reverses due to inadequate polarizing quantities. The zero-sequence element solidly indicated a forward fault.

Rows 24 & 25: 32QT = -4.23 (reverse fault)
32VT =122.17 (forward fault)

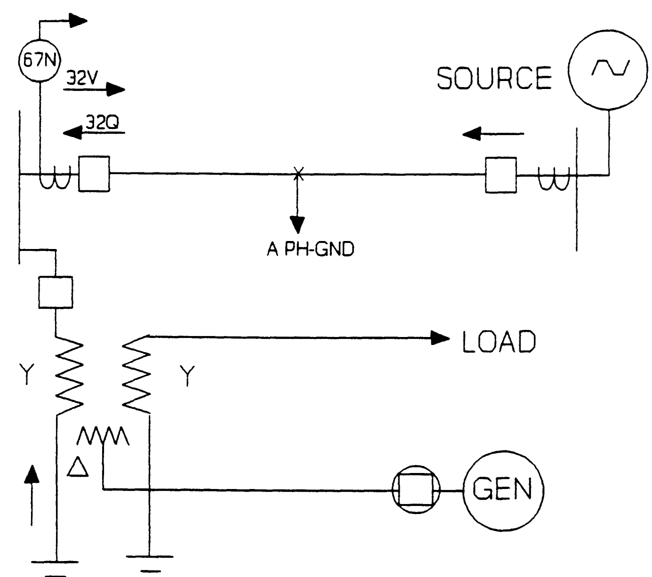

Figure 21: Example III - Fault After 32Q Directional Element Reverses

The V_0 produced by the fault forces an I_0 to flow, limited only by the leakage reactance of the transformer and the line impedance. Consequently, zero-sequence voltage polarization is a much better choice for this application. Note that V_0 polarization is reliable with or without the generator in service.

Using VIEW, we examine the event report for rows 15 & 16, where the fault is sensed in the forward direction and again for rows 24 & 25, where the fault is sensed in the reverse direction.

