Polarizing Choices for Directional Ground Relays

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***Abstract* - Microprocessor relays have provided choices for ground polarizing quantities for years. Many protection engineers by default still apply zero sequence polarizing as their default tried and true selection. This paper is intended to demonstrate that in most cases negative sequence polarizing is a better choice. One of the disadvantages to zero sequence polarizing is that polarizing voltage reversals may occur in certain system configurations, which is not readily understood by many protection engineers. The paper will describe in simple language how zero sequence reversals can occur on both current and voltage, and how to easily identify systems where zero sequence voltage polarizing reversals can occur.**

The paper will describe the implementation and selection of ground polarizing for electromechanical and microprocessor relays, and provide an overview of the advantages and disadvantages of each basic ground polarizing type.

The paper will also point out differences in approach to torque control that may impact coordination and may not be readily apparent. Some microprocessor relays utilize a "block" setting on the ground overcurrent that leads the user to select a reverse polarizing element for torque control (e.g. !32QR logic instead of 32QF). A lessons learned, real life example, will be provided where a relay with a "block" setting, was set with a reverse directional element for torque control and this resulted in an unforeseen relay miscoordination. The lesson learned was to only utilize forward directional elements for ground polarizing, which is the traditional approach by protection engineers. This required going back to many in service relays to make a setting and logic modification (Block = !32QF, instead of 32QR).

I. Background

Pacific Gas and Electric Company (PG&E) is one of the largest combination electric and gas utilities in the United States. It serves about 15 million customers in northern and central California. Approximately 20,000 employees serve its 70,000 square mile territory. It is a vertically integrated utility with Generation, Transmission and Distribution assets. Its transmission system is made up of approximately 18,610 miles of 500, 230, 115, 70 and 60 kV lines. Total number of substations is approximately 800, with 40,000 relays. Approximately 50% percent of the relays are microprocessor type and 50% electromechanical type.

II. Introduction

Microprocessor relays have provided choices for ground polarizing quantities for years. Many protection engineers by default still apply zero sequence polarizing as their default tried and true selection. This paper is intended to demonstrate that in most cases negative sequence polarizing is a better choice.

Additionally this paper will point out differences in approach to torque control in microprocessor relays, and will demonstrate why forward directional elements should be used for torque controlling ground overcurrent elements instead of applying reverse directional elements to block operation for reverse faults.

III. Polarizing Choices

Traditionally, directional elements for electromechanical directional ground overcurrent relays were commonly polarized by either zero sequence voltage, zero sequence current from transformer neutral CT, or dual polarization that included both zero sequence voltage and current. Microprocessor relays also now offer negative sequence voltage polarizing as a standard selection. Negative sequence polarizing offers some distinct advantages. Following is an overview of the basic ground polarizing types.

A. Zero Sequence Voltage Polarizing

The most common polarizing choice traditionally for directional ground relays was zero sequence voltage, where the relay operated on zero sequence quantities, 3Io and 3Vo. These quantities were easily attainable and measurable, 3Io from the residual current connection, and 3Vo from broken-delta secondary potential connection. The 3Vo broken-delta potential was obtained by wiring a set of three PTs with wye-grounded primary and open delta on the secondary as shown in Figure 1. A dual winding PT or CCVT is typical with one secondary winding used for the phase relays, and the other used for the ground relays for the broken delta connection. If the PT or CCVT did not have a dual winding then an auxiliary potential transformer was used for creating the broken delta connection.

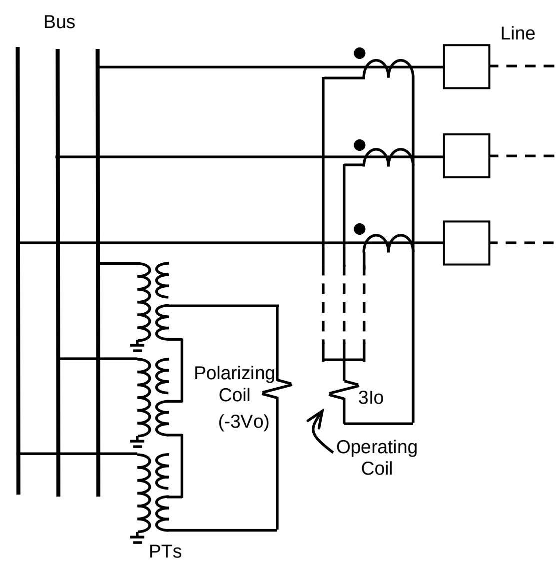

Fig. 1. Zero Sequence Voltage Polarizing

The 3Vo polarizing potential is generated by the collapse on the faulted phase potential. The resulting 3Vo potential ($V_A+V_B+V_C$) is 180 degrees out from the faulted phase potential. For the relay polarizing connection, -3Vo is used. This shifts the relay polarizing potential 180 degrees so it is back in phase with the faulted phase potential as shown in Figure 2.

