Protecting Mutually Coupled Transmission Lines: Challenges and Solutions

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Protecting Mutually Coupled Transmission Lines: Challenges and Solutions

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***Abstract*—This paper is a tutorial on the protection of mutually coupled transmission lines. It discusses how mutual coupling affects the polarizing quantities of ground directional elements, the reach of ground distance elements, and the accuracy of single-ended fault locating algorithms. The paper provides settings guidelines for instantaneous directional overcurrent and ground distance elements. It discusses in detail how transmission line mutual coupling causes overreaching or underreaching of ground distance elements. It also discusses the impact on these elements of grounding the mutually coupled line at both line ends during maintenance. The paper analyzes whether mutual coupling compensation offers any benefits to line protection. The ease and benefit of line current differential schemes are contrasted in the discussion. Lastly, the paper examines a case when a double-circuit transmission line is operated as a single circuit with jumpers placed across similar phases along the line. This situation typically arises when the utility company needs to free one of the bays to bring an additional line into the substation. The protection engineer needs to decide where to install jumpers to parallel the two circuits in order to avoid distance element underreaching. The paper provides an analysis of this problem and offers suggestions on how to address it.**

I. Introduction

Electric utilities frequently use multiple lines to transport large amounts of power through narrow right-of-way line corridors. In many cases, two or more lines share the same right of way, or two or more circuits use the same transmission towers. Constructing a multiple-circuit line is less expensive than building separate transmission lines. Magnetic mutual induction occurs in multiple-circuit lines and also in single-circuit lines that run in close proximity to each other using the same right of way. Mutually coupled lines may have the same or different voltage levels. These lines bring about particular protection challenges.

Modeling mutually coupled lines for short-circuit analysis requires considering multiple factors, including line geometry and the multiple couplings that can take place in the right-of-way corridors. Lines can be coupled for only part of their length, which makes it necessary to create additional nodes at the points where mutual coupling starts and ends.

Magnetic mutual coupling affects mainly the zero-sequence networks. Ground directional overcurrent elements and ground distance elements, which respond to zero-sequence quantities, can be affected by mutual coupling. The user must either set these elements considering mutual coupling or apply compensation methods. Using negative-sequence directional elements and line current differential schemes solves these problems.

Mutual coupling also causes errors in single-ended zero-sequence fault locating algorithms. Negative-sequence multi-ended fault locating algorithms and traveling wave algorithms are not affected by mutual coupling.

Sometimes there is no more room in a substation to add a bay, and the utility company needs to free one of the bays to bring an additional line into the substation. A solution to this problem is to operate a double-circuit transmission line as a single circuit with jumpers placed across similar phases along the line. In these cases, the protection engineer needs to decide where to install jumpers to parallel the two circuits in order to avoid distance element underreaching.

This paper is a tutorial on the protection of mutually coupled transmission lines. It discusses the problems outlined previously and provides guidelines for solving them.

II. Transmission Line Protection Principles

Transmission line protection can use any of the following principles [1]:

- Directional overcurrent protection
- Distance protection
- Directional comparison protection
- Current differential protection

Directional overcurrent protection uses directional elements to supervise the operation of overcurrent elements. The high-speed protection zone reach varies with changes in the source impedance. Phase directional overcurrent protection (67) must be set above load current, which limits protection sensitivity and speed. Adding a negative-sequence overcurrent element improves sensitivity and speed for phase-to-phase faults. Ground directional overcurrent protection (67N), which responds to the zero-sequence current, is more sensitive than ground distance protection.

Distance protection uses voltage and current to determine the zone of the fault. A distance protection scheme generally includes three phase distance elements (21) and three ground distance elements (21N), with three or more protection zones each. Source impedance changes have almost no effect on the high-speed zone reach of distance protection.

Directional overcurrent and distance schemes provide primary line protection and also provide backup protection to adjacent lines and buses. These schemes do not require communications channels, but their high-speed protection zones do not cover 100 percent of the protected line. Thus, the clearing of line-end faults may be time-delayed, which could jeopardize power system stability, affect power quality, cause equipment damage, and be more of a safety risk. Directional overcurrent and distance schemes are typically used in subtransmission and distribution lines.

