Coordinating Dissimilar Line Relays in a Communications-Assisted Scheme

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***Abstract*—Communications-assisted (pilot) protection schemes are used to provide high-speed simultaneous fault clearance from each end of a line. The most common pilot schemes used in the industry are permissive overreaching transfer trip (POTT) and directional comparison blocking (DCB). For secure operation, ensuring coordination between the local and remote relays is absolutely necessary. A common myth is that POTT schemes do not have to be coordinated. However, when applying modern POTT schemes that include advanced features such as current reversal and echo logic, reverse blocking elements play an important role and need to be properly coordinated.**

Good engineering practice suggests using the same type of relay at both terminals in a pilot scheme. However, sometimes this is not possible due to construction, project schedule timing, or budget constraints. Further, when the line is a tie line, transmission facility owners often mutually agree to select dissimilar relays to prevent having to vary from their standards for maintenance, spare equipment, and training reasons. Using different models, manufacturers, and vintages of microprocessor-based relays in a pilot scheme presents coordination difficulties due to different operation principles that result in different sensitivities, speeds, and transient responses. This paper presents a number of such problems and challenges discovered in real-world applications. The paper then proposes solutions to minimize the risk of misoperation and achieve good fault coverage. Finally, the paper discusses the pros and cons of the proposed solutions, keeping in mind the effect power system faults have on power quality and system stability.

I. Introduction

Though originally developed for voice transmission, communications channels have long been used by protection engineers to add speed and selectivity to transmission line protection schemes. Without communication between relays at opposite ends of a protected line, elements providing high-speed tripping must be set short of the remote terminal to avoid miscoordination with adjacent zones. The result is time-delayed tripping for faults on the remote portion of the protected line. This limitation led to the development of pilot schemes that use communications channels between relays at all line terminals to allow selective high-speed clearing of faults on the entire line.

The addition of pilot protection to basic step distance or overcurrent protection requires careful application of the additional relay elements and logic unique to the pilot scheme design of the chosen line relay. For reliable operation of the pilot scheme, it is recommended to choose line relays of identical make, model, and firmware versions at each end. When using dissimilar relays in a pilot scheme, differences in relay design, speed, and element sensitivity must be taken into account. Failure to recognize and compensate for these differences in line relay performance can result in an undesired high-speed trip for an external fault.

American Electric Power (AEP) is an investor-owned utility with approximately 40,000 transmission circuit miles in portions of 11 states and a service territory of approximately 200,000 square miles, making it the largest electric transmission system in the United States. The size of its footprint contributes to the large number of AEP transmission voltage interconnect circuits—more than 350, representing over 40 different neighboring utilities. A mismatch of relays in a pilot scheme can be found on transmission lines with both terminals owned by AEP when the timing of relay installation or relay replacement projects is such that both terminals cannot be completed simultaneously. However, it is the interconnecting transmission lines that are most likely to be protected with a communications-assisted scheme featuring dissimilar relays.

As transmission facility owners gain their own experience and develop familiarity with specific relay models, their relay standards evolve independently and are likely to be unique to their company. Quantity discount pricing, a desire to minimize emergency spare inventories, and a narrower focus on product training can be disincentives to stray from their standards. Protection engineers should always strive to achieve reliable operation of the protection scheme, regardless of whether it involves an interconnecting transmission line. Further incentive is provided by the desire of transmission facility owners to maintain system stability and continuity of service to their customers while avoiding undesired operations that can require compliance-related reporting activities.

The recommendations in this paper are those of the authors and do not represent official AEP protection philosophies. The examples used in the paper to illustrate real-world applications come from the AEP system and tie lines.

II. Background

The AEP standard panel design for transmission line protection includes the use of two sets of microprocessor-based line relays. The reasons for using two microprocessor-based relays to protect the same zone are to avoid the possibility that one relay failure would leave the zone unprotected and to facilitate periodic testing without requiring the line to be removed from service. While it is possible to depend on only one microprocessor-based relay for all the protection and control functions desired for a specific zone, failure of a single component within the microprocessor-based relay, such as a power supply, would result in a loss of all functions provided by the relay. In addition to microprocessor-based relay redundancy, the standard AEP transmission line relay panel also features relays made by two different manufacturers with the objective of limiting the number of possible common-mode failure scenarios. However, many of the utilities on AEP tie lines use two relays from the same manufacturer. This increases the likelihood of having at least one pair of dissimilar relays on a tie line.

The two most common impedance relay-based pilot schemes in use at AEP are directional comparison blocking (DCB) and permissive overreaching transfer trip (POTT). Of these, the most common has been power line carrier-based (PLC-based) DCB, due to the relatively low cost of providing the pilot channel and the preference for line protection dependability. POTT schemes are considered as lacking an acceptable level of dependability when PLC is used for the communications channel. Although a variation of POTT, directional comparison unblocking (DCUB) can increase the dependability of a carrier-based POTT scheme. AEP normally reserves the implementation of POTT schemes for lines when a fiber-optic channel is available. The relatively small percentage of lines with an associated fiber-optic channel has contributed to the smaller percentage of POTT schemes in the AEP system, although transmission lines with an optical ground wire (OPGW) are increasing in number. As OPGW is included in new transmission line construction and line reconductoring projects with greater frequency, the range of options for communications-assisted relay schemes is increased.

The preference at AEP for line protection when OPGW is available is line current differential. When all terminals of a line with OPGW are owned by AEP, the panel often applied is the AEP standard dual line current differential panel. If an interconnecting line includes OPGW and a differential scheme can be implemented with one of the relays from a common manufacturer, a second high-speed scheme can also be implemented with the second pair of relays (which are dissimilar) for little additional cost, if another fiber pair is available in the OPGW. The most common choice for the second scheme in this scenario is POTT. The availability of a fiber-optic communications channel greatly reduces the most significant dependability disadvantage of a carrier-based POTT scheme: the higher probability of a loss of the pilot channel during an internal fault. To overcome differences in the fiber communications methods available in the dissimilar relays, the permissive signal can be sent between the relays using a generic interface, such as a contact transfer device.

Consider the example one-line diagram shown in Fig. 1. The example has two parallel circuits and a station with three seldom-run hydroelectric generators. The protected line employs dissimilar line relays in a carrier-based DCB scheme. During a scenario when the hydrogenerators are offline, the source behind Relay L1 might not provide an adequate positive- or negative-sequence polarizing quantity. However, the wye-connected windings of the generator step-up transformers connected to Bus L will provide a zero-sequence source for ground faults on either line. Relay L1 uses impedance-based polarizing quantities for ground faults that are chosen based on the order of predetermined options until a measured polarizing quantity is found that meets minimum thresholds. The polarizing quantities in this relay include negative-sequence voltage and zero-sequence voltage. Relay R1 uses a fixed, torque-based polarizing quantity. This relay can be set to use either negative-sequence voltage or zero-sequence voltage as the polarizing quantity. See Section V, Subsection D for more details on impedance versus torque-based directional elements.

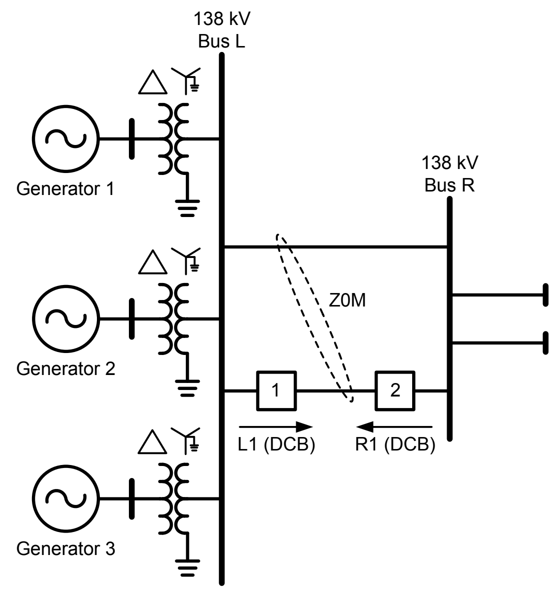

Fig. 1. System one-line diagram.

Normally, negative-sequence voltage polarization is preferred, especially on mutually coupled lines, because zero-sequence voltage quantities can be unreliable. In this example, setting the polarizing quantities for the relays at each end of the protected line is difficult because negative-sequence polarizing quantities are unreliable when the hydroelectric generators are offline. Thus, selecting negative-sequence voltage as the polarizing quantity provides dependability only when the generators are in service. Zero-sequence voltage is available at all times, regardless of whether the hydrogenerators are in service. However, selecting zero-sequence voltage as the polarizing quantity can affect the security of the DCB scheme due to mutual coupling.