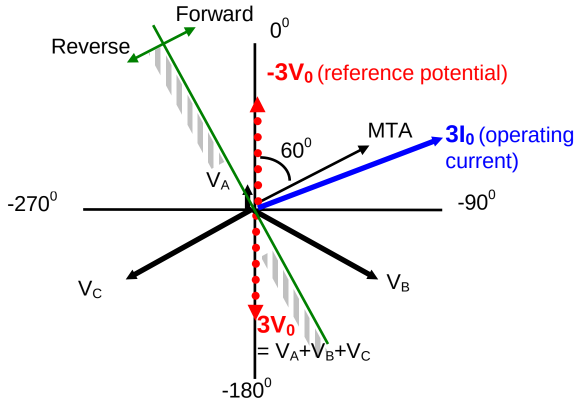

Fig. 2. Zero Sequence Voltage Polarizing Vectors for A-Ground Fault

Zero sequence polarizing generally proved sufficient, except for high duty busses, where there may be little 3Vo available for some end of line ground faults. The zero sequence voltage profile for a radial fault is shown in Figure 2 below. Note that Vo is maximum at the point of the fault and minimum at the reference bus. For high duty strong source busses, line-end fault conditions may not result in very much voltage collapse on the faulted phase at the station bus location, so the resulting 3Vo polarizing voltage could be minimal. For high duty busses with low source impedance the Station Bus approaches the Reference Bus in Figure 3.

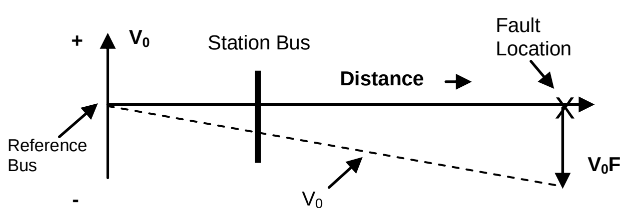

Fig. 3. Zero Sequence Voltage Profile for Radial Line Fault

B. Zero Sequence Current Polarizing

When 3Vo was not sufficient, ground current polarizing was normally the alternative for electromechanical relays. The directional ground element would use 3Io operating current from the line, and 3Io from one or more power transformer neutral CTs as the reference. These quantities were attainable and measurable, but required additional CT connections and were difficult to functionally test.

When current polarization was implemented, it was common to connect the neutral CTs in parallel from two or more transformers to provide the polarizing current. This provided a more reliable polarizing source in case one of the transformers was out for maintenance.

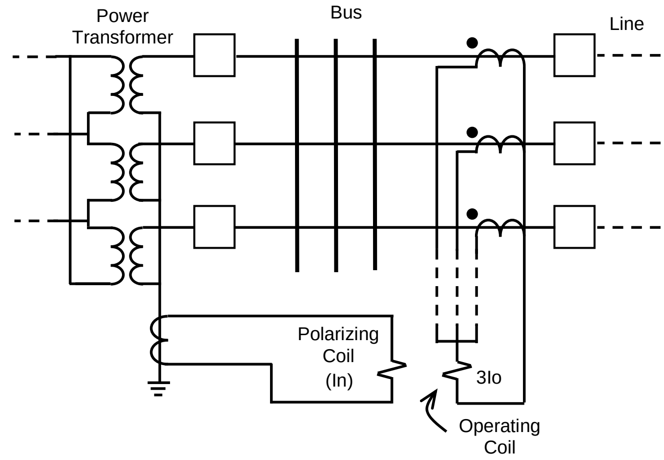

Fig. 4. Current Polarization from Transformer Neutral Current

Figure 4 shows a delta-wye power transformer providing the current polarization. A wye-delta-wye transformer may also be utilized as shown in Figure 5, in which case a polarizing CT is put in the grounded neutral of both wye windings. The neutral CTs are paralleled and CT ratios should be inversely proportional to the voltage ratings of the wye windings. This is done to prevent reversals of the polarizing current for faults on the low side of the transformer.

