Considerations and Benefits of Using Five Zones for Distance Protection

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Abstract—**This paper discusses application considerations for communications-assisted line protective relays using five distance zones. This discussion includes how modern microprocessor-based relays can benefit the power system when properly applied to pilot protection and backup step-distance schemes. Different problematic scenarios—like mutual coupling, series compensation, long lines with adjacent short lines, current transformer saturation, and the use of coupling-capacitor voltage transformers (CCVTs)—are discussed. The paper analyzes using multiple zones in step-distance and pilot protection schemes such as permissive overreaching transfer trip (POTT), directional comparison unblocking (DCUB), and directional comparison blocking (DCB).**

I. INTRODUCTION

Distance element protection is widely used as the main protection function for transmission systems. Due to complexities in the transmission network, a step-distance scheme is usually restricted from tripping instantaneously for 100 percent of the protected line. Instead, the instantaneous distance element reach is typically set to cover 80 percent of the line, and the remaining 20 percent is covered by a time-delayed distance element (typically set for 20 cycles) that is coordinated with the remote terminal.

Tripping times for the remaining 20 percent can be further improved with a pilot protection scheme using a communications channel. This communications-aided scheme allows both relays to exchange binary information to provide fast tripping for 100 percent of the line, reducing the total fault-clearing time.

In the case of electromechanical relays, the same distance zones were applied for both the pilot protection scheme and the time-delayed step-distance scheme. This approach was applied because the relays had a limited number of zones available to configure. However, modern microprocessor-based relays offer an increased number of distance zones, making it possible to apply dedicated and distinct zones for pilot protection and step-distance schemes. This inherently increases the performance, security, and dependability of the line protection and, consequently, the power system.

Even with the availability of additional zones, many pilot protection schemes are still applied traditionally. The overreaching and reverse zones are combined for pilot protection and time-delayed step-distance schemes instead of taking advantage of the additional zones offered by modern relays. Too often, the purpose of the additional zones is misunderstood and their reaches are set incorrectly, creating security concerns for the protection schemes and jeopardizing power system stability.

Long reaches for the step-distance elements can be dangerous; they have been one of the causes or aggravating factors of many major blackouts around the world [1]. Step-distance elements with excessive reaches are prone to trip under the unusually heavy load situations that can occur during system contingencies, as shown in Fig. 1.
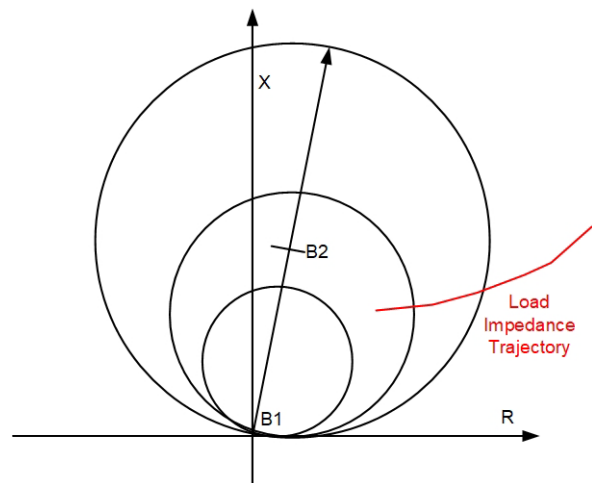

Fig. 1. Load Impedance Trajectory Coming Into the Overreaching Zones

Overreaching zones from step-distance schemes set with a very long reach come into conflict with line loadability requirements. Applying the five zones available in modern distance relays wisely is necessary for protection engineers to increase power system reliability and security.

The use of independent and dedicated zones for pilot protection and step-distance schemes, when properly applied, can benefit the power system by solving or minimizing the effects of different problematic scenarios, such as mutual coupling, series compensation, long lines with adjacent short lines, heavy load, current transformer (CT) saturation, and multiterminal lines.

II. MODERN DISTANCE RELAYS

As new protection schemes were developed in the past, more zones were needed to apply them properly. With the limited zones of electromechanical relays and limited panel space for additional relays, utilities faced challenges when trying to apply secure and dependable protection schemes for various scenarios. With the introduction of digital relays, the number of zones became a simple programming matter, providing a cost-effective way to create new protection guidelines to overcome the challenges of traditional electromechanical relays. Modern digital line protective relays have many advantages over

electromechanical relays, including additional protection zones for distance elements, control functions, and communications capabilities.

Limiting the distance protection to three zones, as depicted in Fig. 2, requires compromises between speed and selectivity. Modern relays commonly provide up to five zones to solve challenging problems, including the option to apply high-speed zones as dedicated elements for pilot protection schemes [2] and conventional distance elements for time-delayed step-distance zones. This enables cost-effective solutions that eliminate extra devices and improve the overall dependability and security of the protection scheme [3].
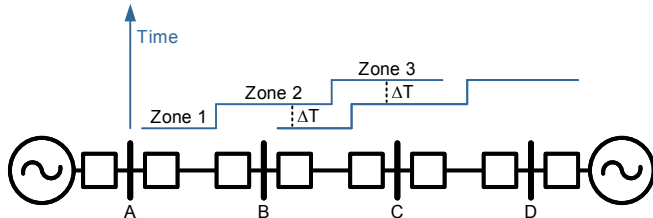

Fig. 2.   Distance Zones (ΔT = Coordination Time)

In addition to increasing the number of zones for line distance protection, modern relays also integrate flexible programming. Flexible programming allows protection engineers to create custom protection schemes for their transmission system. These two features—along with improved speed and logic to counter situations such as coupling-capacitor voltage transformer (CCVT) transients, series compensation, and out-of-step conditions—have allowed relay engineers to conquer many of the issues faced when using electromechanical relays.

Modern relays introduce new technologies to help solve existing and future problems. As power systems change and new equipment and technology are introduced, protective relays need to evolve as well. Power systems are reaching their limits, and utilities are trying to avoid building new lines by looking for any possible way to transmit more power across existing lines. With expanded monitoring capabilities and communications, utilities are learning more and more about their power systems and are understanding the need to migrate to new technology.