Pilot protection, or teleprotection, uses a communications channel to compare information from the line terminals and provide high-speed fault clearing for 100 percent of the protected line. Pilot protection includes directional comparison and current-based schemes (phase comparison and line current differential schemes).

In directional comparison protection, instantaneous directional overcurrent or distance elements exchange fault direction information over the communications channel. Directional comparison protection can work with any high-speed, dedicated channel. Channel impairments may affect scheme dependability or security, depending upon the scheme logic (tripping or blocking logic).

Line current differential protection compares current information from the line terminals over the communications channel. Phase comparison protection only compares current phase angle information, which reduces the channel bandwidth requirements. However, line current differential protection, having sequence differential elements, is more sensitive than phase comparison protection [2]. Line current differential protection is secure and more dependable than other types of protection in response to the effects of unbalances, power swings, mutual coupling, and voltage inversion. Line current differential protection performs well for evolving, intercircuit, and cross-country faults.

III. Modeling Mutually Coupled Transmission Lines

A. Self and Mutual Impedances

The characterization of the self and mutual impedances of transmission lines is a topic widely discussed in [3], [4], and [5]. In a paper published in 1926 [4], Dr. John Carson derived the widely accepted equations describing the electromagnetic wave propagation in electrical conductors with a returning ground path. These equations describe a self-impedance (z_{ii}, where i is the index of the conductor) and a mutual impedance between two conductors (z_{ij}, where i and j are the indexes of both conductors). The simple three-conductor system in Fig. 1 can be described using Carson's equations that include the effect of the ground return (shown as a return conductor with current I_d and self-impedance z_{dd}). Equation (1) describes the voltage drop in the line.

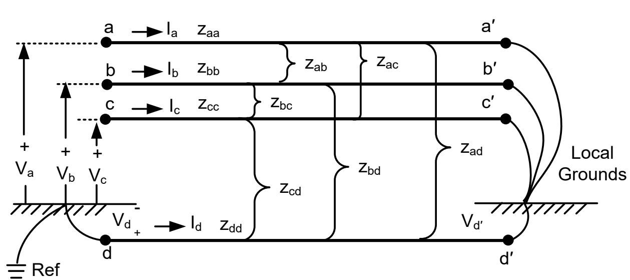

Fig. 1. Three-phase line with ground return.

$$\begin{bmatrix} V_a - V_{a'} \\ V_b - V_{b'} \\ V_c - V_{c'} \\ V_d - V_{d'} \end{bmatrix} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} & z_{ad} \\ z_{ba} & z_{bb} & z_{bc} & z_{bd} \\ z_{ca} & z_{cb} & z_{cc} & z_{cd} \\ z_{da} & z_{db} & z_{dc} & z_{dd} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_d \end{bmatrix} \quad (1)$$

Equation (1) can be reduced to (2) using Kron's reduction method. Using the left side of the line as our reference, we can solve for voltages V_a, V_b, and V_c because $I_d = -(I_a + I_b + I_c)$ and $V_{a'} - V_{d'}$, $V_{b'} - V_{d'}$, and $V_{c'} - V_{d'}$ equal zero.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (2)$$

The expressions for the self and mutual impedances of transmission line conductors can be extended to a system of several conductors. Typical dual-circuit tower configurations have a set of phase conductors and ground wires that can be described using Carson's equations for the self and mutual impedances. The matrix system can become fairly large if bundled phase conductors are used. Mathematical techniques can be used to simplify the system to an expression of the type of (3), which can be extended to any number of conductors [6].

