Diagnosis of Protection Misoperations Due to Mutually-Coupled Transmission Lines

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I. Abstract

A degree of mutual coupling exists between transmission lines that are routed in parallel for a substantial distance. For these configurations, a fault on one line can induce a large zero-sequence current in the unfaulted parallel line. This induced current may impact zero-sequence line impedance and zero-sequence polarizing quantities. Consequently, it can lead to inappropriate tripping of the unfaulted line. These events may be incorrectly diagnosed as proper operations since mutual coupling can result in tripping at both ends of the unfaulted line.

This paper will present a high-level summary of mutual coupling properties. In addition, it will address an actual case where a carrier blocking scheme for an unfaulted line failed to operate properly due to mutual coupling. For this event, the observed impact on phase currents, ground current, and zero-sequence polarizing quantities on the unfaulted line is presented. The benefit of using negative-sequence polarizing quantities in applications where mutual coupling is of concern is also addressed.

II. Introduction

Although there have been numerous papers, articles, and references that have attempted to address the theory of mutual coupling between parallel transmission lines, this phenomenon is not well understood in the electric power industry. As such, mutual-coupling events may be incorrectly diagnosed as either unexplained operations or simultaneous faults. With the enforcement of PRC-004, it is imperative that power utilities accurately diagnose the cause of each misoperation that impacts the Bulk Electric System.

This paper avoids the theoretical derivation of the mutual-coupling phenomenon and focuses on a real-world scenario. However, basic principles and properties of mutual coupling are restated to facilitate understanding of the real-world scenario presented.

III. Properties of Mutual Coupling

Basic properties of mutual coupling are summarized below:

1. Mutual coupling can occur when two or more transmission lines are routed in parallel for a significant distance due to the magnetic fields between the lines. These parallel lines may share the same structure or right-of-way. The magnetic coupling results in a zero-sequence mutual impedance between the lines, denoted as Z_{OM} in Figure 1 (References 2 and 5).