Directional elements play a crucial role in the reliable operation of pilot schemes. It is therefore very important that the engineer setting the relay understand the operational principles of these directional elements and how they can be set based on the system configuration to offer a good balance between dependable and secure operation of the protection scheme. This paper addresses the different sensitivities of microprocessor-based relays and provides possible solutions for setting elements when dissimilar relays are being used in a pilot scheme. Although the scenario at AEP that most often presents a pilot scheme coordination challenge involves DCB, proper operation of POTT schemes also depends upon agreement between the two line relays on the direction of the fault. The addition of advanced functions (such as echo logic) in hybrid POTT schemes, which depend on the use of reverse elements, introduces the same coordination challenge inherent in DCB schemes. DCB, POTT, and hybrid POTT schemes are discussed in greater detail in the following section.

III. Pilot Schemes

Distance protection is widely used for the protection of high-voltage and extra-high-voltage (EHV) transmission and subtransmission lines. To achieve easier coordination and improve system stability, there is a need to quickly detect, classify, and isolate faults on the transmission lines. This led to the development of high-speed pilot protection schemes. Pilot schemes require a communications channel between all ends of the protected transmission line in order to provide high-speed fault clearing for 100 percent of the protected line. For reliable operation of a pilot protection scheme, a good balance of speed, security, and dependability is required. Various pilot protection schemes, namely directional comparison and current-only schemes, have been developed to meet these requirements. The focus of this section is limited to the application of directional comparison schemes using microprocessor-based multifunction distance relays.

Directional comparison schemes are a form of pilot protection that employs directional overcurrent and/or distance elements at both ends of the line terminals. Forward overreaching and reverse-looking elements at each terminal are used to differentiate between internal and external faults. The forward-looking elements at both terminals operate for internal faults. However, for an external fault, the forward-looking elements at one terminal and reverse-looking elements at the remote terminal operate. This information, compared between the terminals, is then used either to provide high-speed tripping for internal faults on the protected line or to prevent a trip for external faults. To ensure reliable operation of the scheme, the forward-looking elements must be set to overreach the remote terminal with sufficient margin to detect all internal faults. The reverse elements must be more sensitive than the corresponding forward-looking elements at the remote terminal.

The most prevalent directional comparison schemes are DCB and POTT.

With further improvements to enhance dependability and security, traditional DCB and POTT schemes have evolved into hybrid versions and are discussed in the following subsections.

A. Directional Comparison Blocking

Fig. 2 shows a section of a power system with a line protected by relays at both terminals, aided by DCB logic. At each line terminal, pilot tripping elements are set to overreach the remote terminal with a sufficient margin to detect all internal faults. Reverse-looking pilot blocking elements, set to overreach the remote pilot tripping elements, are used to block trip for external faults. Pilot tripping occurs for an internal fault if the local pilot tripping elements operate and the remote pilot blocking elements do not operate.

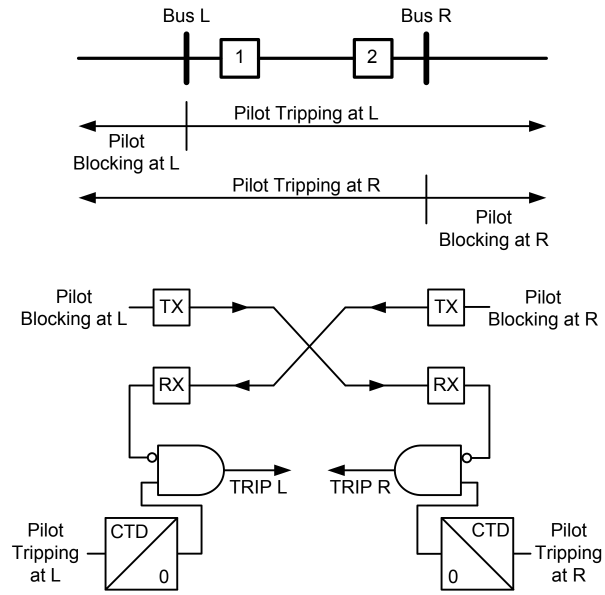

Fig. 2. Directional comparison blocking logic.

To ensure that the protective relaying associated with Breaker 1 does not issue a trip for an external fault beyond Bus R, the overreaching elements associated with the relays at Breaker 1 should be blocked before they can trip the breaker. A carrier coordination pickup time delay (CTD) is therefore added to the pilot tripping elements, as shown in Fig. 2. This delay timer ensures that the local pilot tripping elements wait for a possible blocking signal from the remote terminal before tripping the breaker. Factors that affect CTD include the relative response time of the remote pilot blocking elements versus the local pilot tripping elements and the blocking signal transmit time.

In many applications, to speed up sending a blocking signal, a fast nondirectional element is used to start blocking. In these cases, the blocking signal is quickly turned off by the forward pilot tripping elements when an internal fault is detected. This variation is called nondirectional carrier start because a PLC channel is the most often used with DCB schemes. These PLC transceivers usually include both a start and a stop input to control transmission of the carrier signal. The stop input has precedence over the start input to facilitate the nondirectional carrier start logic.

DCB schemes are typically applied with on/off PLC transceivers and have the advantage of not being affected by a possible loss of signal for internal faults because no signal from the remote end is needed for operation. Therefore, this scheme tends toward higher dependability.

DCB schemes are preferred for weak terminal applications because they always allow the strong terminal to trip for an internal fault. For an external fault behind the weak terminal, the weak terminal sees the same current as the strong terminal. Thus, the reverse-looking pilot blocking elements at the weak terminal have no problem asserting and sending a blocking signal to the remote strong terminal, preventing operation for an external fault.

For an external fault behind the strong terminal, the weak terminal will likely not even see the fault and, therefore, will rarely operate for an external fault. If the terminal is considered weak because there is no source behind it, direct transfer trip from the remote strong terminal is used to trip the weak terminal. In some cases, once the strong terminal opens, current redistribution will cause the weak terminal to see a larger fault current magnitude, thus resulting in faster tripping and quicker isolation of the fault.

An important consideration in designing DCB schemes is the effect of a communications channel failure on the scheme. Loss of the communications channel may result in overtripping for external faults, making the scheme less secure. Some of the complications and concerns associated with DCB schemes are discussed below.

For an external fault, such as one beyond Bus R in Fig. 2, if the blocking signal drops out momentarily due to noise, coupling capacitor spark gaps firing, or other channel-related problems, the overreaching pilot tripping elements associated with Bus L may overtrip for that fault after CTD expires. Thus, to enhance security, a user-settable dropout timer (RX block extension) is added to the block trip input from the remote end, as shown in Fig. 3. The RX block extension timer blocks the trip signal in nondirectional start applications, so it is desirable to make this delay as short as possible while maintaining security [1]. When nondirectional carrier start logic is used, it is recommended not to use the block extension timer.

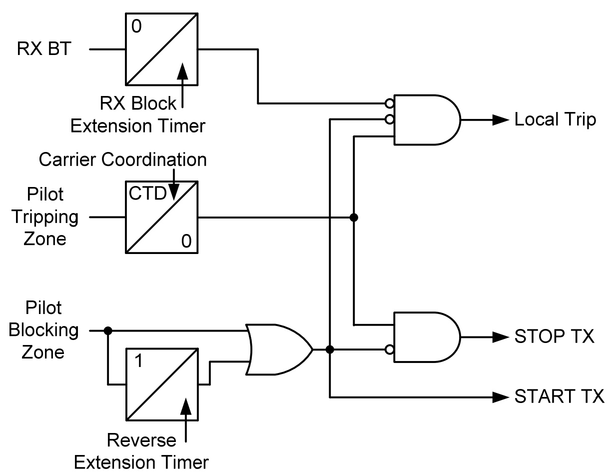

Fig. 3. Advanced DCB logic.

In double-circuit line applications or where there is a relatively short parallel path in the transmission system between line terminals, faults closer to one end of the line may result in a sequential trip operation when the underreaching instantaneous elements trip the breaker nearest to the fault. This sequential fault clearing results in a current reversal condition in the healthy parallel line, causing the reverse elements to deassert before the remote forward elements deassert, resulting in an unwanted trip. To prevent this, the reverse extension timer, as shown in Fig. 3, asserts an additional blocking input to the local trip AND gate for a period of time to allow the remote pilot tripping elements to drop out.