Equation (3) describes the voltage drop in the conductor system of two mutually coupled three-phase lines.

$$\begin{bmatrix} [V_{ABC}] \\ [V'_{ABC}] \end{bmatrix} = \begin{bmatrix} [Z_{ABC}] & [Z_{MABC}] \\ [Z_{MABC}]^T & [Z_{ABC}] \end{bmatrix} \begin{bmatrix} [I_{ABC}] \\ [I'_{ABC}] \end{bmatrix} \quad (3)$$

where:

$[V_{ABC}]$ and $[V'_{ABC}]$ are voltage vectors given by (2) for each of the lines.

$[Z_{ABC}]$ and $[Z'_{ABC}]$ are line impedance matrices similar to those in (2) for each of the lines.

$[I_{ABC}]$ and $[I'_{ABC}]$ are current vectors similar to those in (2) for each of the lines.

B. Sequence Impedances

Complex equations of the type of (3) do not tell much about the interaction between two mutually coupled lines. Fig. 2 simplifies the concept and makes the interaction between the lines easy to understand.

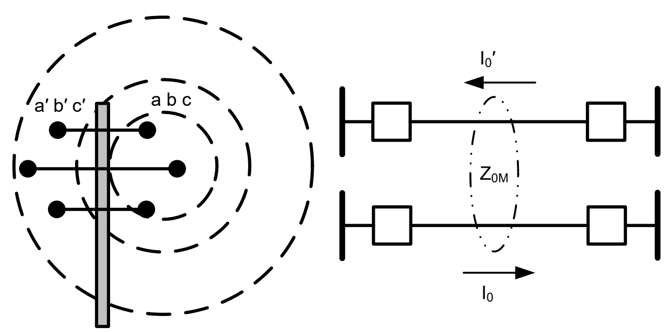

Fig. 2. Two mutually coupled lines.

The magnetic flux of one line that links with the other line is a function of the sum of the currents in that line, as shown in Fig. 2. The phase currents can be decomposed into symmetrical components expressed as the sum of positive- (I_1), negative- (I_2), and zero-sequence (I_0) components. The positive- and negative-sequence currents add to zero. The positive- and negative-sequence flux linkages to the adjacent line depend on the relative position of the phase conductors but are very low. As a result, the positive- and negative-sequence mutual impedances are zero for practical purposes.

On the other hand, zero-sequence currents do not add to zero. The zero-sequence flux linking the adjacent line is significant, and its magnitude is inversely proportional to the distance between conductors. As a result, the zero-sequence current flowing on one line induces a zero-sequence voltage in the other line. We can visualize the mutual impedance in the zero-sequence network as a single-turn transformer where a zero-sequence current (I_{0M}) induces a current-dependent zero-sequence voltage along the coupled line, as shown in Fig. 3.

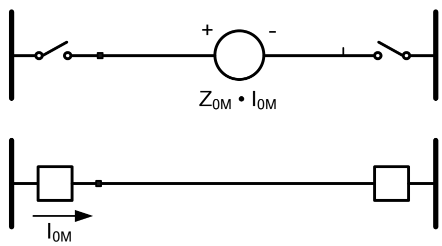

Fig. 3. Zero-sequence mutual impedance modeling.

Equation (4) relates the phase quantities to the symmetrical components.

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = [A] \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \quad (4)$$

where [A] is defined in (5).

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad (5)$$

$$a = e^{j120^0}$$

Equation (4) allows us to convert phase domain (abc) equations like (2) and (3) to the symmetrical component domain. For example, (3) can be expressed in sequence components, as shown in (6).

$$\begin{bmatrix} [A] & [0] \\ [0] & [A] \end{bmatrix} \begin{bmatrix} [V_{012}] \\ [V'_{012}] \end{bmatrix} = \begin{bmatrix} [Z_{ABC}] & [Z_{MABC}] \\ [Z_{MABC}]^T & [Z'_{ABC}] \end{bmatrix} \begin{bmatrix} [A] & [0] \\ [0] & [A] \end{bmatrix} \begin{bmatrix} [I_{012}] \\ [I'_{012}] \end{bmatrix} \quad (6)$$