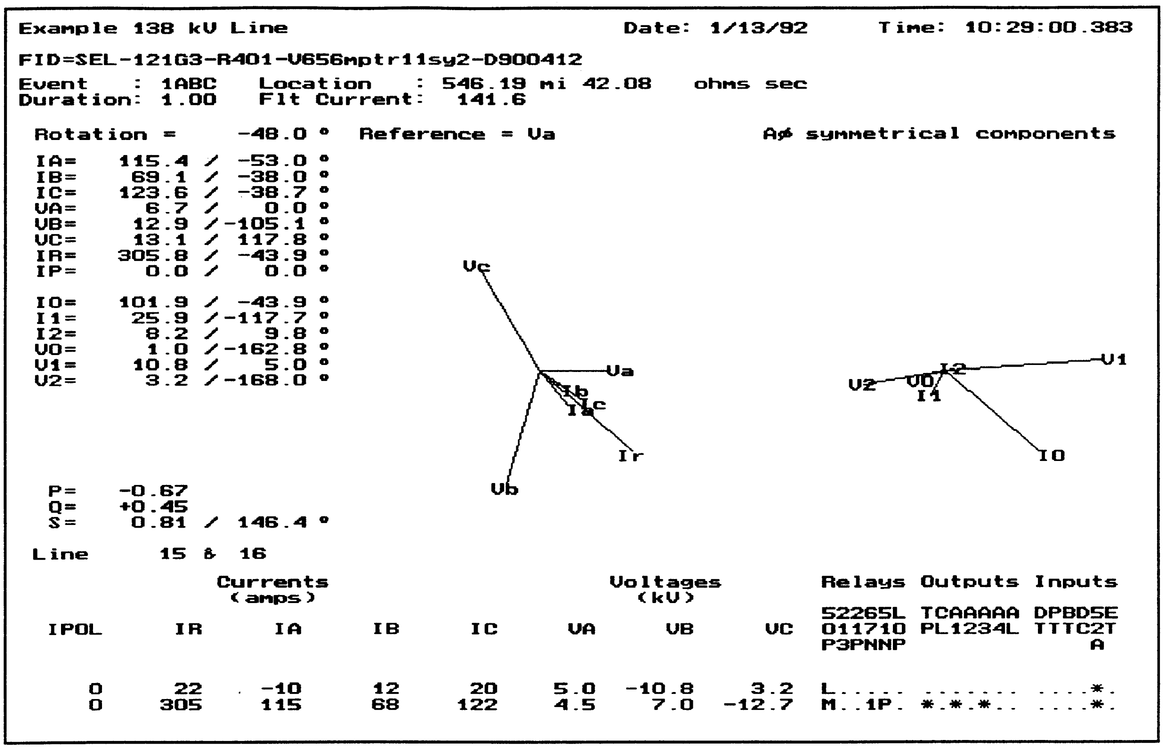

Figure 22: Phasors for Rows 15 & 16

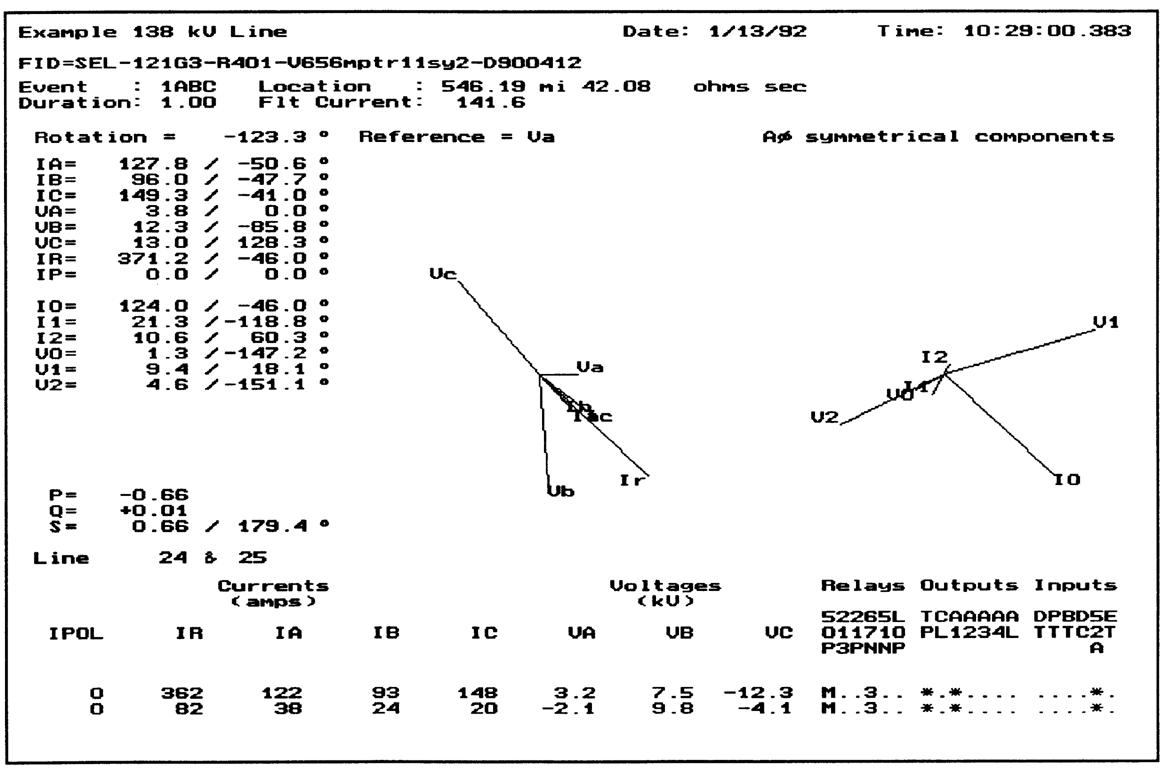

Figure 23: Phasors for Rows 24 & 25

Using the oscillographic plot from VIEW, the three-phase voltages and currents are plotted, with the trip condition marked by the vertical line.