B. Permissive Overreaching Transfer Trip

The traditional POTT scheme (see Fig. 4) uses overreaching pilot tripping elements to send a permissive signal to the remote end and trip the local breaker. The pilot tripping elements can be forward directional overcurrent and/or distance elements. If the pilot tripping elements associated with the relays at Breaker 1 detect a forward fault, a permissive signal is sent to the remote relays associated with Breaker 2. If the pilot tripping elements associated with the relays at Breaker 2 also detect a forward fault, a permissive signal is sent to the relays associated with Breaker 1, tripping both Breakers 1 and 2. During an external fault, such as one behind Bus R, the pilot tripping elements associated with the relays at Breaker 1 may detect a forward fault and send a permissive signal to the remote relays associated with Breaker 2. However, because the pilot tripping elements associated with the relays at Breaker 2 do not detect a forward fault, a permissive signal is not sent to the relays associated with Breaker 1. The protected line relays therefore do not trip their respective Breakers 1 and 2.

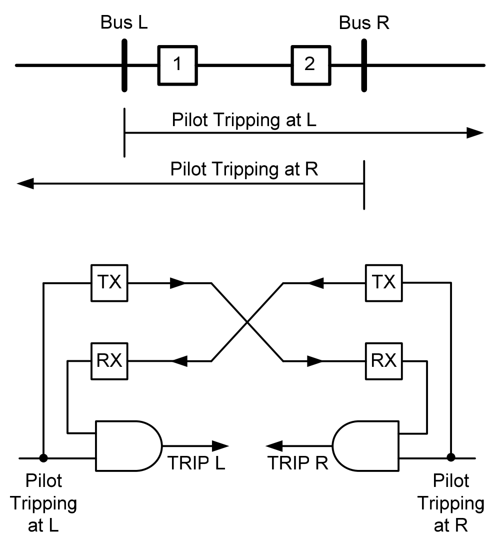

Fig. 4. Permissive overreaching transfer trip logic.

An advantage of the POTT scheme is its inherent security for external faults. The POTT scheme will not operate for external faults because both the local and remote terminals need to detect a forward fault for high-speed fault clearance. However, the POTT scheme is only as dependable as the communications channel sending and receiving the permissive signal. If the communications channel fails during an internal fault, the local and remote breakers will have to be tripped by the underreaching instantaneous or backup overreaching time-delayed elements.

The performance of the POTT scheme is also affected by a weak infeed or remote terminal open condition. If the local breaker detects a forward fault but the remote breaker does not, due to a weak source supplying the fault (weak infeed) or if the breaker is open, the fault will not be cleared at high speed by the elements in the POTT scheme. Current reversals on a parallel line can also cause a misoperation when a traditional POTT scheme is applied. These complications in the traditional POTT scheme led to the development of the hybrid POTT scheme to help increase dependability for weak infeed scenarios and security for current reversal conditions.

C. *Hybrid Permissive Overreaching Transfer Trip*

The addition of reverse pilot blocking elements to the traditional POTT scheme (see Fig. 5) plays a crucial role in the echo, week infeed, and current reversal logic.

It is imperative that the reverse pilot blocking elements be set to coordinate with the overreaching pilot tripping elements at the remote end. This coordination ensures that the echo logic will be blocked for all external faults that the remote pilot tripping elements can detect. If the pilot blocking elements are not coordinated, the hybrid POTT scheme may be susceptible to overtrip for external faults, similar to a DCB scheme.

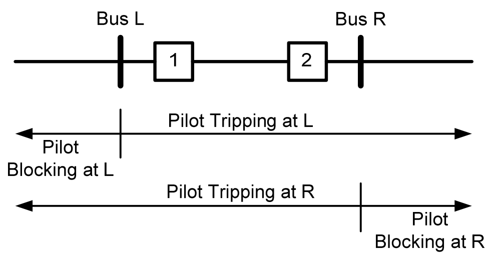

Fig. 5. Relay elements in a hybrid POTT scheme.

The echo logic in the hybrid POTT scheme increases dependability during weak infeed and remote open terminal conditions. Echo logic works by allowing the remote relay to return the permissive signal if it does not see a reverse fault. Fig. 6 shows that echo keying occurs if no reverse pilot blocking elements are asserted and a permissive signal has been received (RX PT) for a settable time, referred to as the echo qualifying timer. The echo duration timer limits the length of the echo key signal and therefore has to be set greater than the communications channel operation time plus the remote breaker trip time. The echo logic includes a security feature (echo block timer) to block the echo key signal for a period of time after a forward fault is detected to help prevent echo in a current reversal condition.

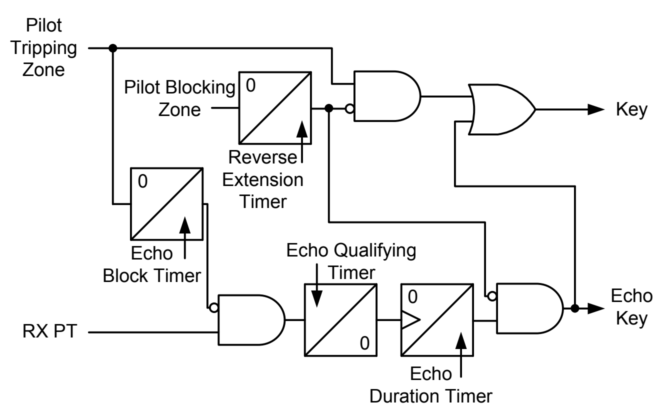

Fig. 6. Echo and current reversal logic in the hybrid POTT scheme.

The hybrid POTT scheme also provides additional logic for weak infeed terminals to trip at high speed for faults near the weak terminal. As shown in Fig. 7, the weak infeed logic uses phase undervoltage or residual overvoltage elements to detect a weak infeed condition. During a fault near the weak terminal, as long as the breaker is closed, a permissive signal is received from the remote strong terminal, no reverse pilot blocking elements pick up, and the phase undervoltage or ground overvoltage elements pick up, a trip at the weak terminal will be initiated.

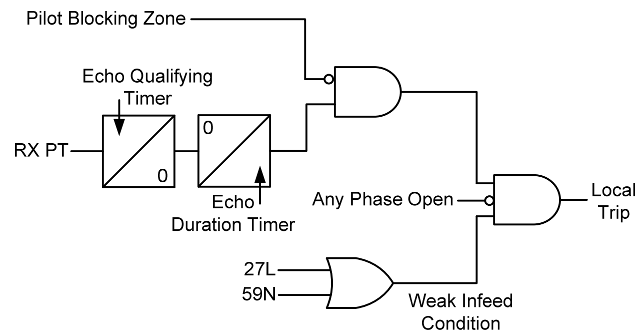

Fig. 7. Weak infeed logic in the hybrid POTT scheme.

Similar to a DCB scheme, the POTT scheme is susceptible to overtripping for a current reversal condition in the healthy line. The local relay receives a permissive signal while the fault is behind it. Once the external fault is cleared by the underreaching instantaneous elements associated with the breaker nearest to the fault, the forward pilot tripping elements can assert before the permissive trip signal from the remote relay deasserts. To prevent this, the reverse pilot blocking elements in the hybrid POTT scheme include a dropout timer to prevent POTT tripping and keying immediately after a reverse fault has been detected. Fig. 6 shows the reverse extension timer in the keying logic.

IV. Sensitivity Considerations

With about 70 percent of faults being single-line-to-ground faults [2], the reliability of ground protection elements is of significant importance. Unlike phase faults, ground faults can include significant resistance in the fault loop due to high tower footing resistance, soil properties in the vicinity of the downed conductor, dryness of trees, and other items that the conductor may come into contact with. Further, ground faults are most likely to result in hazards to people and property, so fast clearing is desirable to improve safety. Conversely, fast clearance of ground faults is less of a concern for power system stability [3]. So time-delayed clearing of ground faults, especially high-impedance ground faults, is acceptable from this point of view.

Sensitivity, most commonly expressed by the maximum fault resistance coverage, is one of the most important functional requirements of the protection elements that determine the reliable operation of the protection scheme. Higher fault resistance coverage implies more sensitivity and, therefore, higher dependability and, unfortunately, reduced security. It is important to balance sensitivity and speed in order to balance dependability and security while considering public safety. Voltage and current thresholds, volt ampere limits, and directional sensitivity are some of the factors that determine the fault resistance coverage of the relay elements. Reference [4] identifies limits to directional element sensitivity and its effects on pilot scheme performance.

The mho ground distance and directional ground overcurrent elements are most commonly used for ground fault protection. The directional ground overcurrent element provides excellent coverage for high-resistance faults. However, the sensitivity of the overcurrent element varies with changes in system configuration. Having a zone of protection that is a fixed percentage of the protected line impedance is one of the main advantages of distance elements. Also, the mho elements are less influenced by the system homogeneity and offer a good balance between fault resistance coverage for internal faults and security against overtripping for external faults. A detailed comparison of different ground fault detection methods on the basis of security and dependability is explained in [5]. In this section, the sensitivity of the mho ground distance elements to resistive ground faults is discussed.