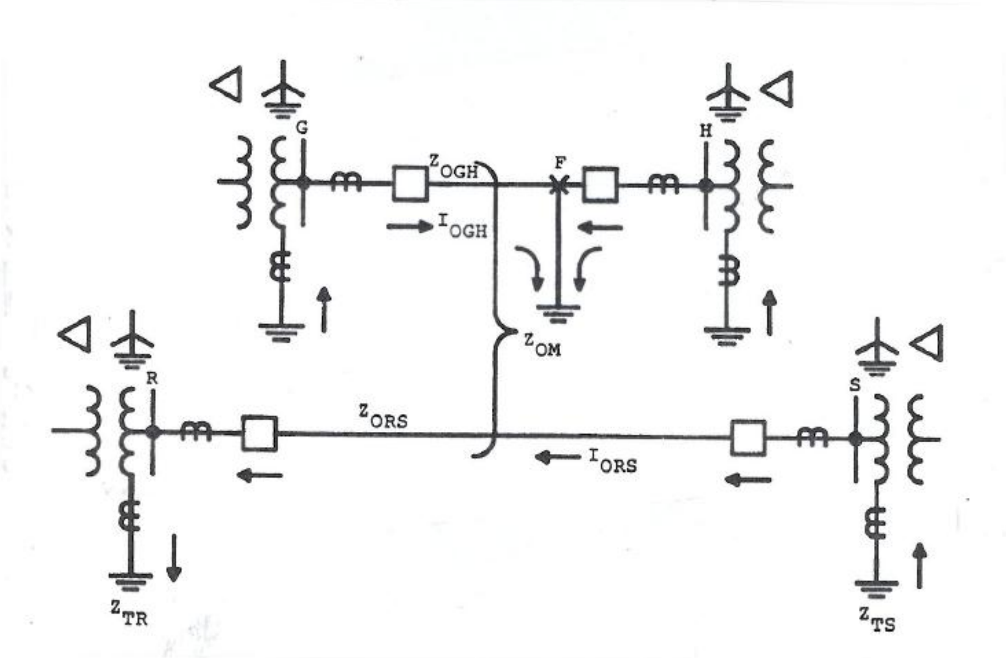


Figure 1
Excerpt from Reference 2

2. The combination of the line's self impedance and the mutual impedance results in an apparent line impedance. The apparent line impedance is a function of the direction and magnitude of the currents in each line. Apparent impedance increases when the zero-sequence currents in each line are in the same direction and decreases when the zero-sequence currents in each line are in the opposite direction. Consequently, mutual coupling can cause overreaching or under reaching of ground impedance relays (References 2 and 5).
3. During a mutual-coupling event, a zero-sequence voltage will be induced on the healthy line when a line-to-ground fault occurs on the other line. This induced voltage forces a zero-sequence current to flow in the healthy line (Reference 3).
4. The magnitude of induced zero-sequence current on the healthy line is a function of the proximity of the healthy conductor to the faulted conductor, the system voltage levels involved, the distance the lines are coupled, the magnitude of the fault, and the location of the fault (Reference 4).
5. The mutual impedance can be as high as 70 percent of a line's zero-sequence self impedance. Therefore, it can have a substantial impact on the healthy line's zero-sequence apparent impedance. Mutual coupling impacts the positive-sequence and negative-sequence impedances by less than seven percent. Hence, the mutual coupling phenomenon is primarily a zero-sequence event. (References 2, 3, and 4)
6. The induced zero-sequence current on the healthy line, if large enough, can cause a reversal of the zero-sequence polarizing current. CT orientation is typically chosen so that polarizing current flows up from ground in the grounded neutral for all faults (both in front or behind the bus) as shown in Figure 1 for the faulted line. The polarizing current serves as a reference for ground directional relays. Ground faults flowing into the line (in

phase with the polarizing current) are typically defined as forward faults. Ground currents flowing into the bus (180 degrees out of phase with the polarizing current) are defined as reverse faults. The induced current may cause the polarizing current to flow down to ground in the grounded neutral at one terminal as shown for terminal R in Figure 1. The reversal of the reference quantity will cause the relay directional unit to inappropriately operate as current in and down the neutral is equivalent to up and out of the line.

If the zero-sequence voltage induced on the healthy line is large enough, it may cause a phase reversal of the $3V_0$ quantity at the same terminal. As this quantity may be used to provide reference for ground directional relays, it may also cause a ground directional unit to determine the ground current to be in the wrong direction (References 1, 2, and 3).

Since the electrical connection in the power system is typically more dominate than the mutual coupling effect, zero-sequence polarizing quantity reversals are most likely to occur where mutually coupled lines are in two electrically isolated networks (Reference 1).

IV. Diagnosis of a Mutual-Coupling Event

If a mutual coupling condition is suspected on a line, addressing the following questions can aid in determining if mutual coupling was involved:

1. Did the subject line operate simultaneously with a second line that was known to be faulted? Is the line with the suspect operation routed in parallel with the line known to have faulted? Is it clear that the line operation was not caused by carrier overreach?
2. Was there a valid line-to-ground fault on the suspect line?
   a. Was an actual fault location confirmed in the field for the suspect line?
   b. Was the voltage depressed on the phase believed to be involved in the fault during the event?
   c. Did the current of the apparent faulted phase flow into the line from both terminals?
   d. Did the residual current at both terminals flow into the line or did the residual current flow through the line (i.e., into the line at one terminal and out of the line at the other terminal)?
3. Was there evidence that the fault was cleared by external breakers (i.e., the magnitude of currents returned to load values before the line breakers tripped)?
4. Was the phase relationship between the line ground current and the polarizing quantities (current polarizing, $3V_0$, or both) shifted 180 degrees from expected? The knowledge of the ground current direction at both ends is critical in addressing this step. Determining ground current direction is relatively easy where digital relays have been deployed provided they captured the event. However, for electromechanical schemes monitored by a Digital Fault Recorder (DFR), this may be more difficult. Experience has shown that DFR CT shunts monitoring residual currents are often installed incorrectly and reflect a current that is 180 degrees out-of-phase with the actual flow of ground current.