III.   Directional Comparison Pilot Schemes

Traditional distance protection has many challenges, including outfeed, infeed, series compensation, measurement errors, inaccurate line models, and line nonhomogeneity. Clearing a fault as fast as possible requires an instantaneous element. To deal with these challenges, step-distance approaches need to reduce the reach of the instantaneous zone to avoid overreaching and tripping for a fault in the next line segment. This reduced reach improves the selectivity of the protection system and allows adequate time for the proper relay to clear the fault. The instantaneous zone can be set to 80 percent of the line length in most cases, but can be set as low as

20 percent in series-compensated lines or disabled in some cases of overcompensation. Reducing the reach affects fault-clearing times in the last portion of the line. To overcome the reduced reach, pilot schemes using communications were introduced to cover 100 percent of the line with high-speed fault-clearing. Pilot protection provides rapid and near-simultaneous tripping at all terminals for any fault on the protected line.

The following subsections briefly discuss various pilot schemes. Each scheme has its own advantages and disadvantages. All pilot schemes only require very limited bandwidth channels, which makes them cost-effective to implement [4].

A.   Permissive Overreaching Transfer Trip

A permissive overreaching transfer trip (POTT) scheme uses overreaching distance zones at both terminals of the line, as shown in Fig. 3. If both relays declare the fault as forward, then accelerated tripping occurs. The speed of the protection is limited only to the detection of the fault by the relay and the communications channel delay from both ends. This clears faults almost instantaneously while remaining secure for most situations.

Fig. 3 illustrates a POTT scheme implemented with Zone 2 as the overreaching zone from each relay. As a fault is detected by the forward overreaching Zone 2 element from Terminal S, the information is transmitted to the remote relay at Terminal R. If the Terminal R relay also detects a fault within its forward overreaching Zone 2, then the relay trips and sends a permissive signal back to Terminal S.
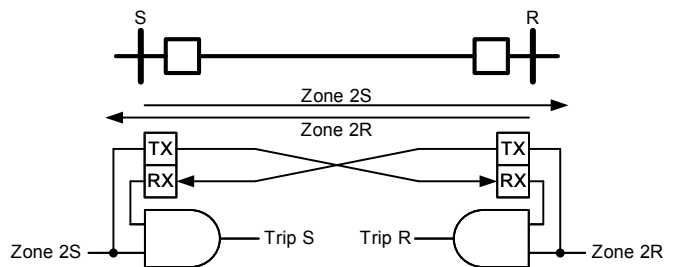

Fig. 3.   POTT Scheme

Creating a POTT scheme with a limited number of zones can be challenging. For instance, using the same distance element in both the POTT scheme and the backup step-distance scheme can present contradictory requirements, as explained in Section VII. By introducing additional zones, it is possible to apply a dedicated zone for the pilot scheme and separate zones for the step-distance scheme, thereby removing the contradictory requirements.

Some challenges for a POTT scheme include infeed from multiterminal lines, current reversal in parallel lines, and mutual coupling. Infeed from one terminal in a multiterminal line can cause the distance elements used in the POTT scheme to underreach. To overcome the underreach, the overreaching zone can be extended. However, doing so may aggravate other issues, such as current reversal. A current reversal occurs when

a communications scheme is protecting a parallel line and a fault occurs in which the overreaching zone from one line sees the fault in the parallel line, as shown in Fig. 4.
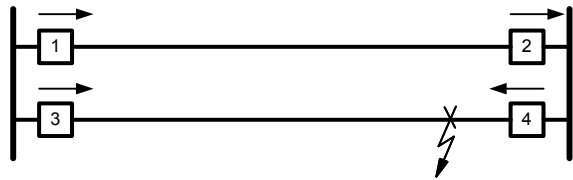

Fig. 4.   Fault in the Parallel Line

In Fig. 4, the relay at Breaker 1 detects the fault within its overreaching zone and sends a permissive signal to the relay at Breaker 2. Breaker 2 does not trip because the relay detects the fault in the reverse direction and restrains for it. The instantaneous zone for the relay at Breaker 4 clears instantly, causing the currents to reverse back through the healthy line, as shown in Fig. 5.
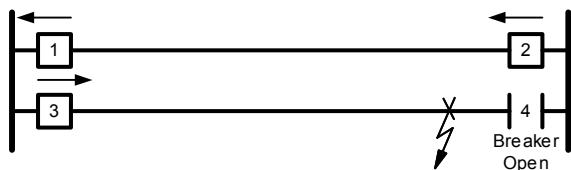

Fig. 5.   Current Reversal Through Healthy Line

As the current reverses, the relay at Breaker 2 detects the fault in the forward direction, while still receiving the permissive signal from the relay at Breaker 1, thus causing the relay at Breaker 2 to operate for the fault. One solution for this is to apply current reversal guard logic in which, if the relay at Breaker 2 previously saw a fault in the reverse direction, it would add an additional delay to allow time for the relay at Breaker 3 to clear the fault [5].

Finally, mutual coupling from parallel lines can cause a ground distance element to overreach or underreach. An element underreaches if the relay measures an impedance larger than that to the fault. The element overreaches if it measures an impedance smaller than the impedance to the fault.

B.   Directional Comparison Unblocking

A directional comparison unblocking (DCUB) scheme uses essentially the same logic as a POTT scheme and can be considered a variant of it. A DCUB scheme is applied when there is the possibility of losing the communications channel during an internal fault. Frequency-shift keying (FSK) communication is commonly applied with this scheme. The scheme sends a monitoring signal called a guard signal at one frequency and a trip signal at a different frequency. One challenge is that an in-section fault can disrupt the communications and the permissive signal may not be transmitted. Because a guard signal is always transmitted, if the remote relay does not receive a permissive or guard signal, it enables loss-of-guard logic. This logic opens a small window of time in which the relay is allowed to high-speed trip, even

without the permissive signal from the remote end. This does, however, lead to the possibility of tripping for an out-of-section fault because the guard signal is bypassed.