To evaluate the fault resistance coverage of the mho distance element with respect to the reach setting, a simplified equivalent system model, shown in Fig. 8, is used. The protected line shown in the system model is configured for a POTT scheme.

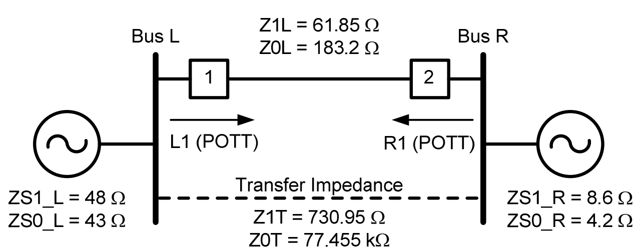

Fig. 8. Simplified equivalent system model (all values are in primary ohms).

Fig. 9 and Fig. 10 show the fault resistance coverage of the different ground distance zones associated with relays at Breaker 1 and Breaker 2, respectively. Using ASPEN OneLiner™ software, single-line-to-ground faults with varying fault resistances (0 to 100 Ω) were placed at 50 percent of the protected line. It can be seen that improved fault resistance coverage is achieved by an increased reach setting. Therefore, to increase high-speed fault resistance coverage in pilot schemes, it is recommended to set the pilot trip element equal to the longest overreaching element setting instead of the medium overreaching element. During normal operation of the power system, assuming loads are more resistive, the load impedance is a point outside the mho circles and closer to the *R* axis. However, when an internal fault occurs, the load impedance changes to a value equal to the fault impedance, which is a point inside the mho circles. When this transition from load to fault impedance occurs, the impedance trajectory will first cross the 200 percent zone and then the 120 percent zone. This implies that the fault impedance takes less time to reach the 200 percent zone than it does to reach the 120 percent zone, resulting in faster detection of the faults. Therefore, setting the pilot tripping element equal to the longest overreaching zone not only improves fault resistance coverage, it also speeds up tripping, improving the overall performance of the pilot scheme.

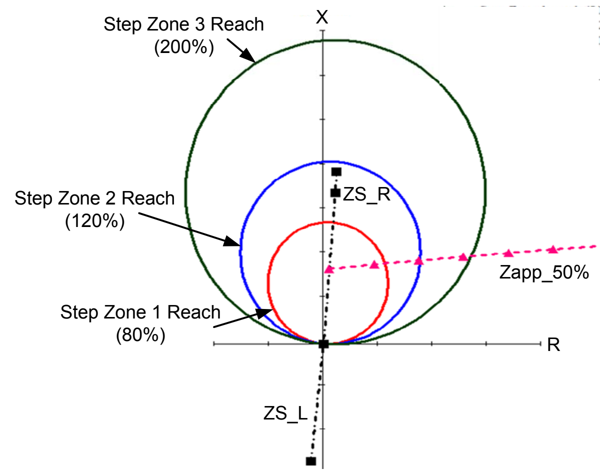

Fig. 9. Mho ground distance elements at Bus L.

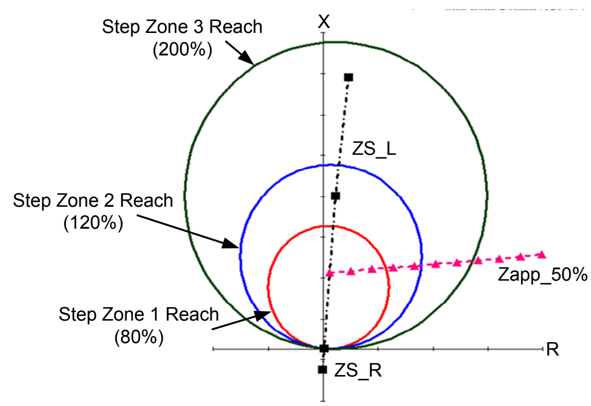

Fig. 10. Mho ground distance elements at Bus R.

Remote infeed also plays a significant role in the fault resistance coverage of mho elements. During faults, the voltage measured by the distance elements equals the sum of the line voltage drop to the fault and the voltage drop across the fault resistance. This voltage drop across the fault resistance equals the product of the total fault current from both terminals and the fault resistance. In looped systems, because the fault is fed from both the local and remote end sources, the total fault current and therefore the apparent fault impedance are dependent on the remote infeed. An increase in remote infeed causes the relay to measure larger apparent impedance, which results in a reduction in fault resistance coverage.

Distance elements have many polarizing techniques to choose from, including self-polarizing, cross-polarizing, and positive-sequence polarizing. While self-polarizing techniques offer no expansion and are unreliable for zero-voltage faults, cross-polarization techniques offer good expansion and are dependable for most faults except zero-voltage three-phase faults. Positive-sequence dynamic memory polarization provides the greatest fault resistance coverage due to the expansion of the mho circle and is dependable for all fault types [6]. The amount by which the mho circle expands depends on the strength of the source behind the relay. The weaker the source, the greater the expansion will be.

The above discussion shows that the fault resistance sensitivity for a given element on a given line terminal is dependent on the interaction of the following factors:

- Power system network characteristics
- Fault location
- Protection element characteristics
- Protection element settings

Reference [7] provides a detailed analysis of the impact of these various factors on fault resistance sensitivity. To obtain the plots used in this section, we used ASPEN OneLiner software to account for all of these factors for our example application.

Advances in pilot protection (e.g., the addition of echo logic in a POTT scheme) help increase the sensitivity of the protection system. As discussed in Section III, in a traditional POTT scheme (i.e., with echo logic disabled), the relays at both terminals have to see the fault in order to allow high-speed tripping. If either terminal fails to detect the fault while the other does, high-speed tripping will not occur, relying on underreaching elements or time-delayed elements to clear the fault. However, in a POTT scheme with echo logic enabled, it is sufficient if either relay sees the internal fault to allow high-speed tripping.

To better understand the advantage of echo logic in increasing the sensitivity of the ground elements, consider the system shown in Fig. 8. A single-line-to-ground fault was placed at every 10 percent of the protected transmission line, and the fault resistance limits of each of the ground distance elements were determined. The study was made looking at ground distance elements, but similar conclusions can be drawn regarding ground overcurrent elements.

The ground distance elements at both ends of the protected line are positive-sequence memory polarized. Effects of remote infeed, source strength, and mho expansion were considered for this study. For the purpose of this discussion, the analysis is based on the assumption that once the local terminal clears the fault at high speed, current redistribution helps the remote or weak terminal see the fault and also trip at high speed.

To support the analysis, a graph of varying resistive fault impedance versus fault location on the protected line is shown in Fig. 11. The fault resistance coverage achieved by the ground distance elements in Fig. 11 considers the scenario when both the local and remote terminals are closed. Fig. 12, showing fault resistance coverage with the remote terminal open, is provided to support the stated assumption that, once the strong or near terminal opens, the remote or weak terminal is able to see the fault and trip at high speed. From Fig. 11, it is evident that in spite of a weak source behind Relay L1 and, therefore, greater mho expansion, the fault resistance coverage achieved by these mho elements is less when compared with the mho elements associated with Relay R1. The lesser fault resistance coverage of the mho elements associated with Relay L1 can therefore be attributed to the strong remote infeed from Bus R. However, once the strong terminal at Bus R opens, the fault current contribution from the strong terminal will now flow through the transfer impedance and contribute to the fault from behind the weak terminal at Bus L. This leads to an increase in fault current magnitude measured by the Relay L1. In addition to this, removal of the strong remote infeed considerably lowers the apparent impedance measured by Relay L1, thereby improving the fault resistance coverage at the weak terminal. The increased fault resistance coverage achieved by the ground distance elements considering removal of remote infeed is shown in Fig. 12.

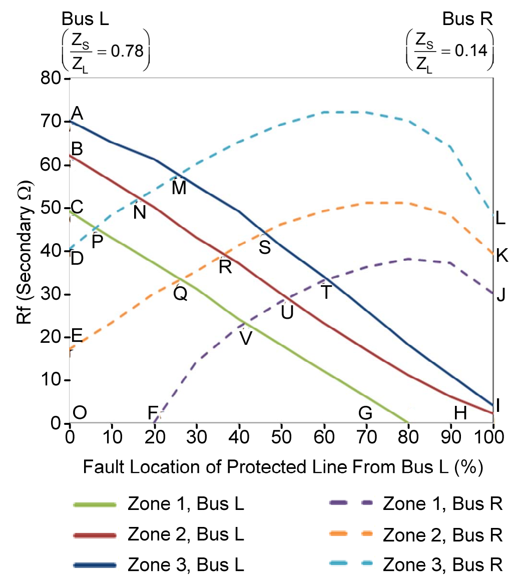

Fig. 11. Fault resistance coverage with remote end closed.