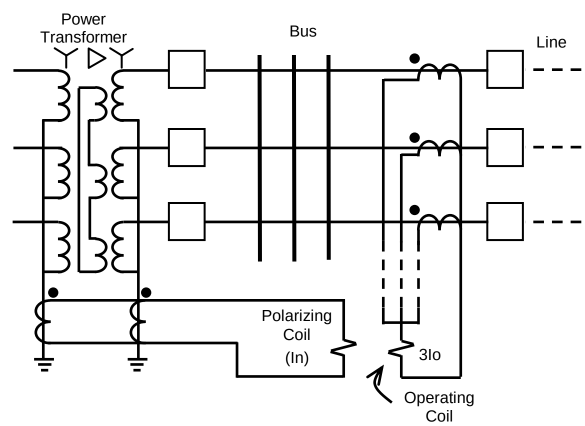

Fig. 5. Current Polarization from Wye-Delta-Wye Transformer

C. Dual Polarizing

Some electromechanical relays and also modern day microprocessor relays have the capability to polarize the directional ground relay with both zero sequence voltage and current. Dual polarization offers some distinct advantages. At times one type of polarizing may be unavailable if the equipment providing the polarizing source is disconnected from the system. Dual polarization allows the relays to remain in service as long as one polarizing source is available. Also, sometimes one polarizing quantity by itself may prove insufficient, but the combination of both current and voltage may provide strong polarization.

Dual polarization with both current and voltage is not as commonly applied today since microprocessor relays offer both zero sequence and negative sequence voltage polarizing, and one or the other usually proves adequate. This avoids the additional wiring and test complications associated with current polarizing.

D. Negative Sequence Voltage Polarizing

With the advent of microprocessor relays negative sequence quantities as well as zero sequence are calculated in the relay and are readily available for ground polarization. Modern microprocessor relays offer negative sequence ground polarizing as a selection, in addition to zero sequence voltage (3Io and 3Vo) and zero sequence current (3Io and In). Negative sequence polarizing has some advantages that provide merit for using it as the first choice for ground relay polarizing.

IV. Polarizing Selection

When selecting a polarizing quantity for directional ground overcurrent protection, either negative or zero sequence voltage polarizing can be applied reliably in most cases. As a first choice it is recommended to select negative sequence voltage polarizing. Fault studies should be used to verify the polarizing quantities are sufficient in either case. As an example, PG&E setting criteria requires 5 volts 3Vo or 2.5 volts V2 for acceptable polarizing voltage thresholds at the relay for in-section faults. The protection engineer can change the polarizing selection from negative sequence to zero sequence if it is a better choice for a particular application based on the fault study results.

Why Use Negative Sequence Ground Polarizing?

"Negative-sequence polarized directional elements have the following two major advantages when compared to zero-sequence voltage polarized directional elements:

1. Negative-sequence directional elements are insensitive to zero-sequence mutual coupling associated with parallel transmission line applications. They are suitable for isolated zero-sequence source systems.

2. If the bus behind the relay location is a strong zero-sequence source, the negative-sequence voltage available at the relay location is higher than the zero-sequence voltage." [1]

Additionally, negative-sequence impedances are the same as positive-sequence impedances (with the possible exception of impedances in generators), and they are more homogeneous (similar impedance angles) than the zero-sequence network impedances. The negative sequence is not affected by ground impedance or transformer grounding connections. As a result the network models for the negative sequence will be more accurate than the zero sequence, and there will be fewer errors in fault study calculations for end of line polarizing values.

Zero-sequence polarizing can be susceptible to incorrect directionality and possible relay system misoperation due to polarizing voltage reversals caused by mutually induced fault currents on parallel lines. The parallel lines normally have to be isolated for this to occur and the voltage reversal may happen as breakers open or due to line-end fault conditions. The induced zero sequence current in the isolated unfaulted line circulates through the line and ground. A zero sequence polarizing voltage reversal may occur at on end of the line where the zero sequence current flows down the transformer neutral instead of up. Usually polarizing reversals on the isolated non-faulted line will not cause coordination problems for non-pilot protection since the operating current is typically much lower on the isolated non-faulted line. However for pilot protection schemes using directional ground overcurrent elements for keying permissive or block signals, misoperation may occur on relays that use zero sequence voltage polarizing when a polarizing voltage reversal occurs.