   For a valid line-to-ground fault, the residual current will be in phase with the line current involved in the fault. The same is true during a mutual coupling event. Typically, the current of the healthy phase closest to the faulted phase of the other line will be much larger in magnitude than the currents in the other two phases of the healthy line. This current will be nearly in phase with the residual current so that it appears as a line-to-ground fault. One method to determine correct direction of residual current in electromechanical schemes is to confirm that the phase currents recorded at both terminals agree closely in magnitude and direction. Once the magnitudes and directions of these lines have been established, vector addition can be performed to obtain the residual current and its direction since $3I_0$ is the vector sum of the three phase currents.

V. Examination of an Actual Mutual-Coupling Event

Analysis of a real-time mutual coupling event is presented below.

Event Description:
On Friday, September 21, 2012, at 2:16 a.m., the Durham – Falls 230kV line locked out at both ends to an A-G fault when a lightning arrester failed at a customer tap. At the same time the Method – DPC East Durham 230kV line, which crosses over the Durham – Falls 230kV line and shares the same right-of-way on separate structures, operated at both ends to directional ground carrier. The Method – DPC East Durham 230kV line is 21.9 miles in length. This line shares the same corridor as the Durham – Falls 230kV line for 2.7 miles, or approximately 12% of its total line length.

Figure 2 shows the power system configuration for this example. Initial prefault power flow was from the DPC East Durham terminal toward the Method terminal.

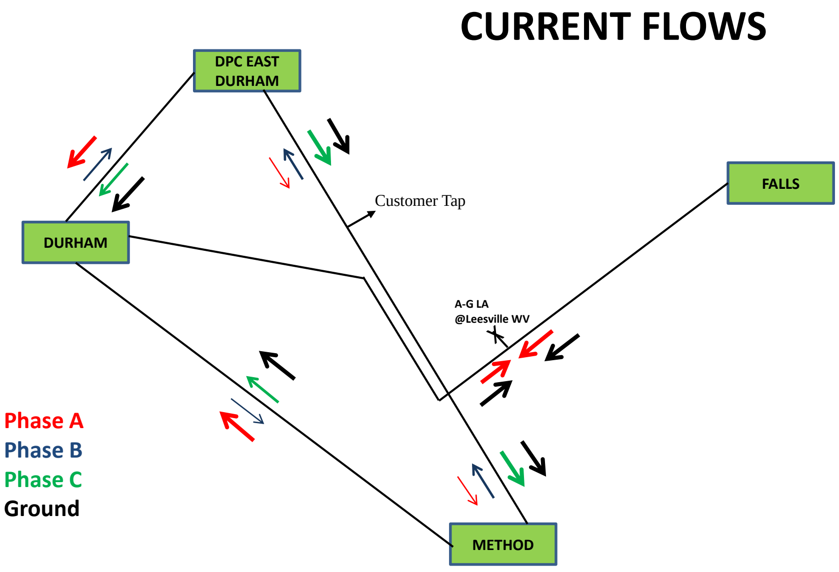


Figure 2

As expected for the A-G fault on the Durham – Falls 230kV line, DFR data indicated that I_A (denoted by red arrows) and I_G (denoted by black arrows), flowed toward the fault from both terminals. At the same point in time, a large magnitude of I_C (denoted by green arrows) and I_G flowed from the DPC East Durham terminal and into the Method terminal. During the fault, I_B (denoted by blue arrows) reversed direction.

Figure 3 shows the physical orientation of the unfaulted line with respect to the faulted line in the area where the two lines are routed in parallel. Since the degree of mutual coupling is a function of the physical separation between the conductors involved, it would be expected that phase C of the healthy line would be most impacted and that phase A of the healthy line would be least impacted. As indicated by the size of the arrows in Figure 2, this was the case.