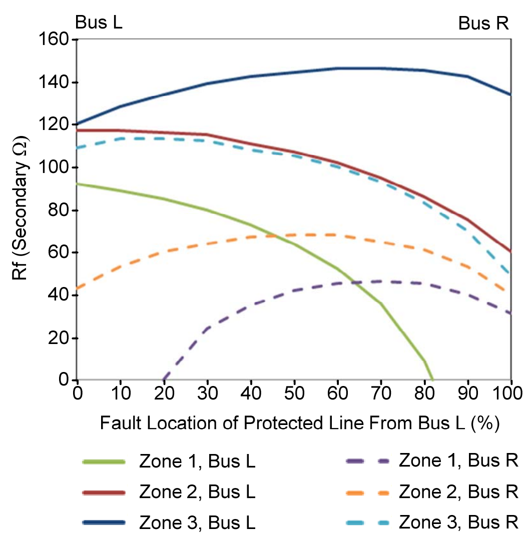

Fig. 12. Fault resistance coverage with remote end open.

The area under Line CG in Fig. 11 represents the fault resistance coverage achieved by the step distance Zone 1 ground distance element associated with Relay L1, set to cover 80 percent of the protected line. The area under Line JF represents the fault resistance coverage achieved by the step distance Zone 1 ground distance elements associated with Relay R1, set to cover 80 percent of the protected line. The areas under Lines BH and AI represent the fault resistance coverage achieved by the step distance Zone 2 and Zone 3 elements associated with Relay L1, set to cover 120 and 200 percent of the protected line, respectively. The areas under Lines KE and LD represent the fault resistance coverage achieved by the step distance Zone 2 and Zone 3 elements associated with Relay R1, set to cover 120 and 200 percent of the protected line, respectively. Due to different protection philosophies of the utilities on either end of the protected tie line, the pilot tripping elements associated with Relays L1 and R1 are set to 200 and 120 percent of the protected line, respectively.

With echo logic disabled, high-speed fault resistance coverage is possible only when the fault is in the Zone 1 reach of either relay or is within the pilot reach of the relays at both ends. With the pilot tripping zone associated with Relay R1 set at 120 percent of the protected line and with echo logic disabled, the fault resistance coverage achieved by the protection system is represented by the area defined by Points C, Q, S, T, J, H, and O. However, if the pilot tripping zone associated with Relay R1 is set equal to 200 percent of the protected line and with echo logic disabled, the fault resistance coverage achieved is represented by the area defined by Points C, P, M, T, J, H, and O. Thus, the additional coverage provided by setting both pilot tripping elements to 200 percent is represented by the area defined by Points P, M, S, and Q.

If echo logic is enabled, high-speed fault resistance coverage occurs when the fault is within the pilot tripping reach of either relay or when the remote terminal is open. With the pilot tripping zone associated with Relay R1 set at 120 percent of the protected line and with echo logic enabled, the fault resistance coverage is represented by the area defined by Points A, S, K, H, and O. However, with the pilot tripping zone associated with Relay R1 set at 200 percent of the protected line and with echo logic enabled, the fault resistance coverage achieved is represented by the area defined by Points A, M, L, H, and O.

From Fig. 11 and Fig. 12, it is evident that using the long reach zone as the pilot tripping zone and enabling echo logic maximize the high-speed fault resistance coverage of the ground distance elements without compromising the security of the scheme. For completeness, it is necessary to point out that the fault resistance coverage of the hybrid POTT scheme with echo logic enabled discussed in this section applies to a DCB scheme as well.

V. Response of Elements

Typically, discussions of coordination of dissimilar relays have centered on speed of operation. The focus has been on blocking schemes, where how fast the blocking signal arrives is critical. Speed of response for faults at different multiples of reach and source impedance ratio (SIR) conditions between relays can be easily mitigated by increasing the CTD to sacrifice speed for security. The purpose of this paper is to highlight the issue of different sensitivities to boundary faults between relays of different manufacturers.

So far in this paper, we have concentrated on how pilot schemes work and how each of the features available in modern pilot schemes enhances sensitivity, dependability, and/or security. We have determined that blocking schemes and hybrid POTT schemes with echo logic are susceptible to tripping for external faults if the pilot tripping element sees a fault and the remote pilot blocking does not.

For an external fault, the two relays see the same through current in the line. The voltages are obviously different, with the pilot blocking element closer to the external fault than the pilot tripping element. This helps the pilot blocking element typically perform slightly faster for an external fault—aiding time coordination. This is the basis for the time-honored practice of always using relays of the exact same type in blocking and, now, hybrid POTT schemes. Because like relays have the same operating principles and see the same current, their transient and steady-state performance (speed and sensitivity) will be similar—ensuring sensitivity coordination if the reaches and/or pickups are appropriately set.

In addition to obvious differences in the protection elements themselves (such as mho versus compensator distance versus quadrilateral distance) that may be used in relays of different manufacturers, implementations of similar elements can be quite different as well. Modern multifunction relays have many supervisory elements that were not part of electromechanical (EM) relay systems. These additional supervisory functions increase the opportunity for protection elements to behave differently at boundary fault conditions.

It is important to understand that the external faults that are of interest are the remote boundary faults at the ragged edge of reach. Variations in the response of the supervisory elements between different manufacturers may prevent a pilot blocking element from asserting when a pilot tripping element from the other manufacturer asserts—even when the protection elements themselves are properly coordinated. Because the external faults can be anywhere on the system, the exposure to misoperation is quite high.

A. *Which Elements Should We Be Most Concerned With?*

There are a number of good references that discuss differences in characteristics and sensitivities of protection elements used in pilot protection systems, so they will not be detailed here [4] [6] [8] [9] [10] [11]. The point of this paper is to help the reader identify when differences in relays are actionable and when special measures should be taken to help ensure security.

Distance elements generally present much less of an issue because the reach of the pilot tripping elements is usually limited to between 120 and 300 percent of the protected line. For this reason, fault currents and voltages presented to various supervisory elements, such as fault detectors, directional elements, and sequence component ratio checks, are often adequate and the supervisory elements do not get in the way of asserting a protection element.

Phase elements generally present less of an issue because significant arc resistance is not a problem. Arc resistance moves the apparent impedance of the fault off of the maximum torque angle reach line of the element in the RX plane. The reaches are coordinated on the maximum torque angle line, but once off of that line, differences in polarizing memory (which affects mho expansion) and supervisory elements can result in more variation in sensitivity.

Directional ground overcurrent elements are the most problematic for the following reasons:

- They are usually set very sensitive to cover resistive ground faults and therefore respond to external faults on more of the adjacent power system. Thus, there is more exposure to picking up for an external fault.
- There is much greater likelihood of significant fault resistance, increasing the possibility of faults not being on the maximum torque angle line, where the reach or pickup settings are coordinated.
- There is much greater variation in implementations of ground fault tripping elements and ground directional elements between manufacturers.

Later in the paper, we present options to turn off directional ground overcurrent elements. To better understand the tradeoffs, Fig. 13 provides a comparison of the fault resistance coverage provided by directional ground overcurrent elements versus ground distance elements. The example uses the system model shown in Fig. 8, with the distance elements set to 200 percent of the line impedance and the directional ground overcurrent elements set to 600 A primary at both terminals. For simplicity, the plot only looks at the magnitude of the ground fault current and assumes that the directional element will operate. It can be seen that the directional overcurrent elements are more sensitive and therefore provide greater fault resistance coverage when compared with ground distance elements.

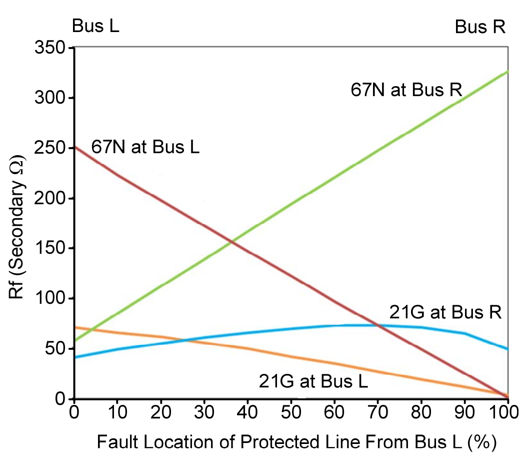

Fig. 13. Fault resistance detection (21G versus 67N elements).