Example – Zero Sequence Polarizing Reversal

The zero sequence polarizing reversal phenomenon is associated with mutually coupled lines that have isolated zero sequence sources. An example where this actually occurred in the PG&E system is shown in Figure 6. The 230kV system feeding startup power at Station C is isolated from the 500kV system where the generators interconnect. The nearest 500/230kV transformer is 79 miles away. However the 230kV lines and one of the 500kV lines share the same right of way for 5 miles and are mutually coupled. Ground faults on the 500kV line result in zero sequence polarizing reversals on the 230kV lines that can cause misoperation on relays that use zero sequence voltage polarizing. The 230kV lines used to have directional comparison blocking schemes with zero sequence polarized directional ground relays, and misoperations occurred due to zero sequence polarizing reversals. The relays have since been replaced with an unblocking (hybrid POTT) scheme utilizing negative sequence directional polarizing to remedy the misoperation problem.

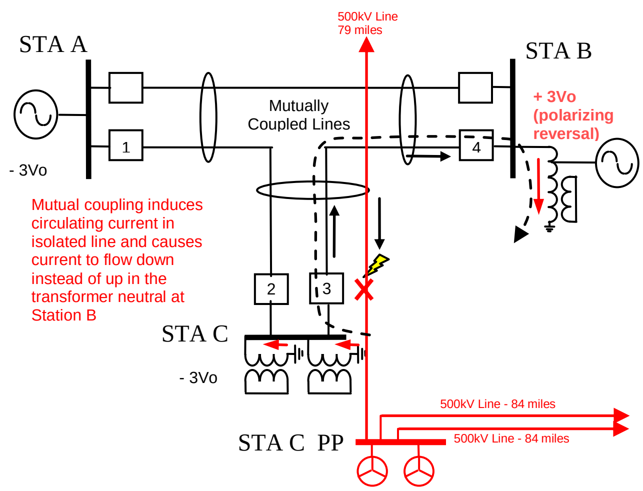

Fig. 6. Zero Sequence Polarizing Voltage Reversal Example 1

Lines that do not have isolated zero sequence sources may also become electrically isolated due to switching or line-end fault conditions. This may also lead to zero sequence polarizing reversals. The polarizing reversal example shown in Figure 7 is actually the same 230kV configuration as shown in Figure 6. This example demonstrates how lines that are mutually coupled but

[1] Jeff Roberts and Armando Guzmán, "Directional Element Design and Evaluation", page 15.

normally not isolated, make become isolated, and then become susceptible to zero sequence polarizing voltage reversals.

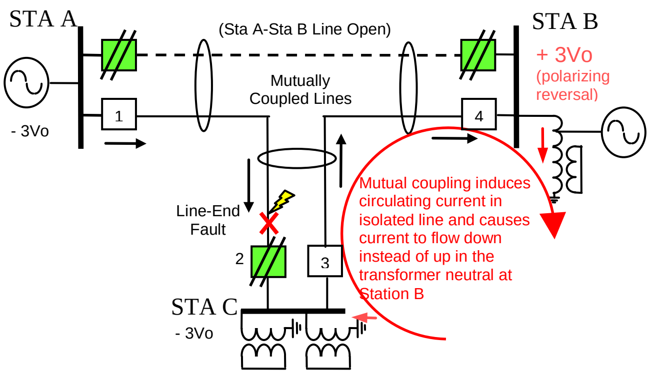

Fig. 7. Zero Sequence Polarizing Voltage Reversal Example 2

The polarizing reversal example shown in Figure 8 below demonstrates how Line 1 and Generator 1 could become isolated from Line 2 and the rest of the system. This would occur when CB 4 is operated normally open, and then a line-end fault occurs near CB 1. This creates a polarizing voltage reversal for the relays on CB 3.