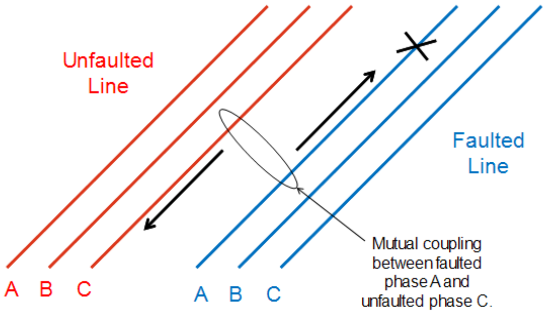
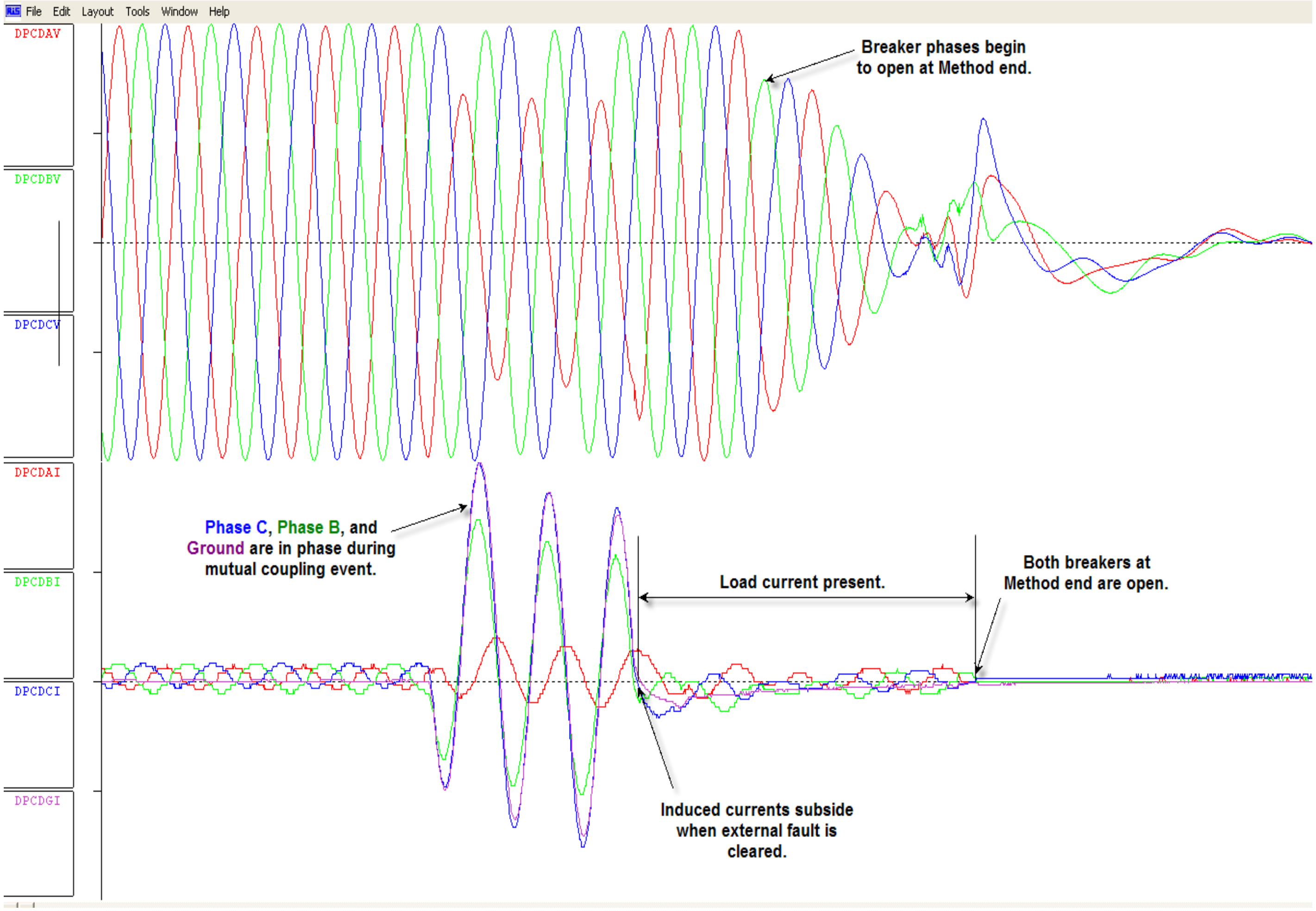