C.   Directional Comparison Blocking

A directional comparison blocking (DCB) scheme uses a reverse zone to send a blocking signal to the remote relay, as shown in Fig. 6. An overreaching zone in the remote relay assumes that all faults are internal and, therefore, needs to be delayed by a communications channel delay to allow proper blocking if the fault is external to the protection zone. This scheme requires a fast and very dependable communications channel. DCB schemes can be implemented with power line carrier or other types of communications.
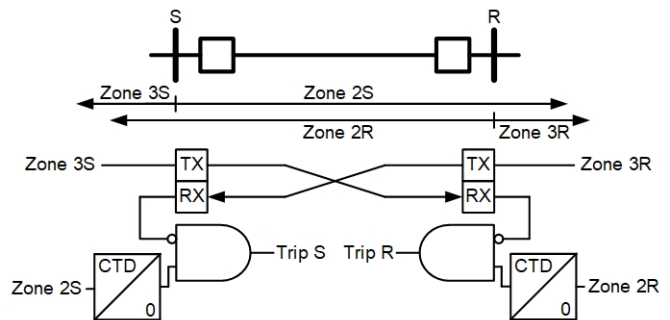

Fig. 6.   DCB Scheme

Coordinating DCB schemes can be challenging, and a few guidelines are generally followed. First, the reverse zone in the local relay, which provides the blocking signal, must reach beyond the overreaching zone from the remote relay. This ensures that the block signal is sent to the remote relay for an out-of-section fault behind the local relay. A coordination time delay is used to ensure that the local pilot overreaching zone is delayed long enough to receive the blocking signal from the reverse zone of the remote relay. The reverse zone in the remote relay must be set properly in order to be faster than the local forward overreaching zone and to allow for a reduced coordination time delay, as explained in Section V.

Finally, when an external fault is being cleared, the reverse zone in the local relay must drop out more slowly than the forward overreaching zone of the remote relay by means of an extension timer; otherwise, the forward overreaching zone may not drop out prior to the blocking signal dropping out, thus issuing a trip. Also, the extension timer is used to avoid misoperation caused by the current reversal that may occur in the case of parallel lines, as previously explained.

IV.   EFFECTS OF CT SATURATION ON DISTANCE ELEMENT PERFORMANCE

CTs are integral to providing accurate measurement signals to protective relays. When not properly selected for a protection system, CTs can cause adverse effects on the overall security and dependability of the scheme. Properly selecting a CT

requires considerations for dc offset, fault current, X/R ratio, and maximum fault-clearing time. The criterion to avoid saturation is demonstrated in [6] and is shown in (1).

$$20 \geq \left(\frac{X}{R} + 1\right) \cdot I_f \cdot Z_b \qquad (1)$$

where:

I_f is the maximum fault current in per unit (pu) of the CT primary rating.

Z_b is the CT burden in pu of the standard burden.

X/R is the ratio of reactance to resistance of the primary fault circuit.

Failure to properly select CTs can lead to CT saturation, which can cause delays in fault clearing, affect the sensitivity of the distance element reach, and affect a relay's ability to properly identify the fault type and/or location, as shown in Fig. 7.
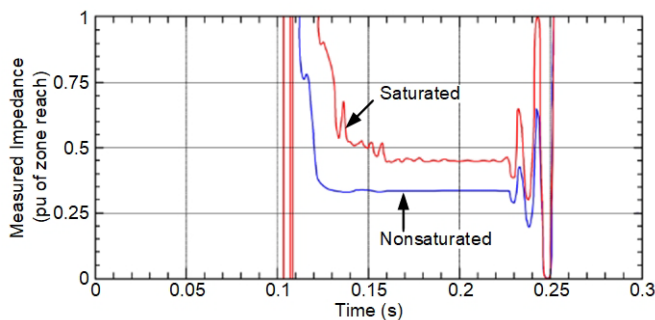

Fig. 7.   Calculated Reach Value With Saturated and Nonsaturated CTs

Reference [7] demonstrates that CT saturation can affect the reach of the distance element, and the overreaching zone may not have the reach expected. In Fig. 8, for a fault applied at 100 percent of the line impedance, the CT barely saturated two cycles into the event. The overreaching zone element operated within one cycle, stayed asserted for two cycles, dropped out for two cycles during the saturation, and then reasserted.
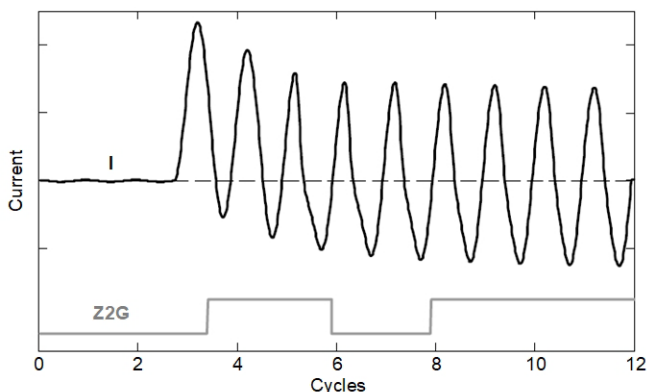

Fig. 8.   Secondary Current and Zone 2 Output

The reach calculation in Fig. 9 shows that the measured impedance is within the overreaching zone reach setting; however, as the CT begins to saturate, the impedance increases to a value greater than the reach setting, causing the element to reset and drop out. As the CT comes out of saturation, the impedance measurement falls within the reach setting.

One option to counter the underreach caused by the CT saturation is to increase the reach of the overreaching zone applied exclusively to the pilot scheme and to use a different overreaching zone for the step-distance scheme that is coordinated properly with the adjacent lines. Extending the reach to a minimum of 200 percent improves the element performance and decreases the possibility that the element will drop out during CT saturation. CT saturation cannot cause issues for a pilot scheme with dedicated distance elements applied for both the forward and reverse zones.
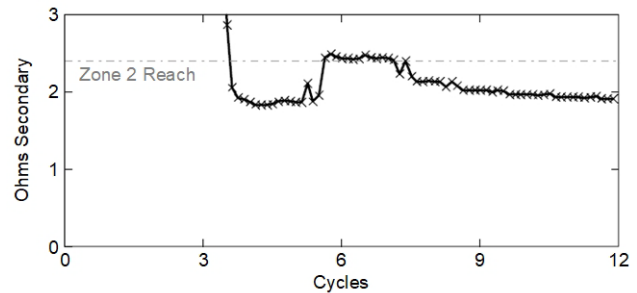

Fig. 9.   Measured Impedance and Zone 2 Reach Setting

V.   DCB SCHEME EXTENDED REVERSE ZONE REACH

As previously mentioned, a DCB scheme uses an overreaching zone for high-speed tripping and a reverse zone for blocking. These zones can comprise both distance and directional overcurrent elements, both with independent coordination timers.