Equation (6) yields (7) and (8):

$$\begin{bmatrix} [V_{012}] \\ [V'_{012}] \end{bmatrix} = \begin{bmatrix} [A] & [0] \\ [0] & [A] \end{bmatrix}^{-1} \begin{bmatrix} [Z_{ABC}] & [Z_{MABC}] \\ [Z_{MABC}]^T & [Z'_{ABC}] \end{bmatrix} \begin{bmatrix} [A] & [0] \\ [0] & [A] \end{bmatrix} \begin{bmatrix} [I_{012}] \\ [I'_{012}] \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} [V_{012}] \\ [V'_{012}] \end{bmatrix} = [Z_{SEQ}] \begin{bmatrix} [I_{012}] \\ [I'_{012}] \end{bmatrix} \quad (8)$$

Because the zero-sequence currents in the phase conductors are of equal magnitude and phase, regardless of the number of transpositions in the line, the zero-sequence mutual term Z_{0M} cannot be eliminated; but, if we properly transpose the transmission line at symmetrical distances, the sequence impedance matrix takes the form of (9).

$$[Z_{SEQ}] = \begin{bmatrix} Z_{00} & 0 & 0 & Z_{0M} & 0 & 0 \\ 0 & Z_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{22} & 0 & 0 & 0 \\ Z_{0M} & 0 & 0 & Z'_{00} & 0 & 0 \\ 0 & 0 & 0 & 0 & Z'_{11} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z'_{22} \end{bmatrix} \quad (9)$$

All the off-diagonal elements equal zero, except for Z_{0M}, as shown in (9). If the lines are highly coupled due to the proximity of the conductors, Z_{0M} can be of the same order of magnitude as the positive-sequence impedance Z_{11}.

For practical purposes, as mentioned previously, no positive- or negative-sequence mutual impedances are considered when analyzing mutually coupled lines with symmetrical components. The zero-sequence network, however, should include the mutual zero-sequence impedance Z_{0M}.

C. Modeling Mutually Coupled Lines

Using (8) and (9) and concentrating on the zero-sequence network, we can describe the effect of the mutual coupling from one line to the other with (10).

$$V'_0 = Z_{0M} I_{0M} \quad (10)$$

For short-circuit analysis, the positive- and negative-sequence networks do not include any mutual effects, as shown in Fig. 4 for an A-phase-to-ground fault in a two-source system. In the zero-sequence network, however, the mutual impedance must be accounted for with a voltage source, shown with red stripes, which directly affects the zero-sequence measurements at the terminal under study. For completeness, the influence of the mutual impedance between the two parallel lines is represented with the corresponding voltage sources and polarities in the two sections of the length, *m* and (1 – *m*), where:

m is the per-unit length of the line.

I_0 is the zero-sequence current in the terminal under study of the faulted line.

I_0' is the zero-sequence current in the remote terminal of the faulted line.

I_{0M} is the zero-sequence current in the unfaulted line.

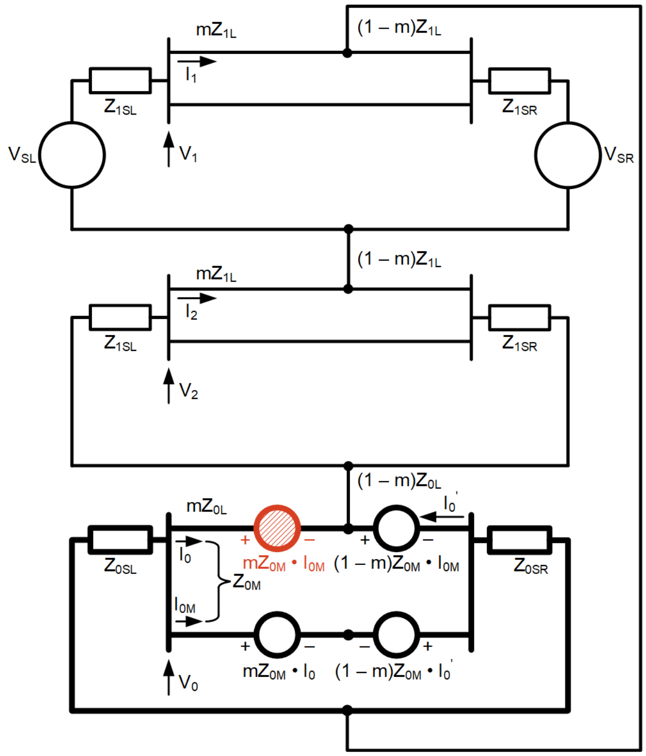

Fig. 4. Sequence network interconnection for a single-phase-to-ground fault in a two-source system.