Figure 3
Orientation of Conductors

Figure 4 shows DFR data recorded at the Method 230kV Substation during the event. Several noteworthy observations can be made from this DFR screenshot including:

1. The induced currents were present for three cycles.
2. Load current was present for at least two cycles after the large current subsided. This indicated the fault was cleared by breakers external to the line.
3. I_C and the residual current were in phase and very near the same magnitude. I_B was nearly in phase with I_C and the residual current but smaller in magnitude. I_A was much smaller in magnitude and lagged the other currents by approximately 80 degrees. The magnitude and phase relationship of the currents were consistent with their physical proximity to the faulted phase.



Breaker phases begin to open at Method end.

Phase C, Phase B, and Ground are in phase during mutual coupling event.

Load current present.

Both breakers at Method end are open.

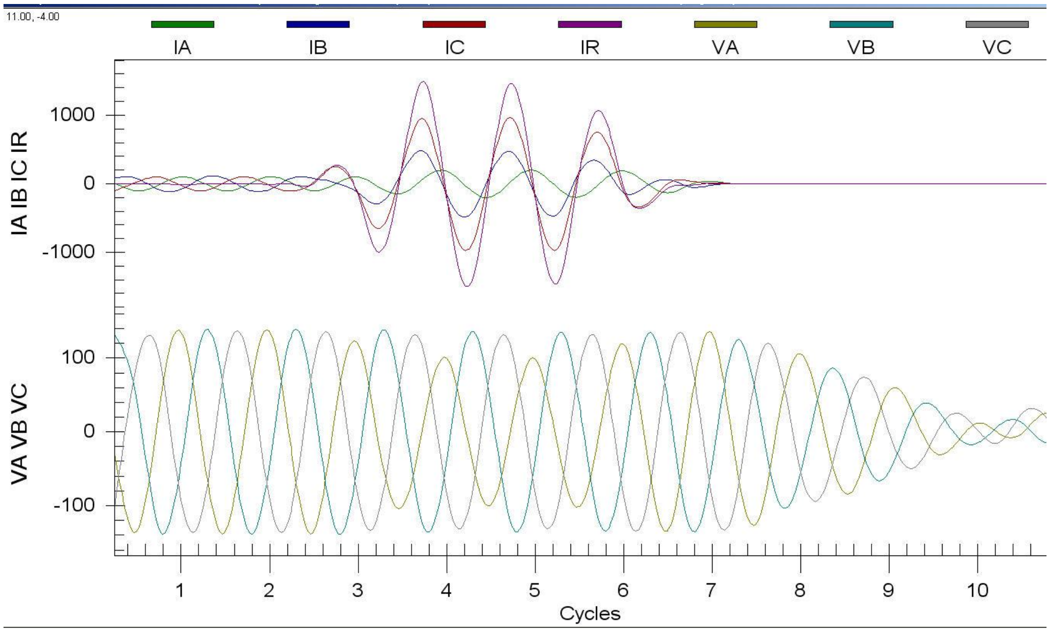
Induced currents subside when external fault is cleared.

Figure 4
DPC East Durham Terminal at Method 230kV Substation

4. I_B experienced a current reversal during the event.
5. V_C and V_B were not significantly depressed during the event as would be expected given the increased magnitudes of I_B and I_C. Rather, V_A was substantially depressed due to the phase A-to-ground fault on the other line. As shown in Figure 2, the Method Bus is electrically connected to the faulted line through the Durham 230kV Bus.