The coordination timers are set to coordinate with the block trip signal sent from the remote terminal. If a fault occurs behind the remote terminal, the local relay asserts its overreaching zone (if the fault is within the reach) while the remote relay asserts its reverse zone. When the remote relay asserts the reverse zone, it should immediately send a blocking signal to the local relay. The coordination timer delay (CTD) on the overreaching zone allows time for the relay to receive the block from the remote relay. A simple overview of this logic is shown in Fig. 10.
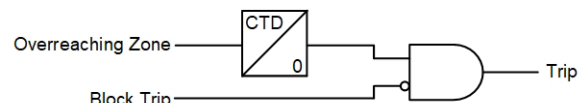

Fig. 10.   DCB Trip Logic

The coordination timer allows time for the block trip signal to arrive. For maximum effect, this timer must take into account the communications channel latency, control input recognition time, and remote reverse zone maximum time. If a blocking signal is not received before the coordination timer expires, the relay high-speed trips, even for an external fault within the reach of the overreaching zone.

Decreasing the margin of the coordination time delay requires that the reverse element asserts as soon as possible for the fault. Speeding up the operation requires the reverse elements to have a larger distance reach or a lower overcurrent setting. Focusing on just the distance elements, the reach of the remote reverse zone can be set at a minimum to match the local

relay's overreaching zone. If the local overreaching zone is set at 200 percent, then the remote reverse zone should be set the same. This results in a fast assertion of the remote reverse zone, as shown in Fig. 11.
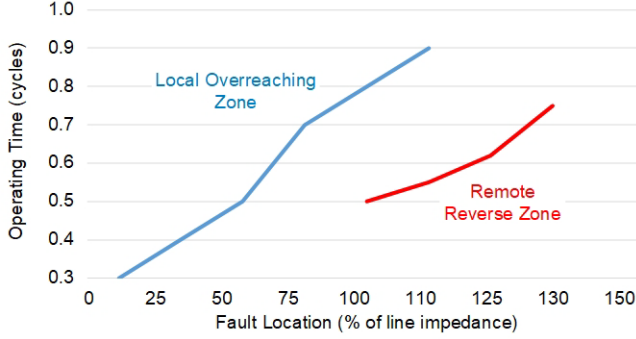

Fig. 11. Tripping Times for the Local Overreaching Zone and Remote Reverse Zone Applied to a DCB Scheme

Setting the remote reverse zone properly allows the remote relay to operate faster for external faults, thereby sending the blocking signal sooner. Reference [8] proposes setting the remote reverse zone equal to 150 percent of the local overreaching zone minus the line impedance, as shown in (2).

$$\text{Reverse DCB Zone} = 1.5 \bullet (\text{Overreaching DCB Zone}) - Z1L \quad (2)$$

This approach allows the coordination time of the local relay to be reduced to operate faster for internal faults, thus improving the coordination margin. This leads to faster fault-clearing times and improvements to system stability. The additional conventional distance zones, for instance Zone 4 and Zone 5, can then be set as the regular step-distance backup elements, with reaches set according to the coordination requirements of such schemes [8].

VI. Mutually Coupled Parallel Lines

Transmission lines that share the same tower structure or common right-of-way experience a zero-sequence mutual coupling between the conductors. This coupling affects the impedance measurement of the distance elements, particularly the ground distance elements. The overreaching zones should be compensated to make sure the zero-sequence mutual coupling does not reduce the desired reach.

In Fig. 12, two parallel mutually coupled lines terminate at the same stations. For example, an A-phase-to-ground fault occurs at the end of Line 1, which is protected by the relay as shown.
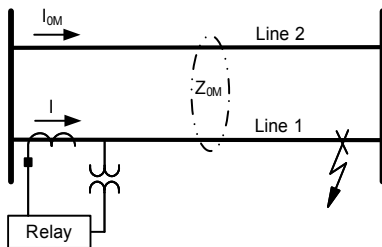

Fig. 12. Mutually Coupled Lines

For this A-phase-to-ground fault, the current used for the A-phase ground distance element is $I = I_a + k_0 \bullet I_r$, where k_0 is the zero-sequence compensation factor. The voltage used, V_a, is provided by (3).

$$V_a = mZ_{1L}\left(I_a + k_0 \bullet I_r\right) + mZ_{0M} \bullet I_{0M} \quad (3)$$

The zero-sequence mutual coupling alters the apparent impedance of the fault that the ground distance element measures, as shown in (4) [9].

$$Z_{APP} = \frac{V_a}{I_a + k_0 \bullet I_r} = mZ_{1L} + mZ_{0M} \bullet \frac{I_{0M}}{I_a + k_0 \bullet I_r} \quad (4)$$

This apparent impedance is different on each phase depending on the fault location, the location of the conductors between the two lines, whether the ground wires are segmented or continuous, and whether or not the line is transposed.

The effect of the zero-sequence mutual coupling in the distance element is an underreach when currents I_r and I_{0M} flow in the same direction, which can prevent the overreaching zone from detecting a fault within the line if the coupling is strong enough [10]. To ensure overreaching for the pilot protection scheme, typical settings need to be much greater than the standard 125 percent. Applying the same overreaching zone for both the pilot scheme and the step-distance scheme may cause coordination problems. On the other hand, applying a dedicated zone for pilot scheme protection ensures optimized settings for mutually coupled lines.

VII. Lines of Different Lengths

In power systems, a long transmission line may arrive at a bus with a short transmission line leaving that same bus. When this scenario occurs, it becomes difficult to coordinate the requirements of the overreaching time-delayed distance element used in the step-distance scheme and the requirements of the overreaching distance element used for pilot protection.