The user often has the choice of using ground distance elements, directional ground overcurrent elements, or both in the pilot scheme. Both have their pros and cons. Directional negative-sequence overcurrent elements are also an option. It is important that differences be minimized.

B. Phase Distance Elements

Phase pilot tripping elements are usually distance elements. Microprocessor-based relays can use positive-sequence memory or other polarized phase mho, compensator distance, or quadrilateral distance elements, which also have a variety of polarizing methods and characteristics. In some cases, the principle is user selectable. For example, the authors are aware of relays from one manufacturer that allow the user to select either positive-sequence memory-polarized mho or compensator distance. Another relay allows the user to select mho or quadrilateral. Another allows the user to select mho, quadrilateral, or both.

In some cases, the user can modify the memory polarization time duration or time constant. At least one manufacturer includes a user setting to select whether each mho element is self-polarized or memory-polarized. Another relay designed for series-compensated lines includes logic to dynamically adjust the memory time constant if a voltage inversion is detected. Different polarization methods result in different transient responses.

In most cases, there are current fault detectors that can respond to the phase or the delta (phase-to-phase) current magnitude. These should be coordinated in primary amperes, if possible.

Most modern distance elements also include directional element supervision. The directional element can be a traditional element that responds to phase quantities. Or, it can make a directional decision based on sequence component quantities.

If the principles, polarizing methods, supervisory directional elements, and so on are different, there is no guarantee that the pilot tripping and blocking elements at each end of the line will respond the same to all external faults. However, the risk is often acceptable if the principles are at least similar (both positive-sequence memory polarized, for example) because the reaches beyond the protected line are typically not that great and high-resistance phase faults are not that prevalent.

C. Ground Distance Elements

All of the variations in phase distance element implementations that were detailed in the previous subsection also apply to ground distance elements. However, ground distance elements also include more options and variations for directional supervision.

Similar cautions apply as with phase distance elements. If the principles, polarizing methods, supervisory directional elements, and so on are different, there is no guarantee that the pilot tripping and blocking elements at each end of the line will respond the same to all external faults. However, the risk is often acceptable if the principles are at least similar (both positive-sequence memory polarized, for example) because the reaches beyond the protected line are typically not that great in either the *X* or *R* reach on the RX plane.

D. *Directional Ground Overcurrent Elements*

Directional ground elements are typically polarized by zero-sequence voltage, zero-sequence current, or negative-sequence voltage. In many cases, all three choices are available and can be enabled in parallel. In other cases, the relays use only one directional element at a time in a user-settable order of preference [12]. If the relays use different quantities, they will likely not respond the same for all external fault conditions.

If the line is mutually coupled, it is usually recommended to use negative-sequence quantities and exclude zero-sequence quantities. But, in some cases, such as the example in Fig. 1, the negative-sequence quantities are not always reliable when generation is offline.

Modern directional elements are very sophisticated in their implementations. Many include ratio checks of negative- and zero-sequence quantities to positive-sequence quantities to prevent ground directional elements from operating due to three-phase faults or normal system unbalances, such as untransposed lines. Others may use positive-sequence restraint to dynamically adjust the pickup of the negative- or zero-sequence element. For this reason, the sensitivity of these elements can be affected by load flow conditions (positive-sequence current) at the time of the fault. Because we rarely consider load flow in fault studies, these differences are not readily apparent.

Probably the most significant difference is whether the directional elements calculate torque (3V2 • 3I2 • ∠MTA and 3V0 • 3I0 • ∠MTA) or impedance (3V2/3I2 and 3V0/3I0) for the negative-sequence element and the zero-sequence element, respectively. A torque-based directional element requires a minimum magnitude of 3I0 and 3V0 to get a useable angle between the two quantities. Historically, dual polarized (3V0 and 3I0) directional relays were used when near a strong zero-sequence source because the 3V0 for an end-of-line fault may not be great enough to develop enough torque to operate the element. Today, the thresholds in digital emulations of this principle are much lower—but not zero.

An impedance-based directional element measures the source impedance for the fault. That is, for a forward fault, the relay measures the impedance behind the terminal, which is a negative number. For a reverse fault, the relay measures the impedance in front of it (the line and the remote source impedance), which is a positive number. Historically, in setting the impedance thresholds for this element, we assumed that for a reverse fault, the relay would measure at least the impedance of the line. The boundary was set between forward and reverse at half the line impedance.

To put this setting philosophy another way, the directional element, when set this way, operates on the principle that if the fault is not reverse, it must be forward. The relay declares a forward fault if the measured 3V2 or 3V0 is zero. This results in a directional element that is extremely sensitive—even in the presence of extremely strong sources. To illustrate the real-world sensitivity that can be obtained with these elements, [13] describes a case where these elements, applied on a 500 kV line, responded to a fault on a 132 kV bus many buses away from the protected line.

As with distance elements, there is no guarantee that the pilot tripping and blocking elements from different manufacturers will respond in the same way to all external faults. In this case, the risk is usually unacceptable due to the typically high sensitivity of the element settings and the major differences in the principles of operation and supervisory elements. The risk can be mitigated somewhat by raising the pickup levels such that the pilot tripping element does not see faults very far beyond the line. However, it is usually better to use only ground distance elements in the pilot scheme, if similar and available, and leave tripping for high-impedance ground faults to sensitive time-delayed elements.

E. *Additional Coordination Issues*

Coordinating the pickup of the pilot elements in primary amperes is especially important when different current transformer (CT) ratios are used at each end of the line. We often ignore the fault detectors supervising distance and directional elements and leave them at their default secondary ampere values. This can result in the fault detectors for the pilot tripping elements at one end being more sensitive than the fault detectors for the pilot blocking elements at the other end, resulting in a misoperation for a boundary condition fault.

Some manufacturers have separate tripping elements that are controlled by directional elements. A common error made by the engineer setting the relay is to coordinate the pilot blocking element with the remote pilot tripping element but forget to do the same for the forward and reverse directional elements that supervise those elements.

Another issue can occur when using different firmware versions of the same relay. The authors are aware of one relay that originally had the pickup of its negative-sequence polarized ground directional element respond to 1I0. Later, the firmware was changed such that the element responded to 3I0. In this case, if the engineer set the pilot tripping element to 1 A in the 3I0 relay and the pilot blocking element to 0.5 A in the 1I0 relay, the blocking element would not assert for an external fault unless the 3I0 measured by the relay reached 1.5 A. This would result in a misoperation if the external ground fault fell within 1.0 and 1.5 A.

VI. Recommendations

As discussed in the previous sections, for reliable operation of the pilot scheme, relays at each end must have similar sensitivities. Different element sensitivities at either end may lead to a possible misoperation. This section proposes certain solutions that minimize the risk of such misoperations in DCB and POTT schemes.

When coordinating different relays that have different directional element sensitivities in a DCB scheme, it is extremely difficult to ensure coordination for all external faults. It is therefore recommended that the sensitive directional overcurrent elements be disabled in a DCB scheme employing dissimilar relays and ground distance elements be used if the operating principles for the relays at each terminal are similar (e.g., each is positive-sequence memory polarized). Also, it is important to note that coordination between dissimilar relays cannot be achieved by simply increasing the coordination time delay. These coordination timers only delay the operating time of the pilot elements and do not address the issue of different sensitivities.

With dissimilar relays being employed in a hybrid POTT scheme, enabling both echo logic and the sensitive directional overcurrent elements increases the risk of misoperation for external faults. If enabling the directional overcurrent elements to provide high-speed fault clearance of high-resistive faults is absolutely necessary or if the distance elements in both relays are not of similar principles, disabling the echo logic is highly recommended. The main advantage of this solution is its simplicity, because no reverse pilot blocking elements are required for coordination. While implementing the traditional POTT scheme makes the scheme more secure, especially when using dissimilar relays at either end, it is not dependable for weak infeed or secure for current reversal conditions. With respect to remote open breaker conditions, open breaker keying logic can be implemented manually in the relay programmable logic.

A major advantage of the hybrid POTT scheme, though, is to ensure rapid fault clearance of all internal faults for a weak infeed or remote terminal open condition. Also, as discussed in Section IV, enabling the echo logic increases the sensitivity of the protection scheme and helps maximize the fault resistance coverage of the ground elements. With the principles of the positive-sequence polarized mho distance element being relatively similar and with the limited reach of the distance elements, enabling the echo logic while disabling the sensitive directional overcurrent elements offers a good balance between the security and dependability of the hybrid POTT scheme. Because reverse elements are required in a POTT scheme with echo logic, coordination is essential. As for concerns regarding better fault resistance coverage, the sensitive ground time-overcurrent elements can cover such faults. This is acceptable given that high-resistance faults have little impact on the system stability as long as the fault is cleared in a reasonable time delay. Therefore, high speed is not absolutely required to clear high-resistance faults.