IV. Ground Directional Overcurrent Protection Considerations

A. Ground Directional Elements

1) Elements Performing Phase Comparison

Traditional directional elements make a phase comparison of the operating current with the polarizing quantity [7]. Directional elements of digital relays typically calculate a scalar quantity *T* using (11) and compare it with two thresholds. When *T* is positive and above the positive threshold, the element declares a forward fault. When *T* is negative and below the negative threshold, the element declares a reverse fault.

$$T = \mathrm{Re}\left[(S_{POL}) (I_{OP} \cdot 1\angle\phi_{MS})^* \right] \quad (11)$$

where:

S_{POL} is the polarizing quantity.

I_{OP} is the operating current.

ϕ_{MS} is the directional element maximum sensitivity angle (a relay setting).

* is the complex conjugate.

Zero-sequence directional elements that perform phase comparison generally apply (11), with the zero-sequence voltage or current as the polarizing quantity. They use the zero-sequence current as the operating current. The term $1\angle\phi_{MS}$ is removed from (11) when zero-sequence current is used as the polarizing quantity.

Sources of zero-sequence polarizing current are the following [8] [9]:

- For two-winding delta-grounded wye transformers, the grounded neutral current obtained from a neutral current transformer (CT).
- For three-winding wye-delta-wye transformers with both neutrals grounded, the delta tertiary current (obtained from one CT in an unloaded tertiary or from three paralleled CTs in a loaded tertiary) or the current obtained from paralleled CTs connected to both grounded neutrals.
- For grounded neutral autotransformers with a tertiary, the delta tertiary current. However, this current may reverse (failing to serve as a polarizing quantity) if a small capacity autotransformer with a negative branch in the equivalent circuit is connected to a system with a small zero-sequence impedance (a very solidly grounded system).

Negative-sequence directional elements that perform phase comparison may also apply (11), with the negative-sequence voltage as the polarizing quantity and the negative-sequence current as the operating current.

2) Elements Measuring Sequence Impedances

Measuring a sequence impedance is another method of directional discrimination applied in some modern digital relays [10] [11]. A negative-sequence directional element that measures impedance calculates the scalar quantity z_2 using (12).

$$z_2 = \frac{\mathrm{Re}\left[V_2 (I_2 \cdot 1\angle\phi_{MS2})^* \right]}{|I_2|^2} \quad (12)$$

where:

V_2 is the negative-sequence voltage.

I_2 is the negative-sequence current.

ϕ_{MS2} is a relay setting.

The element compares z_2 with two thresholds. If z_2 is below a forward-fault threshold, the element declares a forward fault. If z_2 is above a reverse-fault threshold, the element declares a reverse fault.

Similarly, a zero-sequence directional element that measures impedance calculates a scalar quantity z_0 using an equation similar to (12), with the zero-sequence voltage and current replacing the negative-sequence voltage and current.

3) Combining Polarizing Quantities

Most traditional ground directional elements require users to select the polarizing and operating quantities for each application. The relay uses these quantities at all times, a restriction that may affect the directional element dependability when the system configuration changes. For example, if the zero-sequence voltage magnitude presented to the relay for a remote fault is too low, the output quantity or torque produced by a zero-sequence voltage-polarized directional element may be too low to cross its minimum threshold. If the source for zero-sequence polarizing current is switched out of service while the transmission line remains in service, the user must rely on the zero-sequence voltage-polarized directional element.