In this example, Zone 2 is applied for both schemes (i.e., a time-delayed zone for the step-distance scheme and an overreaching zone for the pilot scheme). If the zone reach is set to provide a tripping time for the pilot protection as fast as possible, then the local terminal protection may overreach the instantaneous underreaching step-distance zone of the remote line, as shown in Fig. 13 and Fig. 14. Reference [3] suggests that the minimum reach for the step-distance overreaching zone intended to cover the entire line should be at least 1.18 times the line impedance; however, this reach, while providing proper coverage for the time-delayed step-distance scheme, may not provide the fastest tripping time for the pilot protection.
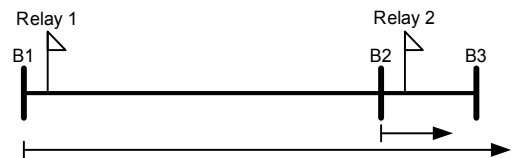

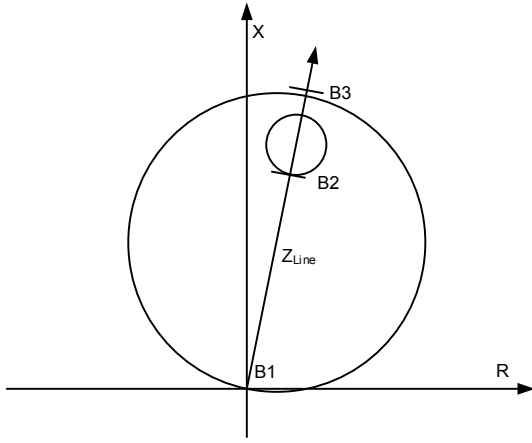Fig. 13. Long Line With Neighboring Short Line

Fig. 14.   Lack of Coordination Between Local and Remote Time-Delayed Overreaching Zones

By 1) setting a dedicated distance zone to be used exclusively as the time-delayed backup step-distance element with appropriate reach and delay to cover the entire line and keep the coordination and 2) setting a dedicated high-speed distance zone as the overreaching distance element for the pilot scheme using an optimized reach, the best of both schemes is achieved and a faster fault-clearing time can be provided by the pilot scheme, as shown in Fig. 15.
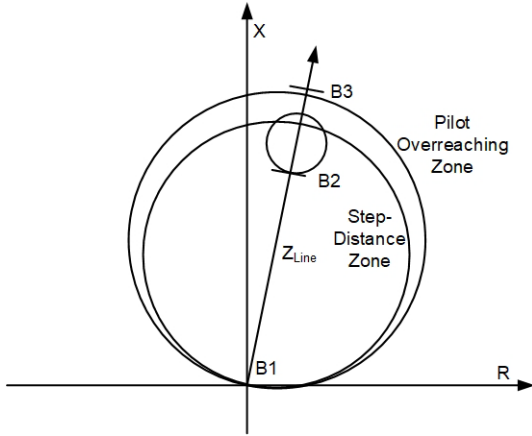

Fig. 15.   Keeping the Coordination With Independent Distance Elements for the Pilot and Step-Distance Schemes

VIII.   MULTITERMINAL LINES

Multiterminal transmission lines have three or more terminals. In some cases, these transmission lines have positive-sequence sources connected to all terminals, as shown in Fig. 16.

Multiterminal lines present additional challenges compared with two-terminal transmission lines. Multiple scenarios in terms of the generation connected to the terminals cause significant changes in the fault current levels and, consequently, in the apparent impedance measured by the distance relays.

For example, consider the case of a bolted three-phase fault at V_Y in the system shown in Fig. 16. Here, the apparent impedance Z_{XApp} measured by Relay X can be expressed by (5).

$$Z_{XApp} = \frac{V_X}{I_X} = Z_X + Z_Y \frac{I_X + I_Z}{I_X} \qquad (5)$$

where:

V_X is the voltage at Terminal X.

I_X is the current measured by Relay X.

I_Z is the current measured by Relay Z.

Z_X is the positive-sequence impedance of Section X of the line.

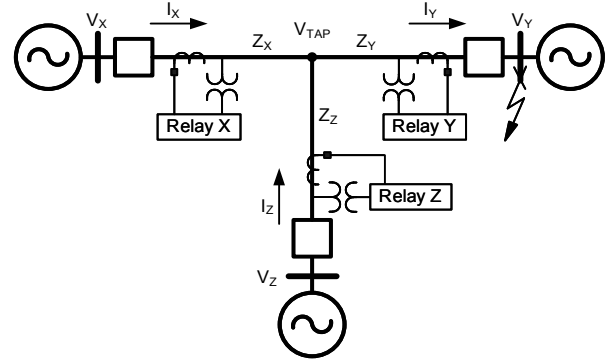Z_Y is the positive-sequence impedance of Section Y of the line.

Fig. 16.   Three-Terminal Transmission Line

Equation (5) shows that Z_{XApp} can be much greater than $Z_X + Z_Y$ if both I_X and I_Z are flowing from bus to line (infeed). If I_Z flows from line to bus, opposite I_X, the apparent impedance seen by Relay X is less than $Z_X + Z_Y$ (outfeed). If Terminal Z is open (i.e., I_Z is equal to zero), there is no infeed or outfeed effect and the apparent impedance seen by Relay X is $Z_X + Z_Y$. Protection engineers must consider all possible scenarios to define the settings for the distance element reach, which very likely will result in contradictory requirements.

If the Zone 2 element is part of the pilot scheme, it must be set to detect faults on all segments of the protected line while considering the effect of infeed from the third terminal [5] [11]. This requirement leads to a very large setting for the Zone 2 reach and can bring additional problems if the same Zone 2 element is used in the time-delayed step-distance scheme. Because the infeed effect can vary quite significantly with generation connected to each terminal, the actual reach of the Zone 2 element varies significantly. When infeed is not present, the Zone 2 element can reach beyond the Zone 1 element in the adjacent line, causing a lack of coordination between the Zone 2 elements of the different lines. Moreover, the distance protection cannot impose restrictions to the transmission line loadability, so a very large zone element reach setting for the step-distance scheme is not practical.

Because of the limitations imposed when the Zone 2 element is used for the time-delayed step-distance scheme and there is an infeed effect in a three-terminal transmission line, it is common to experience sequential tripping in this system configuration [5]. One of the purposes of applying pilot protection is to avoid sequential tripping and to provide fast fault-clearing times on all portions of the transmission line, ensuring a safer and more reliable power system operation [4].

In the case of POTT and DCUB schemes, the infeed in a three-terminal transmission line may prevent the proper operation of the scheme. Having a dedicated overreaching zone element for the pilot protection allows for an optimized setting without the restrictions that can exist for the time-delayed step-distance scheme. This dedicated zone element can be set to detect faults in any section of the protection line while considering the worst case for the infeed effect. Because coordination with zone elements from the adjacent lines is not a problem for the pilot protection, the reach setting for the dedicated zone can be easily based on the largest apparent impedance for faults at the remote terminal [5]. This approach ensures a secure and dependable fast fault-clearing time for the pilot protection schemes.