Note that the solutions discussed for the POTT scheme imply that both echo logic and directional overcurrent elements are available in each of the dissimilar relays in a particular pilot scheme. However, this is not always the case. For example, Case 1 in Section VII presents a scenario in which echo logic was not available in one of the relays involved in a POTT scheme. In this case, the engineer setting the relay had to choose one of the proposed solutions solely because the other was not available.

VII. Case Studies

Protective relay engineers must consider several factors when applying dissimilar relays in a pilot scheme. This section presents real-world applications of dissimilar relays used in DCB and POTT pilot schemes and the proposed solutions that were recommended based on the individual conditions provided in each case.

A. Case 1: Utility A, Dissimilar Relays in a DCB and POTT Scheme

The system configuration for this case study includes a two-terminal 138 kV transmission line owned by the same utility. The line has dissimilar relays at each terminal in both the primary and alternate pilot schemes. Fig. 14 shows a simplified one-line diagram of the protected transmission line and equivalent system sources on each end of the line. Relays L1 and R1 communicate in a DCB scheme via a PLC channel. Relays L2 and R2 communicate in a POTT scheme via an audio tone, frequency shift keyed microwave signal.

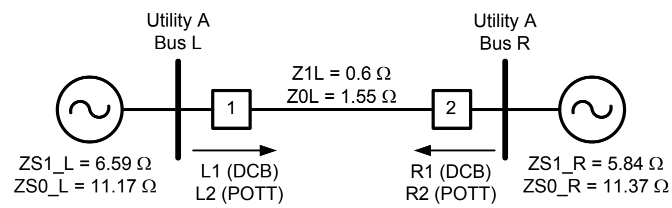

Fig. 14. Protected transmission line for Case 1 (all values are in primary ohms).

The primary DCB scheme consists of relays from different manufacturers. Both Relays L1 [14] and R1 [15] in the DCB scheme contain positive-sequence memory-polarized phase and ground distance elements that were applied for pilot tripping and blocking. While the implementation of the polarizing memory and supervisory elements was not exactly the same, it was determined that the elements were similar enough in principle of operation that they could be used as long as coordination margins were sufficient.

The directional overcurrent elements in Relay L1 determine the direction of a fault using torque, which requires minimum voltage and current requirements to make a directional decision. Relay R1 uses impedance to make a directional decision and has no minimum unbalance voltage or unbalance current requirements. In order to prevent a misoperation for an external fault where the relays at one terminal detect a forward fault but the relays at the remote terminal fail to detect the fault as reverse and send a blocking signal, the ground directional overcurrent elements were disabled in the DCB scheme. This solution desensitized the scheme by disabling the sensitive ground directional overcurrent elements but added to the security of the scheme by preventing a possible misoperation due to the dissimilarity between Relays L1 and R1.

The alternate POTT scheme consists of relays from the same manufacturer but of different vintage. The relays have the following very different features and operating principles:

- The phase distance elements in Relay L2 [16] are compensator distance elements. The phase distance elements in Relay R2 [15] have positive-sequence memory-polarized phase pair mho elements.
- The directional overcurrent elements in Relay L2 determine the direction of a fault using torque, which requires minimum unbalance voltage and unbalance current to make a directional decision. Relay R2 uses negative-sequence impedance (V2/I2) to make a directional decision and has no minimum voltage requirements.
- Relay L2 does not include echo logic. Relay R2 includes echo logic.
- Relay L2 does not include ground distance elements. Relay R2 includes ground distance elements.

Because the operating principles of the phase distance elements and the ground overcurrent elements were dissimilar, the scheme was set up as a simple POTT scheme without echo. Thus, no coordination of pilot tripping and pilot blocking elements was required. The directional ground overcurrent elements provide high sensitivity for resistive ground faults. It is also important to note that because both terminals are supported by equally strong sources, a weak infeed condition is not a concern. If a weak infeed condition did exist on one of the terminals, it would be advantageous to replace both Relays L2 and R2 to take advantage of the added features available in a hybrid POTT scheme.

B. Case 2: Different Utilities, Dissimilar Relays in the Alternate POTT Scheme

The system configuration for this case study includes a two-terminal 345 kV interconnecting transmission line owned by different utilities that use the same relays in the primary DCB scheme but dissimilar relays in the alternate POTT scheme. Fig. 15 shows a simplified one-line diagram of the protected transmission line and equivalent system sources on each end of the line. Both the primary and alternate scheme relays communicate via a PLC channel.

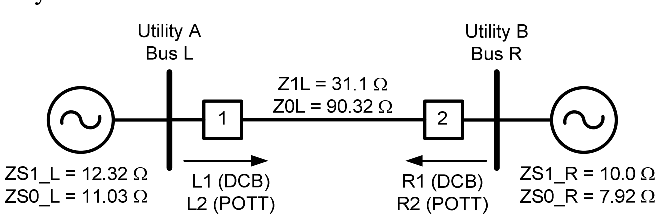

Fig. 15. Protected transmission line for Case 2 (all values are in primary ohms).

Because the primary DCB scheme (Relays L1 and R1) consisted of the same relays at either end, pilot tripping and blocking distance and ground directional elements were enabled in both relays. Coordination between the remote pilot blocking elements and the local pilot tripping elements was ensured.

The alternate scheme consists of relays from different manufacturers. The relays compare in the following ways:

- Both relays use positive-sequence memory-polarized phase mho distance elements.
- The directional overcurrent elements in Relay L2 [17] determine the direction of a fault using torque, which requires minimum unbalance voltage and current to make a directional decision. Relay R2 [18] uses impedance to make a directional decision and has no minimum voltage requirements.
- Both mho and quadrilateral ground elements can be enabled in Relay R2. Either the mho or the quadrilateral element, not both, can be enabled in Relay L2.

To reduce the risk of a possible misoperation for external faults by the alternate POTT scheme, either the echo logic or the ground directional overcurrent elements should be disabled. Enabling the sensitive ground directional overcurrent elements and disabling echo logic ensure good coverage for resistive ground faults and eliminate the possibility of differing sensitivities of pilot blocking and pilot tripping elements.

However, with echo logic disabled, the pilot tripping elements at both ends have to see the internal fault in order to clear at high speed. This results in slower fault clearance of internal faults when either terminal is open or not sensitive enough to declare forward faults. Because the ground directional overcurrent elements are enabled in the primary relays, the protection scheme already has high-speed fault resistance coverage. Therefore, enabling echo logic but disabling the ground directional overcurrent elements was the recommended solution for this case. This solution would ensure rapid clearance of internal faults when either terminal sees a high-resistance fault or when either breaker is open, with some small risk of differing sensitivities to boundary condition faults. Also, maximum utilization of the ground distance elements is achieved with echo logic enabled.

The preference of Utility B was to enable the quadrilateral and directional overcurrent elements to help achieve greater fault resistance coverage. Therefore, the first solution (namely, to disable echo logic and enable the ground directional overcurrent elements) was implemented. As for dependability of the protection scheme during remote open breaker conditions, open breaker keying logic was added to both of the relays in the alternate POTT scheme.

C. Case 3: Different Utilities, Dissimilar Relays in the Primary POTT Scheme

Similar to Case 2, the system configuration for this case study also includes a two-terminal 345 kV interconnecting transmission line owned by different utilities that use the same relays in the alternate DCB scheme but dissimilar relays in the primary POTT scheme. Fig. 16 shows a simplified one-line diagram of the protected transmission line and equivalent system sources at each terminal. The source impedance behind Bus L is significantly higher than the source impedance behind Bus R. This implies that the source behind Relays L1 and L2 is weak relative to the source behind Relays R1 and R2. Relays L1 and R1 communicate in a POTT scheme via a fiber-optic multiplexer channel. Relays L2 and R2 communicate in a DCB scheme via a PLC channel.

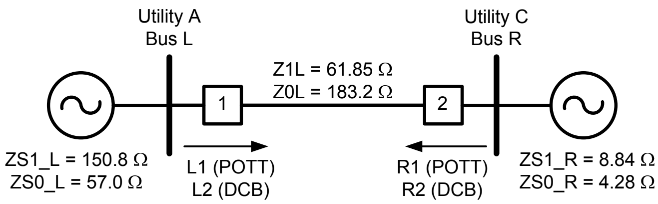

Fig. 16. Protected transmission line for Case 3 (all values are in primary ohms).