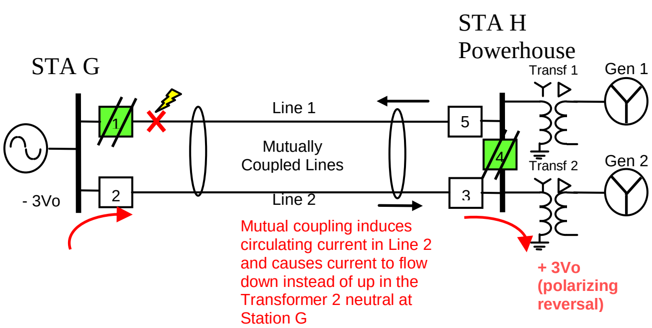

Fig. 8. Zero Sequence Polarizing Voltage Reversal Example 3

Substations with two feeds from separate sources in a loop in loop out configuration and their remote terminals, are particularly susceptible to zero sequence voltage reversals. Figure 9 shows an example system with a loop in loop out configuration where zero sequence voltage reversal may occur. A line-end fault on either line into the looped substation will isolate the two lines which may lead to a zero sequence voltage reversal.

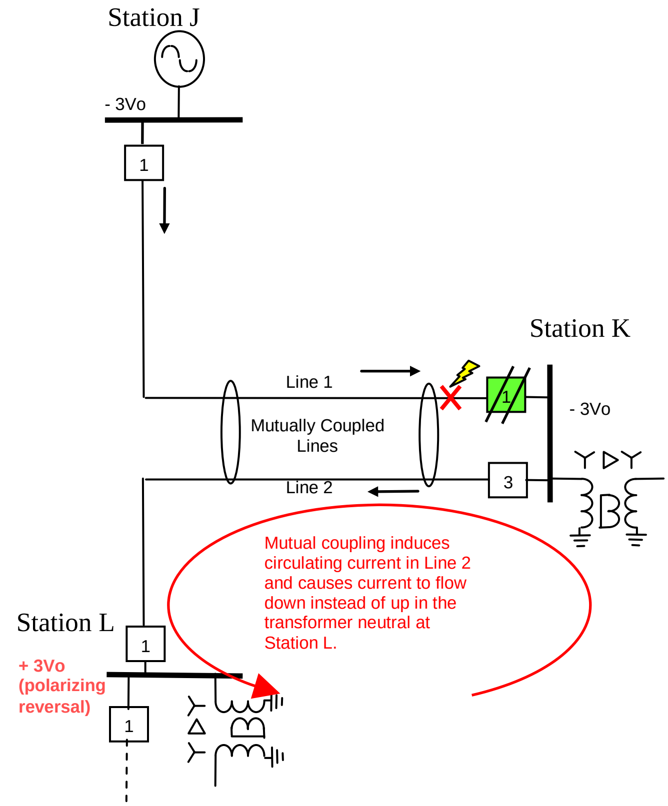

Fig. 9. Zero Sequence Polarizing Voltage Reversal Example 4

For the example in Figure 9 above, the current in the faulted line induces a circulating current in the isolated non-faulted line through mutual coupling. The circulating current flows through the non-faulted line and returns through ground between the two substations. At one of the substations the circulating current will flow down instead of up the transformer neutral. It is this current flowing down the transformer neutral that causes the polarity of the polarizing voltage to be reversed.

V. Microprocessor Relay Polarizing Torque Control Selection

Microprocessor relays offer the protection engineer flexibility in the selection of polarizing quantities, and also how to use the polarizing quantity to torque control the directional ground overcurrent element. Torque control can be done with either forward or reverse directional elements. Some microprocessor relays utilize a “block” setting on the ground overcurrent that leads the user to select a reverse polarizing element for torque control (e.g. !32QR logic instead of 32QF). Careful consideration should be given before utilizing reverse directional elements since there may be impacts to relay coordination that are not readily apparent.

Forward Directional Element Torque Control

Traditionally, ground overcurrent elements meant to operate for forward faults are torque controlled with a forward looking directional element.

The protection engineer verifies adequate polarizing quantities are available by running fault simulations. Checks are done to assure adequate polarizing is available for all in-section line faults for credible worst case contingencies. As an example, PG&E setting criteria requires 5 volts 3Vo or 2.5 volts V2 for acceptable polarizing voltage thresholds at the relay.