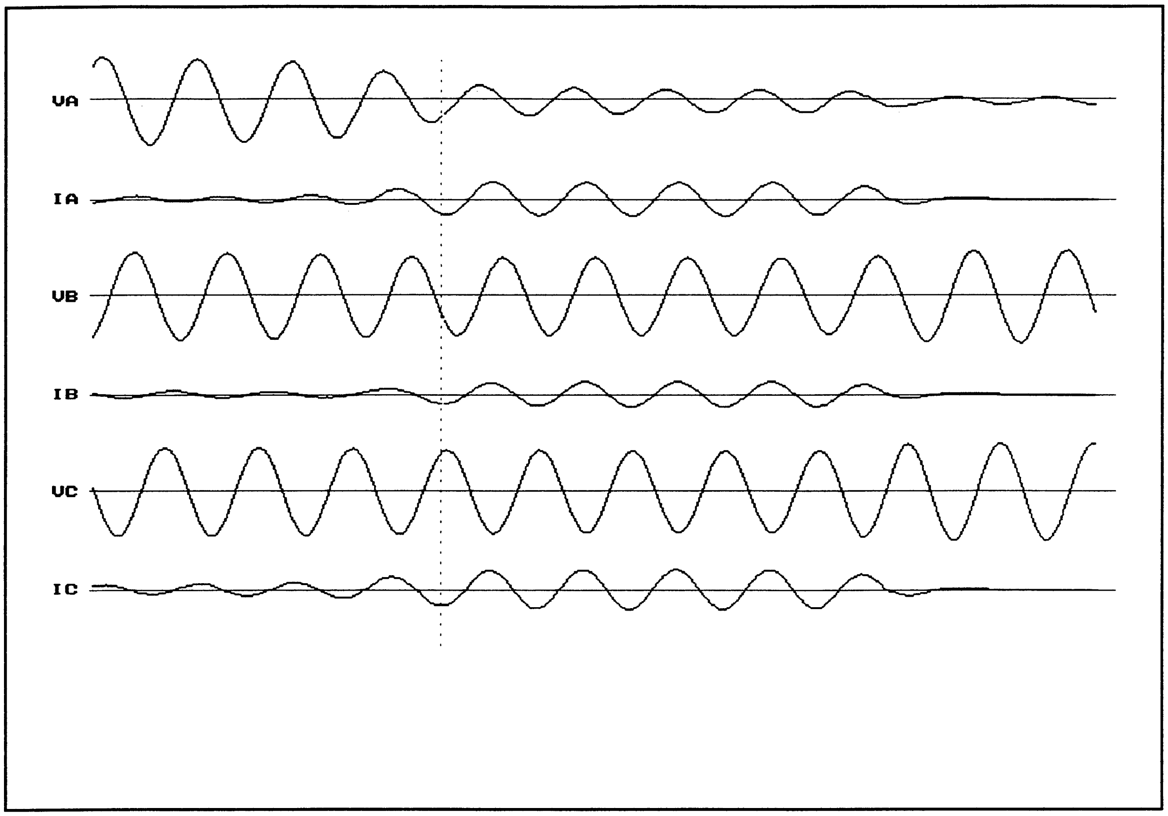

Figure 24: Oscillograph Plot for Event Report

In this example, negative-sequence polarization is a poor choice since it is unreliable when the generator is out of service.

Lessons learned:

1. Be aware of operating conditions which can affect the integrity of the polarizing source.

2. Select the polarizing method that has adequate operating quantities for all system conditions. In this case, select 32V (zero-sequence voltage polarization) over 32Q (negative-sequence polarization).

CONCLUSIONS

Directional elements are polarized by different methods. As long as the source is adequate, negative-sequence polarization is preferred for most applications.

Field data extracted from event reports are a helpful resource in determining directional element performance. The data, when analyzed mathematically and graphically, provides excellent information to Relay Engineers. This enables engineers to better evaluate directional element performance and improves their ability to select the best polarization method.

REFERENCES

1. J. Lewis Blackburn, "Protective Relaying, Principles and Applications", Marcel Dekker, 1987.

2. E.O. Schweitzer III, Jeff Roberts, "Distance Relay Element Design", 19th Annual Western Protective Relay Conference, Spokane, WA, October 20-22, 1992.

3. Jeff Roberts, Edmund O. Schweitzer III, "Analysis of Event Reports", 16th Annual Western Protective Relay Conference, Spokane, WA, October 24-26, 1989.

4. VIEW Program, Rick Bart, Montana Power Co.

5. William M. Strang, "Polarizing Sources for Directional Relaying", 16th Annual Western Protective Relaying Conference, October 24-26, 1989.

APPENDIX I

March 5, 1993
Ground Directional Element Calculation Sheet

$a := -0.5 + i \cdot 0.866$

$deg := \frac{\pi}{180}$

Example 138 kV Line
7-10-92 16:26:02.729
Rows 1 & 2

Relay Settings

$R1 := 12.66$	$X1 := 32.17$	$PTR \equiv 1200$
$Z\% = 143$	$MTA := 75 \cdot deg$	$CTR \equiv 400$

Enter event report voltage sample, $Vx := x + i\,Y$.