The primary scheme consists of relays from different manufacturers. The relays compare in the following ways:

- Both relays use positive-sequence memory-polarized phase mho distance elements.
- The directional overcurrent elements in Relay L1 [17] determine the direction of a fault using torque, which requires minimum voltage and current to make a directional decision. Relay R1 [18] uses impedance to make a directional decision and has no minimum voltage requirements.
- Both relays contain mho phase, mho ground, and ground directional overcurrent elements.
- Both Relays L1 and R1 include echo logic.

In this scenario, enabling the sensitive ground directional overcurrent elements and disabling the echo logic would not provide dependable operation of the POTT scheme when the weak terminal is unable to detect an internal fault.

To ensure fast fault clearance for internal faults during a normally occurring weak infeed condition, it was recommended to enable echo logic and disable the ground directional overcurrent elements. Also, because the alternate DCB scheme consisted of similar relays at either end, the ground directional elements were enabled to provide high-speed fault resistance coverage.

VIII. Conclusion

Directional comparison schemes that employ directional elements are used for transmission line protection because they are highly selective and provide high-speed fault clearance from both terminals for the entire protected line. The most common directional comparison schemes discussed in this paper are DCB and POTT. Similar to the DCB scheme, the hybrid POTT scheme uses reverse elements to block trip for external faults. To maintain security of the scheme, the reverse elements have to be set more sensitive than the forward overreaching pilot elements at the remote terminal.

Sensitivity is most often measured in terms of fault resistance coverage. Directional sensitivity, voltage, and current thresholds are some of the factors that affect the sensitivity of relay elements. “Like” relays have the same sensitivity, element response time, and operating principles. Therefore, for an external fault, because the relays at both the local and remote ends see the same through-fault current, using like relays in a pilot scheme will certainly ensure coordination if the relay elements are set appropriately. Due to construction, project schedule timing, budget constraints, and, in the case of tie lines, different relay standards, pilot schemes having dissimilar relays at either end are used, which compromises the security of the scheme.

Phase and ground distance elements have a variety of polarizing techniques (e.g., positive-sequence memory and compensator distance polarization). Arc resistances affect the apparent impedance and therefore sensitivity. However, because arc resistance is less of a problem with phase faults when compared with ground faults, coordinating phase elements is less of a concern. Apart from different polarizing techniques, ground distance elements include more options for directional supervision, which also need to be carefully coordinated. With differences in operating principles, polarizing techniques, supervisory directional elements, and so on, there is no guarantee to ensure coordination for all external faults. However, the risk of resulting misoperations for external faults is usually acceptable in the case of distance elements, given their limited reaches.

The effect of reach setting, remote infeed, source strength, and polarization techniques on the sensitivity of ground distance elements was studied. In pilot schemes, setting the pilot trip zone equal to the longest overreaching element improves the speed of operation and fault resistance coverage. Fault resistance coverage of distance elements in POTT schemes can be further improved by using echo logic.

Similar to ground distance elements, the ground directional overcurrent elements have a variety of polarizing quantities to choose from. However, the risk of misoperation due to different operating principles and high sensitivity of the directional elements is usually unacceptable. Therefore, it is usually preferred that only ground distance elements be used, if available, in DCB and hybrid POTT schemes employing dissimilar relays.

Given that high-resistance faults have little impact on system stability, the sensitive time-delayed overcurrent elements can be relied on to clear those faults. However, if it is preferred to use the ground directional overcurrent elements to provide high-speed fault resistance coverage, disabling the echo logic in the hybrid POTT scheme is highly recommended.

Enabling the echo logic is highly advantageous because it provides rapid fault clearance of all internal faults for weak infeed, faults with arc resistance, or remote terminal open conditions.

IX. References

[1] Z. P. Campbell, Y. Xue, and R. C. Dixon, "Power Line Carrier Directional Comparison Blocking Misoperation Event Analyses and Avoidance Techniques," proceedings of the 67th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2013.

[2] IEEE PSRC Working Group, "Single Phase Tripping and Auto Reclosing of Transmission Lines," *IEEE Transactions on Power Delivery*, Vol. 7, Issue 1, January 1992, pp. 182–192.

[3] D. Tziouvaras and D. Hou, "Out-of-Step Protection Fundamentals and Advancements," proceedings of the 30th Annual Western Protective Relay Conference, Spokane, WA, October 2003.

[4] J. Roberts, E. O. Schweitzer, III, R. Arora, and E. Poggi, "Limits to the Sensitivity of Ground Directional and Distance Protection," proceedings of the Spring Meeting of the Pennsylvania Electric Association Relay Committee, Allentown, PA, May 1997.

[5] J. Mooney and J. Peer, "Application Guidelines for Ground Fault Protection," proceedings of the 24th Annual Western Protective Relay Conference, Spokane, WA, October 1997.

[6] E. O. Schweitzer, III, and J. Roberts, "Distance Relay Element Design," proceedings of the 46th Annual Conference for Protective Relay Engineers, College Station, TX, April 1993.

[7] G. Benmouyal, A. Guzmán, and R. Jain, "Tutorial on the Impact of Network Parameters on Distance Element Resistance Coverage," proceedings of the 40th Annual Western Protective Relay Conference, Spokane, WA, October 2013.

[8] E. O. Schweitzer, III, N. Fischer, and B. Kasztenny, "A Fresh Look at Limits to the Sensitivity of Line Protection," proceedings of the 37th Annual Western Protective Relay Conference, Spokane, WA, October 2010.

[9] F. Calero, A. Guzmán, and G. Benmouyal, "Adaptive Phase and Ground Quadrilateral Distance Elements," proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[10] K. Zimmerman and D. Costello, "Fundamentals and Improvements for Directional Relays," proceedings of the 63rd Annual Conference for Protective Relay Engineers, College Station, TX, March 2010.

[11] K. Zimmerman and D. Roth, "Evaluation of Distance and Directional Relay Elements on Lines With Power Transformers or Open-Delta VTs," proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[12] A. Guzmán, J. Roberts, and D. Hou, "New Ground Directional Elements Operate Reliably for Changing System Conditions," proceedings of the 51st Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, April 1997.

[13] F. Plumptre, M. Nagpal, X. Chen, and M. Thompson, "Protection of EHV Transmission Lines With Series Compensation: BC Hydro's Lessons Learned," proceedings of the 62nd Annual Conference for Protective Relay Engineers, College Station, TX, March 2009.

[14] GE-DLP-B Instruction Manual, Pub #GEK-100562C. Available: http://store.gedigitalenergy.com/manuals/Documents/DLP/GEK-100562C.pdf.

[15] SEL-321 Instruction Manual. Available: http://www.selinc.com.

[16] SEL-121F Instruction Manual. Available: http://www.selinc.com.

[17] GE-D60 Instruction Manual, Document GEK – 113549. Available: https://www.gedigitalenergy.com/products/manuals/d60/d60man-v1.pdf.

[18] SEL-421 Instruction Manual. Available: http://www.selinc.com.

X. Biographies

William L. Tucker received his BSEE from Texas Tech University in 1986 and an MBA from Oklahoma City University in 2000. He began working for Central and South West Corporation as a Substation Engineer in the West Texas Utilities subsidiary and, in 1996, began working in the System Protection group of Central and South West Services. After Central and South West became part of the American Electric Power system, William held various protection and control positions, including technical support and supervision of protection and control engineering and protection and control field personnel. William is a registered professional engineer in Oklahoma and Texas.

Andrew K. Burich received his BS in electrical engineering, summa cum laude, from the University of Missouri, St. Louis, in 2012. He has been employed with Schweitzer Engineering Laboratories, Inc. as a protection engineer in the engineering services division since his graduation. He is a registered professional engineer intern in the state of Illinois.

Michael J. Thompson received his BS, magna cum laude, from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN), where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a principal engineer in the engineering services division at SEL, a senior member of the IEEE, chairman of the Substation Protection Subcommittee of the IEEE PES Power System Relaying Committee, and a registered professional engineer. Michael was a contributor to the reference book, *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers, and has a number of patents associated with power system protection and control.

RadhaKiranMaye Anne received a BE in electrical and electronics engineering from Andhra University, India, in 2001; an ME in electrical engineering from Osmania University, India, in 2003; and her MS in electrical engineering from the University of Missouri, Kansas City in 2008. She joined Schweitzer Engineering Laboratories, Inc. in 2009. Her expertise includes protection scheme design, power system modeling, transmission line protection, and relay coordination studies. She has more than three years of teaching experience and is a member of IEEE.

Sneha Vasudevan received her BE in electrical engineering from Anna University, India, in 2010 and an MSEE from The Ohio State University at Columbus in 2011. Since graduating, she has been employed with Schweitzer Engineering Laboratories, Inc. as a protection engineer in the engineering services division.

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