A transmission line protective relay with multiple zones provides optimized protection for multiterminal transmission lines via the use of dedicated zones for pilot protection schemes.

IX. SERIES-COMPENSATED LINES

Series-compensated lines are widely applied in extra high-voltage (EHV) transmission systems due to the requirements of environmental permits and operational constraints. This practice allows for increased power transfer using the same number of transmission lines, thus making better use of the existing transmission lines and rights-of-way.

The principle behind the application of series compensation in power systems is the reduction of the total line reactance; the capacitor bank introduces a negative reactance (capacitive) in series with the line reactance (inductive). This effect enhances the power system stability and increases the loadability, or power transfer capability, of transmission corridors.

Per [12], the main benefits of applying series capacitors in transmission systems are:

- Steady-state voltage regulation and an increased voltage collapse limit.
- Increased power transfer capability from raising the transient stability limit.
- Improved reactive power balance.
- Increased power transfer capacity.
- Active load sharing between parallel circuits and loss reduction.
- Reduced power transmission costs due to decreased investment costs for new power lines.

Protection engineers always face challenges in the definition, configuration, and validation of protection schemes for series-compensated transmission lines. Validation generally involves transient testing of the protective relays using real-time digital simulation in a closed-loop environment. By wisely using all the resources available in modern digital protection and communications devices, reliable and secure protection, control, and monitoring systems can be deployed for series-compensated transmission lines, making series compensation even more attractive for utilities.

The application of series compensation typically occurs in transmission systems at the EHV level, usually in large transmission corridors. In these systems, a high-speed protection scheme is a natural requirement because of the large amounts of energy being transported and the need to maintain stability during disturbances. For this reason, it is important to ensure the fastest possible tripping time by the pilot protection.

Capacitor banks can be protected by metal-oxide varistors (MOVs) in parallel with the capacitors. When the MOV resistance changes, the effective capacitance of the series capacitor begins to decrease. Reference [13] shows that the parallel combination of a capacitor and an MOV is equivalent to the series combination of a resistor (R_C) and the capacitive reactance (XC_C). Fig. 17 shows the equivalent circuit of such a system.
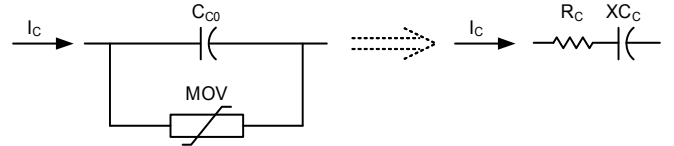

Fig. 17. Capacitor With MOV and the Equivalent Series Impedance Circuit

The values of R_C and XC_C depend on the through current of the series capacitor. Fig. 18 shows a plot of R_C and XC_C versus current. The variation of R_C and XC_C is of concern when determining the fault location for distance protection because the current can vary as a result of the changes in source impedance or fault resistance [14].
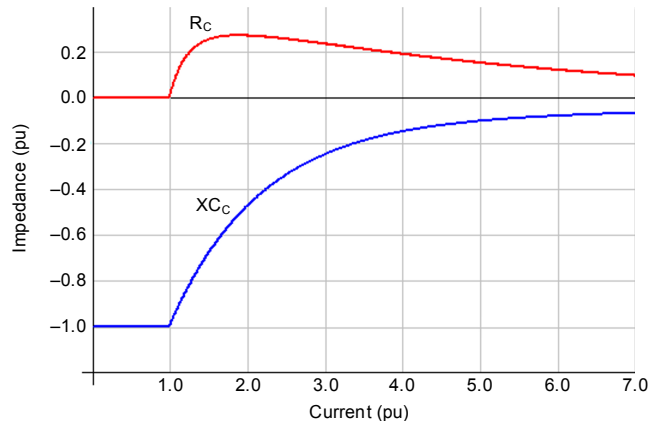

Fig. 18. Variation of R_C and XC_C Versus the Current in the Series Impedance Circuit

Series compensation introduces oscillations in currents and voltages that have frequencies lower than the rated system frequency (i.e., subharmonic frequency oscillations). These oscillations can cause a slower increase of the fault current compared with a noncompensated system [12]. The subharmonic frequency oscillations have a significant impact on the speed of the distance protection because they can cause the overreaching distance element to momentarily drop out (as shown in Fig. 19), resulting in a longer tripping time than is expected by the pilot protection scheme [15].

Typically, on series-compensated transmission lines, the Zone 1 element is reduced because of these subharmonic frequencies to prevent overreach for out-of-section faults. These same subharmonic frequencies can also cause the overreaching Zone 2 element to momentarily drop out if the measured impedance oscillates above the reach point. This

momentary dropout may correspond to the time when the relay receives a permissive signal from the remote terminal, thereby slowing down fault clearing until the measured impedance falls back under the reach point again. For the same reason Zone 1 is reduced, Zone 2 should be increased to prevent this dropout from occurring.
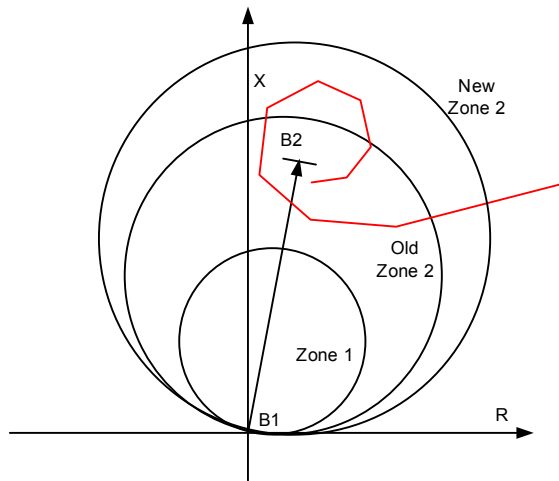

Fig. 19.   Distance Element Impedance Measurement Due to Subharmonic Frequencies

Reference [15] recommends extending the reach of the overreaching zone applied for the pilot protection to accommodate the subharmonic frequency oscillations. Thus, dedicating Zone 2 for the pilot scheme with a reach of 200 to 300 percent while using a dedicated Zone 4 and Zone 5 for the step-distance backup, for instance, is acceptable. This recommendation can be easily applied in a relay with multiple zones. The reach of a dedicated overreaching zone element can be set large enough to provide optimized coverage for faults in the series-compensated line without compromising security.