A traditional solution to this problem is a dual-polarized zero-sequence directional element. One design combines a zero-sequence voltage-polarized directional element and a zero-sequence current-polarized directional element. Another alternative is a design where the directional element can be polarized with voltage, current, or both [7] [8].

Dual-polarized elements can operate reliably when either the zero-sequence voltage or current has a low value or its signal source is out of service. However, in the situation where the current polarizing source is switched out of service and a remote ground fault does not produce enough zero-sequence polarizing voltage, an alternative polarizing technique must be considered, such as the negative-sequence voltage.

A modern solution is an adaptive ground directional element [12] that selects the best polarizing and operating quantities for each ground fault based on system conditions. Applying this new ground directional element eliminates the need to make choices and compromises. Another benefit is that this element does not require user settings (except the selection of the processing order of the different directional elements based on the particular application and user preference).

B. System Configurations Causing Zero-Sequence Polarization Problems

Directional elements make directional decisions by comparing a polarizing reference quantity to an operating quantity, as discussed in the previous section. Traditional ground directional overcurrent elements use zero-sequence voltage and/or current as the polarizing quantity. Zero-sequence voltage or current is an appropriate and simple polarizing quantity as long as the user selects an adequate zero-sequence polarizing source. However, zero-sequence voltage and/or current polarizing quantities are not always reliable.

The zero-sequence voltage is a voltage drop produced by zero-sequence current flowing through the zero-sequence network. The zero-sequence voltage is highest at the fault location and typically decreases as it gets closer to sources of ground current. Strong zero-sequence current buses, having low zero-sequence shunt impedances to the neutral bus, have very small zero-sequence voltage during ground faults, which could affect the polarizing quantity of ground directional overcurrent elements.

In addition, zero-sequence mutual coupling induces a voltage rise in the zero-sequence network that may cause a zero-sequence voltage reversal [13]. The zero-sequence voltage reversal forces zero-sequence current to flow down the neutral, instead of flowing up the neutral, in a wye-grounded transformer at that location, reversing the zero-sequence polarizing current obtained from the transformer neutral CT. This voltage and current reversal can be detrimental to the security of high-speed directional comparison schemes and traditional ground directional overcurrent relays, which depend on zero-sequence voltage or current polarization to make directional decisions during ground faults.

Zero-sequence polarizing quantity reversals occur typically when the mutual coupling between lines is strong enough to dominate over their electrical connection. An extreme case is when the mutually coupled lines are in two electrically isolated networks. In this case, mutual coupling is the only link between the zero-sequence networks, and polarizing quantity reversals are most likely.

The protection engineer should perform appropriate short-circuit studies to determine whether the zero-sequence polarizing quantities of directional elements are of sufficient magnitude and of proper phase relationship with the operating quantities. In addition, the protection engineer should identify the possibility of a zero-sequence network isolation situation during normal operating conditions, during manual switching operations, or because of sequential fault clearing.

Fig. 5 shows a 230 kV network where remote generation is connected radially to Bus S through three transmission lines with mutual coupling. When a single-phase-to-ground (SLG) fault occurs near Bus S in front of Breaker 3, the remote delta-grounded wye transformers contribute zero-sequence fault current toward Bus S. The voltages and currents shown in Fig. 5, expressed in kilovolts and amperes respectively, are the result of a short-circuit study.