Figure 5 shows event data from a digital relay located at the DPC East Durham terminal. The following observations can be made:

1. The induced currents were present for three cycles, same as at the Method end.
2. As noted with the Method terminal, I_C and the residual current are in phase and close in magnitude. I_B is nearly in phase with I_C and the residual current, but smaller in magnitude. I_A is much smaller in magnitude and lags the other currents by approximately 80 degrees.



Method Terminal at DPC East Durham 230kV Substation
Figure 5

3. I_B experienced the same current reversal during the event as experienced on the Method end.
4. V_B and V_C did not experience significant depressions during the event as expected given the large magnitudes of I_B and I_C. V_A experienced a significant depression during the event due to the large I_A on the faulted Durham-Falls 230kV line. As shown in Figure 2, the DPC East Durham bus is electrically connected to the faulted line through the Durham 230kV Bus.

Mutual Coupling Impact on Polarizing Quantities

A digital relay is utilized at the DPC East Durham terminal to provide the carrier block function. This relay, which utilizes a negative-sequence impedance algorithm derived from V_2 and I_2 to determine direction, correctly determined the ground current as being in the forward direction.

A General Electric Type CLPG relay is utilized as the carrier ground relay at the Method terminal. It should be noted that utilization of electromechanical relays at one terminal and digital relays at the other terminal is not a recommended practice for carrier blocking schemes (Reference 3). The CLPG relay uses both current polarization derived from the tertiary of an autotransformer bank and voltage polarization derived from three grounded-wye primary to broken-delta secondary bus PTs.

Unfortunately, the DFR channel monitoring the polarizing current was not functional at the time of this event. Consequently, the relationship of line residual current to polarizing current is not known. Figure 6 shows the relationship between $-3V_0$ and $3I_0$.