X.   EFFECTS OF CCVT TRANSIENTS ON ZONE 1 AND SOLUTIONS

CCVTs are widely used in high-voltage power systems for economic reasons [16]. The basic CCVT circuit is shown in Fig. 20 [3]. The line voltage is measured through a voltage divider formed by Capacitors C1 and C2, stepping down the line voltage to approximately 15 kV. This voltage is applied to a wound step-down transformer through a tuning reactor. The wound step-down transformer further reduces the voltage to the nominal relay burden levels of $115/\sqrt{3}$ V.
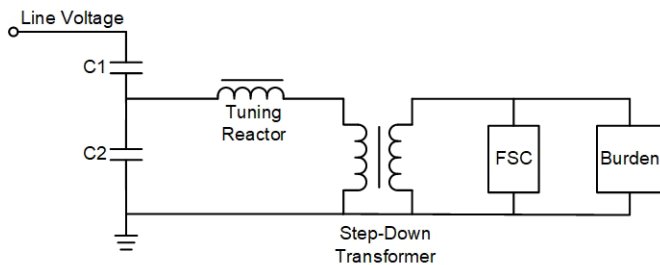

Fig. 20.   Basic CCVT Circuit

Connected in parallel with the secondary of the wound step-down transformer is a ferroresonance suppression circuit (FSC). The FSC is necessary to mitigate the resonance that can result from the interaction of the source capacitance and the magnetizing inductance from the wound step-down transformer and tuning reactor.

CCVTs experience a transient response that usually lasts less than 1.5 cycles when a fault occurs in the transmission line. Many factors affect the severity of the CCVT transient, including the following [16]:

- Point on the voltage wave where the fault occurs (fault inception angle).
- Magnitude of the stack capacitance (values of C1 and C2).
- Design of the FSC (active or passive).
- Composition of the burden connected to the CCVT.
- Turns ratio of the step-down VT.
- Excitation current of the intermediate transformer.

High-capacitance CCVTs and CCVTs with passive FSCs provide a better transient response during a fault. Small and resistive burden values, as found in modern microprocessor-based relays, also improve the CCVT transient response. A fault inception at a voltage zero-crossing produces more pronounced and severe transients.

In applications with high source-to-line impedance ratios (SIRs), the depression in the voltage magnitude caused by a fault in the transmission line is very significant, which leads to more-severe CCVT transients. Even applications with wound VTs can have problems with high SIRs [17].

CCVT transients affect the voltage measured by microprocessor-based relays, where the effect is a reduction in the fundamental component of the fault voltage. The CCVT transients, though lasting less than 1.5 cycles, can cause the distance algorithm to calculate a smaller impedance than the actual apparent impedance to the fault [16]. The CCVT transient causes the distance elements to overreach, causing some security concerns for the Zone 1 element application, which can lead to operations for external faults.

Fig. 21 shows the maximum allowed Zone 1 reach setting, considering only the effect of the CCVT transients for different values of SIR for the worst-case fault inception at the voltage zero-crossing [18]. The Zone 1 reach must be defined while taking into account other factors as well.

Reference [16] indicates that, in applications where the SIR is larger than 4, some measures are necessary to mitigate misoperations due to the Zone 1 overreaching caused by the CCVT transients. Some possible measures to avoid misoperations are to reduce the Zone 1 element reach based on the overreaching caused by the CCVT transients, to delay the Zone 1 element for 1.5 cycles, or even to disable the Zone 1 element.
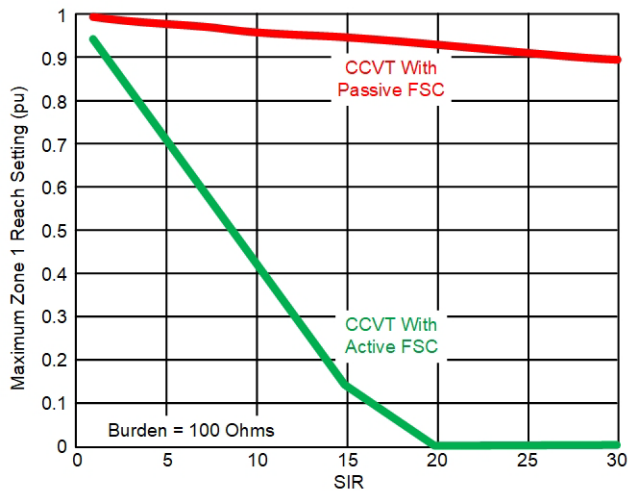
Fig. 21.   Limits for Setting Zone 1 Reach

However, for distance relays with five zones of protection, another mitigation strategy can be easily implemented. The solution consists in splitting the regular coverage of the instantaneous zone (usually 80 percent of the transmission line) into two sections (see Fig. 22). One section is covered by the typical instantaneous element with a reduced reach setting, and the remaining section is covered by an additional zone (Zone 5, for instance) with a time delay of 1.5 cycles. This approach ensures high-speed tripping for bolted, close-in faults and avoids misoperations caused by the overreaching caused by the CCVT transients.
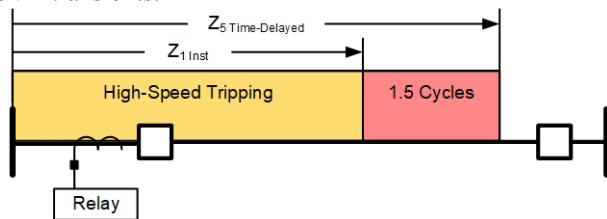

Fig. 22.   Splitting the Regular Zone 1 Coverage Into Two Sections

Some modern distance relays have the option to enable CCVT transient detection logic, which can detect the CCVT transients and dynamically delay the Zone 1 element up to 1.5 cycles [16].

XI.   GENERAL GUIDELINES FOR APPLYING FIVE ZONES

To provide some general guidelines, the following example applications summarize three different approaches to using five distance zones. The three examples use a protective relay that has three high-speed distance elements (Zone 1, Zone 2, and Zone 3) used as the instantaneous step-distance zone and pilot protection zones. The two remaining zones (Zone 4 and Zone 5) are conventional distance elements and, for this reason, are used for the time-delayed step-distance zones.