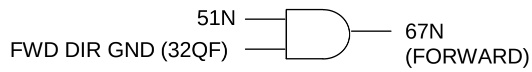

Fig. 10. Forward Directional Element Torque Control

Reverse Directional Element Torque Control (Block Logic)

Reverse directional elements can also be used for providing torque control for forward faults by applying the torque control as a "block" setting. Some microprocessor relays have the ground overcurrent torque control as a "block" setting. If the reverse directional element does not pick up, then forward ground overcurrent tripping is allowed.

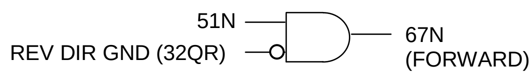

Fig. 11. Reverse Directional Element Torque Control

On the surface, this approach may seem beneficial since it provides a very dependable scheme. In the absence of any polarizing quantity the relay will still allow a trip. However the trade off is with security. Utilizing a "block" setting for torque control may result in unforeseen relay miscoordination for reverse faults as illustrated in the examples below. Verifying proper relay coordination when utilizing reverse polarizing "block" logic can prove extremely difficult. Instead of checking for adequate polarizing for in-section faults, you much check reverse faults to find the point where the relay no longer has adequate polarizing and assure there is no miscoordination when the relay is operating non-directional.

Trouble with Reverse Directional Element Torque Control (Block Logic)

Following are lessons learned, real life examples, where a relay with a "block" setting was set with a reverse directional element for torque control and this resulted in an unforeseen relay miscoordination. The lesson learned was to only utilize forward directional elements for ground polarizing, which is the traditional approach used by most relays. This required going back to many in service relays to make a setting and logic modification (Block = !32QF, instead of 32QR).

The relay event shown in Figure 12 was a line end fault on one of two parallel, multi-tapped lines. One of the relays on the non-faulted line failed to polarize the reverse directional blocking element and miscoordinated since it operated as non-directional. The 115kV system in Figure 11 is fed from Station X. Stations Y and Z do not have any significant positive sequence sources. The line sections are on common towers so there is significant mutual coupling. The relay at Station Y, CB 2, failed to polarize the reverse blocking directional element and miscoordinated with the relay at Station Y, CB 1. The reason CB 2 failed to polarize was there was insufficient I2 (less than 0.5 amps secondary) to operate the negative sequence reverse directional element. For CB 2 the relay 3Io operate current was significant due to the mutual coupling with the faulted line and proved to be enough to cause a race with CB 1. It should be noted that CB 2 had a lower time dial setting than CB 1, so even though CB 1 operating current was higher the relaying times for CB 1 and CB 2 were approximately the same.