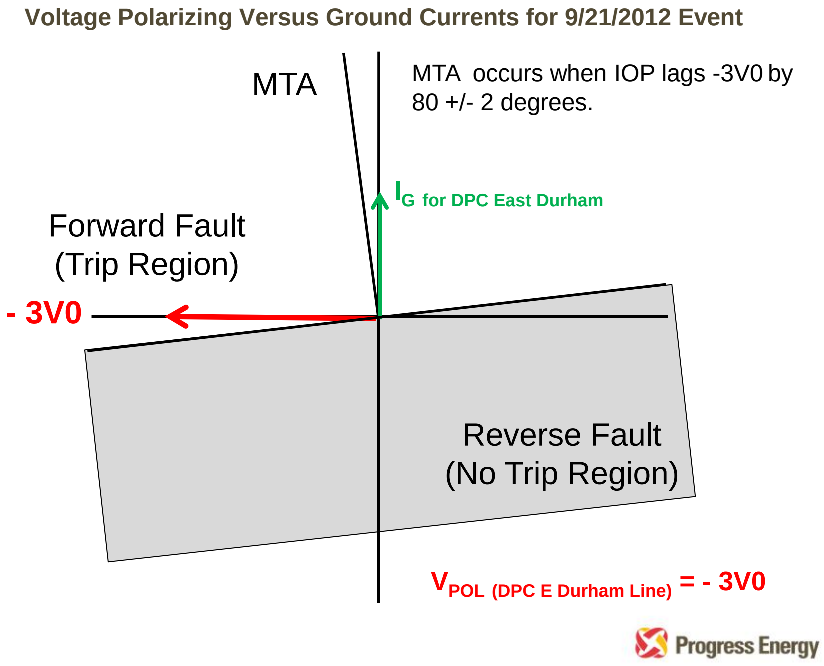


Figure 6
Polarizing for DPC East Durham Terminal at Method 230kV Substation

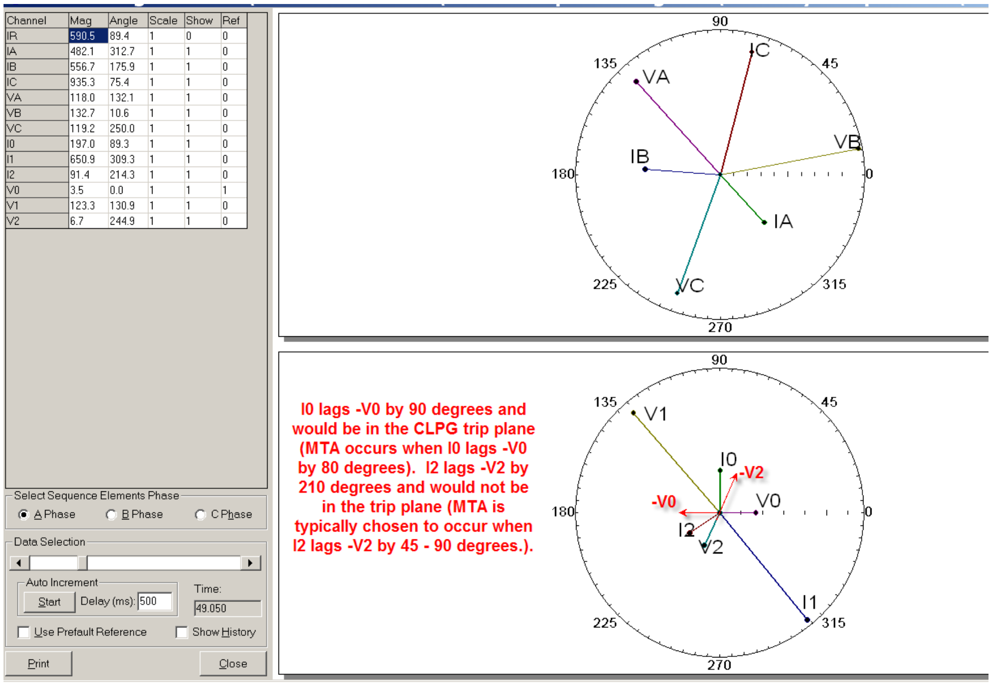
Figure 6 shows that the residual line current lagged $-3V_0$ by approximately 90 degrees. Since Maximum Torque Angle (MTA) for the CLPG relay occurs when $3I_0$ lags $-3V_0$ by 80 degrees, the relay determined that the fault was in the forward direction. This was an incorrect determination by the relay since it has already been established that the ground current was flowing in the reverse direction (i.e., toward Method).

Another zero-sequence relay at the Method Substation, a General Electric Type JBCG, provides directional ground instantaneous and directional ground backup overcurrent protection for the line. This relay did not operate because the ground current was below the instantaneous setting and the duration of the event was less than the backup trip delay.

VI. Potential Solutions/Corrective Actions

Implementation of the following corrective actions should be considered to minimize the possibility of protection misoperations caused by mutual coupling events.

1. Perform configuration review of transmission lines that have the potential to experience mutual coupling and revise fault impedance model - The configuration of transmission lines should be reviewed to determine where and for what distance the lines are routed in parallel. Mutual impedances should be calculated for lines that are routed in parallel (e.g., on same structure or in common right-of-way) for a significant percentage of their total line lengths. A criterion of 10% or more is suggested as a starting point. The fault impedance model should be revised to reflect the mutual impedances between the subject lines. Per Reference 1, mutual impedances should not be distributed evenly along the line. Rather, the mutual impedance should be modeled where the line sections are in parallel. This may necessitate dividing the line into several segments.
2. Review and revise relay settings - The settings of relays that utilize zero-sequence quantities (ground distance relays and directional ground relays) should be reviewed using the revised fault model data and new settings implemented as appropriate.
3. Replace relays that utilize zero-sequence polarizing with digital relays that utilize negative-sequence elements to determine direction – As described previously, mutual coupling events can significantly impact the relationship between the induced ground current and the zero-sequence polarizing quantities. The phase reversal of the zero-sequence polarizing quantities can lead to misoperations in carrier blocking schemes. An effective solution is to replace the zero-sequence polarized relays with digital relays that utilize negative-sequence elements to establish direction (References 1 and 2). As described earlier, negative-sequence quantities are relatively insensitive to mutual coupling events. Figure 7 shows data recorded by a digital relay located at the misoperating terminal of a different line during a mutual coupling event in which the primary carrier blocking scheme misoperated. The digital relay provides backup protection, and its event reporting was triggered by operation of the primary protection.