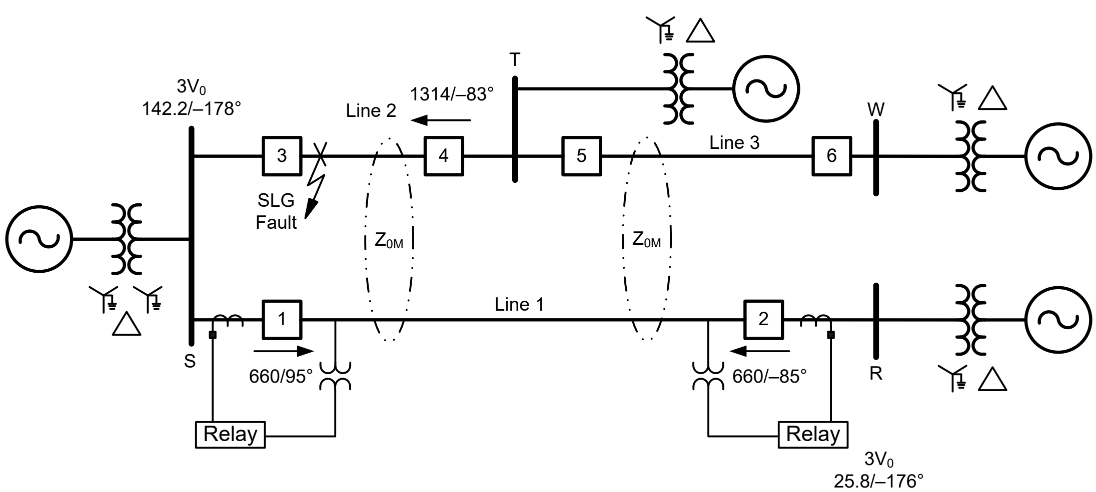

Fig. 5. SLG fault on the line side of Breaker 3. The ground directional elements perform well for this fault.

The zero-sequence voltage polarizing quantity (3V0) at Bus R (Line 1) lags the operating quantity (3I0) by 91°, and the directional element at Bus R correctly declares a forward directional decision. On the Bus S end of Line 1, the zero-sequence voltage polarizing quantity (3V0) leads the operating quantity (3I0) by 87°, and the directional element at Bus S declares a reverse directional decision as expected for an external fault behind it. This result indicates that the mutual coupling is not strong enough to overcome the electrical connection between the lines at Bus S. However, zero-sequence polarizing quantity reversals could occur in this network for different source impedance values, for example.

Assume that Breaker 3 at Bus S opens instantaneously to clear the fault and that Breaker 4 at Bus T has time-delayed operation. The zero-sequence networks are isolated in this switching arrangement, as illustrated in Fig. 6.

Observe from the fault study data in Fig. 6 that the zero-sequence voltage polarizing quantity ($3V_0$) at Bus S lags the operating quantity ($3I_0$) by 94° and the Line 1 directional element at Bus S will declare a forward directional decision. The zero-sequence voltage polarizing quantity ($3V_0$) at Bus R (Line 1) lags the operating quantity ($3I_0$) by 91° and the directional element at Bus R will also declare a forward directional decision. Because both directional elements at Breaker 1 and Breaker 2 on Line 1 declare a forward directional decision, Line 1 could be tripped for the external fault on the mutually coupled Line 2 if the forward directional overcurrent elements in a directional comparison scheme are set below 373 amperes. The cause of this potential misoperation is that the current in the zero-sequence isolated loop (Line 1) causes a zero-sequence voltage reversal at Bus R and the zero-sequence current flows down the neutral of the delta-grounded wye generator step-up transformer.

Fig. 7 illustrates the voltage reversal at Bus R of the system shown in Fig. 6 with Breaker 3 open (the isolated zero-sequence network case). Fig. 7 shows the equivalent zero-sequence network of the system in Fig. 6, the zero-sequence voltages at Bus S (V_{0S}) and Bus R (V_{0R}), and the zero-sequence current on Line 1 (I_{0_SR}). It is clear that the zero-sequence voltages at Bus S and Bus R are approximately 180° from each other (a voltage reversal at Bus R).

The following subsections describe a number of typical network configurations that can cause protection challenges for ground directional overcurrent elements and solutions to mitigate incorrect tripping of transmission lines during external faults in mutually coupled lines.

1) Mutually Coupled Lines Bused at Both Ends

Fig. 8 shows two mutually coupled lines bused together at both ends. SLG faults in this network arrangement produce the proper phase relationship between zero-sequence polarizing and operating quantities, because the electrical connection of the two paralleled lines is so strong that the mutual coupling cannot cause zero-sequence polarizing quantity reversals. Therefore, ground directional overcurrent elements will make correct directional decisions, assuming that the zero-sequence polarizing voltages or currents are of adequate magnitude.