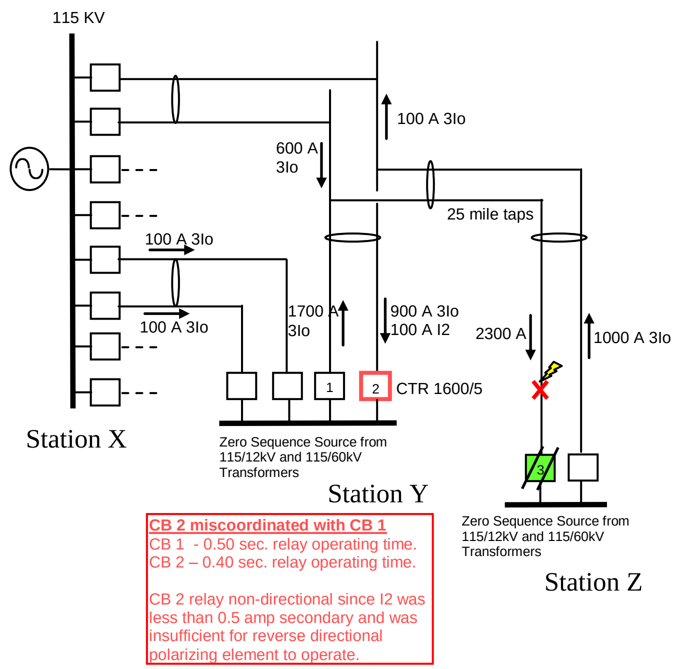

Fig. 12. Miscoordination Event Where "Block" Torque Control Logic was Applied

Another real life example where a relay with reverse directional "block" logic resulted in an unforeseen relay miscoordination is shown in Figure 13. There was a close-in fault on one of the 60kV lines at Station Q. The 60kV bus is fed from two 115/60kV auto transformers. Each 115/60kV transformer has a low side directional relay looking into the transformer for backup protection. The transformer low side directional ground relay element utilized a "block" setting to torque control the ground overcurrent element. The negative sequence reverse directional element was set as the "block" setting. For the operation in question, the close in fault at CB 3 momentarily evolved from a LG to LL fault type. When this happened the negative sequence reverse directional element momentarily dropped out, allowing the relay 67N element for both transformer 1 and transformer 2 to operate. The transformer 1 and 2 low side directional relays miscoordinated with the line relay on CB 3. Both transformer 1 and 2 tripped, deenergizing the 60kV bus and all three 60kV lines.

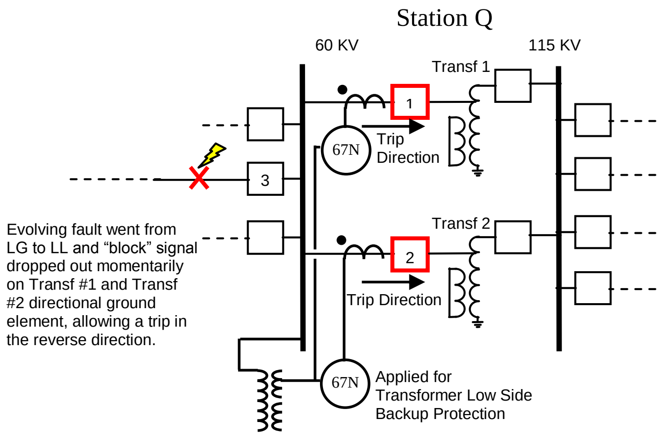

Fig. 13. Miscoordination Event Where "Block" Torque Control

As a result of these misoperations, PG&E has modified the relay logic for microprocessor relays with directional ground elements that have a "block" setting for torque control. Custom logic has been added as shown in Figure 14, to allow using an inverted forward directional element for torque control. If the forward directional element is not picked up, then you block. This allows the ground overcurrent to be supervised by a forward directional element as is traditionally done.

Relay Custom Logic
Ground OC Block (VO1) = Not (NEG SEQ DIR FWD)

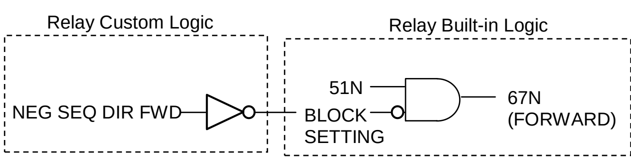

Fig. 14. Setting / Logic Modification to Enable Using Forward Directional Element in Relay "Block" Torque Control Setting.

VI. Concluding Remarks

In conclusion, it is recommended to use negative sequence directionality as the first choice for ground polarizing selection. Negative sequence directional elements are insensitive to zero sequence mutual coupling and zero sequence polarizing reversals.

In addition, it is recommended that the forward ground overcurrent tripping elements be torque controlled by a forward directional negative sequence element. A reverse direction blocking element could be used to increase security but should not be applied as the only directional qualifier to the overcurrent element. This provides consistency in relaying application with traditional directional ground overcurent relays which were torque controlled with forward directional elements, and allows straight forward relay coordination.

VII. References

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VIII. Biography

Aaron Feathers received his BS in Electrical Engineering from California Polytechnic State University, San Luis Obispo in 1992. He started his career with Pacific Gas and Electric Company in 1991 as an engineering intern. Since then he has held various positions including Protection Engineer, Senior Protection Engineer, Substation (Design) Engineer, Maintenance & Construction Engineer, Supervising Substation (Design) Engineer, Supervising Protection Engineer, and Principal Protection Engineer. Aaron was on special assignment from 2004 to 2009 supporting PG&E's Modular Protection and Control (MPAC) initiative providing protection, integration, automation, design and test support and working as part of an MPAC core team responsible for development of standards, processes, templates and overall program oversight. Aaron's current job responsibilities include protecction standards, wide area RAS support, protection system maintenance program development for PRC-005-2, and relay asset management support. Aaron is a registered professional engineer in the state of California and IEEE member. Aaron enjoys playing basketball, woodworking and gardening in his spare time.