Channel	Mag	Angle	Scale	Show	Ref
IR	590.5	89.4	1	0	0
IA	482.1	312.7	1	1	0
IB	556.7	175.9	1	1	0
IC	935.3	75.4	1	1	0
VA	118.0	132.1	1	1	0
VB	132.7	10.6	1	1	0
VC	119.2	250.0	1	1	0
I0	197.0	89.3	1	1	0
I1	650.9	309.3	1	1	0
I2	91.4	214.3	1	1	0
V0	3.5	0.0	1	1	1
V1	123.3	130.9	1	1	0
V2	6.7	244.9	1	1	0

Select Sequence Elements Phase

● A Phase ○ B Phase ○ C Phase

Data Selection

Auto Increment

Delay (ms): 500

Time: 49.050

☐ Use Prefault Reference ☐ Show History

I0 lags -V0 by 90 degrees and would be in the CLPG trip plane (MTA occurs when I0 lags -V0 by 80 degrees). I2 lags -V2 by 210 degrees and would not be in the trip plane (MTA is typically chosen to occur when I2 lags -V2 by 45 - 90 degrees.).

Figure 7
Polarizing for the Misoperating Terminal During a Different Mutual Coupling Event

The carrier blocking scheme utilizes a GE CLPG relay, a zero-sequence polarized electromechanical relay. In this actual scenario, the ground current was flowing into the bus and should have been interpreted by the directional ground relay as being in the reverse direction. However, Figure 7 shows that the induced ground current ($3I_0$) was lagging the polarizing voltage ($-V_0$) by 90 degrees. The $-V_0$ phasor has been added for clarity. Since MTA for the CLPG relay occurs when the operating current lags $-3V_0$ by 80 degrees, the induced ground current would incorrectly appear as a forward fault to the relay. This figure also shows the relationship between I_2 and V_2 as captured by the digital relay. The $–V_2$ phasor has been added for clarity. This digital relay, which utilizes a negative-sequence impedance algorithm derived from V_2 and I_2 to determine direction, correctly determined the ground current as being in the reverse direction.

A traditional negative-sequence polarized relay would also have correctly determined the induced ground current to be in the reverse direction; the MTA for relays that utilize negative-sequence polarizing is typically chosen to occur when I_2 lags $–V_2$ by the line impedance angle (45-90 degrees, depending on the relay characteristic angle of the relay per Reference 3). As seen in Figure 7, I_2 lags $–V_2$ by 210 degrees and is roughly 180 degrees from the MTA. Consequently, a traditional negative-sequence polarized relay would not have misoperated for this mutual coupling event.

A directional element that utilizes a negative-sequence impedance algorithm is adequate for most operating conditions. However, the magnitude V_2 may be very small due to system configurations and not reliable. Consequently, digital relays provide the added advantage of adaptive ground directional elements. This feature allows the relay to automatically select the best polarizing method (zero-sequence or negative-sequence) for each ground fault.

VII. Biography

Terry Bowman, PE, graduated from North Carolina State University with a BS in Electrical Engineering. He has over twenty-nine years experience with a major power utility in a variety of roles including: load flow / short circuit analysis and protective device coordination for power plant electrical distribution systems, system engineer for power plant electrical distribution systems, transmission maintenance engineer, P&C Component and Compliance Engineer, and Technical Support Relay Lead Engineer. In his current role as Technical Support Relay Lead Engineer, Terry primarily provides analysis and follow up for protective system misoperations.

VIII. References

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