The first example application, shown in Fig. 23, uses Zone 5 as an extended-reach step-distance forward backup zone as follows:

- Zone 1 set at 80 percent.
- Zone 2 set at 200 percent or more for forward pilot protection only.
- Zone 3 set at 200 percent or more for reverse pilot protection only.
- Zone 4 set at 118 to 150 percent to cover the end-of-line step-distance backup.
- Zone 5 reach set according to the remote backup requirements for a forward step-distance backup.
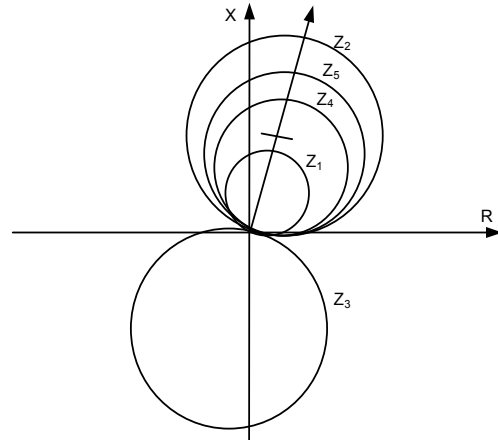

Fig. 23.   Example Application of Five Distance Zones With Zone 5 as the Extended-Reach Step-Distance Backup Zone

The second example application, shown in Fig. 24, uses Zone 5 as a reverse step-distance backup as follows:

- Zone 1 set at 80 percent.
- Zone 2 set at 200 percent or more for forward pilot protection only.
- Zone 3 set at 200 percent or more for reverse pilot protection only.
- Zone 4 set at 118 to 150 percent to cover the end-of-line step-distance backup.
- Zone 5 reach set according to the remote backup requirements for a reserve step-distance backup.
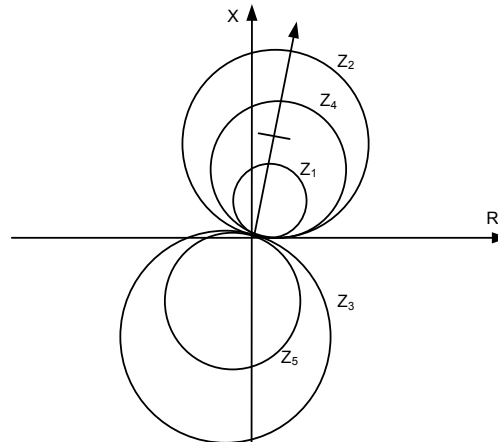

Fig. 24.   Example Application of Five Distance Zones With Zone 5 as the Reverse Step-Distance Backup Zone

The third example application, shown in Fig. 25, uses Zone 5 as an extended Zone 1 with a time delay as follows:

- Zone 1 set according to the maximum SIR.
- Zone 2 set at 200 percent or more for forward pilot protection only.
- Zone 3 set at 200 percent or more for reverse pilot protection only.
- Zone 4 set at 118 to 150 percent to cover the end-of-line step-distance backup.
- Zone 5 set at 80 percent with a 1.5-cycle delay.
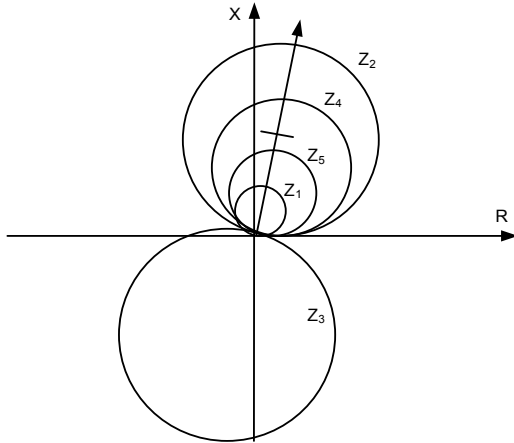

Fig. 25.   Example Application of Five Distance Zones Using Zone 5 as a Delayed Underreach Zone

XII.   CONCLUSION

A pilot protection scheme is intended not only to provide coverage for the entire line, but also to clear faults as fast as possible. To accomplish this, proper settings for the distance zones must be chosen. For many applications, the use of a common overreaching element for the pilot and step-distance schemes has the potential to impose two different and contradictory setting requirements, creating a difficult puzzle for a protection engineer to solve.

Fortunately, modern microprocessor-based relays offer a series of innovations and extended features protection engineers can apply to solve this puzzle. Among these features, the increased number of distance zones can help to increase the performance, security, and dependability of the line protection and the power system through the application of independent and dedicated zones for both the pilot protection and step-distance schemes. Challenging situations, like mutual coupling, series compensation, long lines with adjacent short lines, CT saturation, multiterminal lines, and CCVT transients can be addressed with the solutions and proposed settings for the overreaching zones used in the pilot schemes presented in this paper.

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XIV. Biographies

Ricardo Abboud received his BSEE degree in electrical engineering from Universidade Federal de Uberlândia, Brazil, in 1992. In 1993, he joined CPFL Energia as a protection engineer. In 2000, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a field application engineer in Brazil, assisting customers in substation protection and automation. In 2005, he became the field engineering manager, and in 2014, he became the engineering services manager. In 2016, he transferred to Pullman, Washington, and is currently an international technical manager. He is a certified instructor at SEL University and has authored and coauthored several technical papers.

Jordan Bell received his BSEE from Washington State University in 2006. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008 as a protection engineer in the engineering services group. He performs event report analysis, relay settings and relay coordination, fault studies, and model power system testing using a real-time digital simulator. He is a registered professional engineer in the state of Washington and a member of IEEE.

Brian Smyth received a BSEE and MSEE from Montana Tech at the University of Montana in 2006 and 2008, respectively. He joined Montana Tech as a visiting professor in 2008 and taught classes in electrical circuits, electric machinery, instrumentation and controls, and power system analysis. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2009 as an associate power engineer in the research and development division. Brian is currently a development lead engineer in the transmission department. In addition to working for SEL, Brian joined Montana Tech of the University of Montana in 2014 as an adjunct professor, where he teaches courses in power system protection. He received the Distinguished Alumni award from Montana Tech in 2016 and the IEEE Southwest Montana Chapter Engineer of the Year award in 2017. He is an active IEEE member and a registered professional engineer in the state of Washington.