$Vcp := 17.3 + i \cdot 75.9$	$\lvert Vcp \rvert = 77.847$	$arg(Vcp) = 77.16 \cdot deg$
$Va := 49 + i \cdot -60.3$	$\lvert Va \rvert = 77.699$	$arg(Va) = -50.903 \cdot deg$
$Vb := -78.7 + i \cdot -15.6$	$\lvert Vb \rvert = 80.231$	$arg(Vb) = -168.788 \cdot deg$
$Vc := 17.3 + i \cdot 75.9$	$\lvert Vc \rvert = 77.847$	$arg(Vc) = 77.16 \cdot deg$
$Ia := 76 + i \cdot -107$	$\lvert Ia \rvert = 131.244$	$arg(Ia) = -54.615 \cdot deg$
$Ib := -1145 + i \cdot 1743$	$\lvert Ib \rvert = 2.085 \cdot 10^3$	$arg(Ib) = 123.301 \cdot deg$
$Ic := 120 + i \cdot -245$	$\lvert Ic \rvert = 272.809$	$arg(Ic) = -63.905 \cdot deg$
$Ir := (Ia + Ib + Ic)$	$\lvert Ir \rvert = 1.684 \cdot 10^3$	$arg(Ir) = 124.303 \cdot deg$

$$Va0 := \frac{1}{3}\cdot\left(Va\cdot\frac{1000}{PTR}+Vb\cdot\frac{1000}{PTR}+Vc\cdot\frac{1000}{PTR}\right)$$ $|Va0| = 3.444$ Zero-seq. Volts sec.

$$Va2 := \frac{1}{3}\cdot\left(Va\cdot\frac{1000}{PTR}+a^2\cdot Vb\cdot\frac{1000}{PTR}+a\cdot Vc\cdot\frac{1000}{PTR}\right)$$ $|Va2| = 2.036$ Neg.-seq. Volts sec.

$$Va1 := \frac{1}{3}\cdot\left(Va\cdot\frac{1000}{PTR}+a\cdot Vb\cdot\frac{1000}{PTR}+a^2\cdot Vc\cdot\frac{1000}{PTR}\right)$$ $|Va1| = 65.377$ Pos.-seq. Volts sec.

$$Ia0 := \frac{1}{3}\cdot\left(\frac{Ia}{CTR}+\frac{Ib}{CTR}+\frac{Ic}{CTR}\right)$$ $|Ia0| = 1.403$ Zero-seq. Amps sec.

$$Ia1 := \frac{1}{3}\cdot\left(\frac{Ia}{CTR}+a\cdot\frac{Ib}{CTR}+a^2\cdot\frac{Ic}{CTR}\right)$$ $|Ia1| = 1.881$ Pos.-seq. Amps sec.

$$Ia2 := \frac{1}{3}\cdot\left(\frac{Ia}{CTR}+a^2\cdot\frac{Ib}{CTR}+a\cdot\frac{Ic}{CTR}\right)$$ $|Ia2| = 1.935$ Neg.-seq. Amps sec.

$arg(Va0) = 180\cdot deg$
$arg(Va1) = -47.521\cdot deg$
$arg(Va2) = -86.421\cdot deg$

$arg(Ia0) = 124.303\cdot deg$
$arg(Ia1) = -120.141\cdot deg$
$arg(Ia2) = 5.921\cdot deg$

$$Z1L := (R1 + i\cdot X1)\cdot\frac{CTR}{PTR}$$

$$QT := |Va2|\cdot|Ia2|\cdot\cos(\arg(-Va2) - \arg(Ia2) - (MTA))$$

$$Z32 := Re\left(Va2\cdot\overline{(Ia2\cdot Z1L)}\right)$$

$$vt := |Va0|\cdot\left(\frac{|Ir|}{CTR}\right)\cdot\cos(\arg(-Va0) - \arg(Ir) - (MTA))$$

$Z32 = -42.895$

$QT = 3.844$ Negative-sequence polarized directional element torque
$VT = -13.685$ Zero-sequence voltage polarized directional element torque

Positive values of torque indicate a forward fault direction.
Negative values of torque indicate a reverse fault direction.