2) Mutually Coupled Lines Bused at One End

Opening the tie Breaker 5 at Bus R, as shown in Fig. 9, weakens the electrical connection in the system, and the mutual coupling between Line 1 and Line 2 starts playing a more important role on the zero-sequence polarizing voltages during SLG faults. In this network arrangement, a polarizing quantity reversal could occur, depending on the level of mutual coupling between lines and the strength of the zero-sequence sources. Therefore, appropriate short-circuit studies should be conducted to determine whether zero-sequence voltage or current polarization is adequate or whether other types of directional elements using different polarizing techniques should be applied.

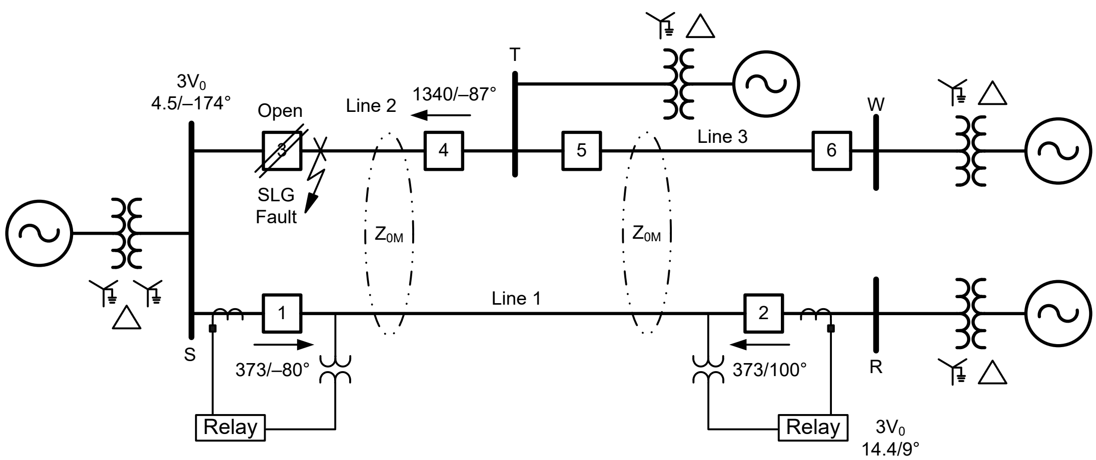

Fig. 6. SLG fault on the line side of Breaker 3. Breaker 3 is open, creating an isolation of zero-sequence networks.

In addition, line-end faults cleared by sequential breaker tripping in the Fig. 9 system (with Breaker 5 open) cause zero-sequence network isolation and may result in ground directional element misoperation in the healthy line. For example, Fig. 10 shows an SLG fault near Bus S for which the Zone 1 ground distance element or the instantaneous ground directional overcurrent element trips Breaker 3 instantaneously. This network arrangement creates a zero-sequence polarizing quantity reversal at Bus R on Line 1, as shown in Fig. 10.

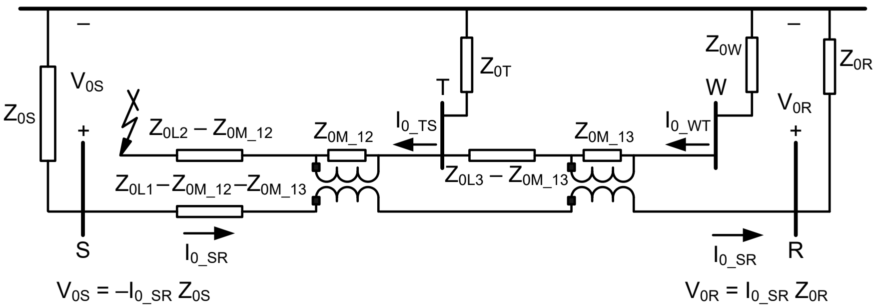

Fig. 7. Zero-sequence network of the Fig. 6 system showing the voltage reversal.

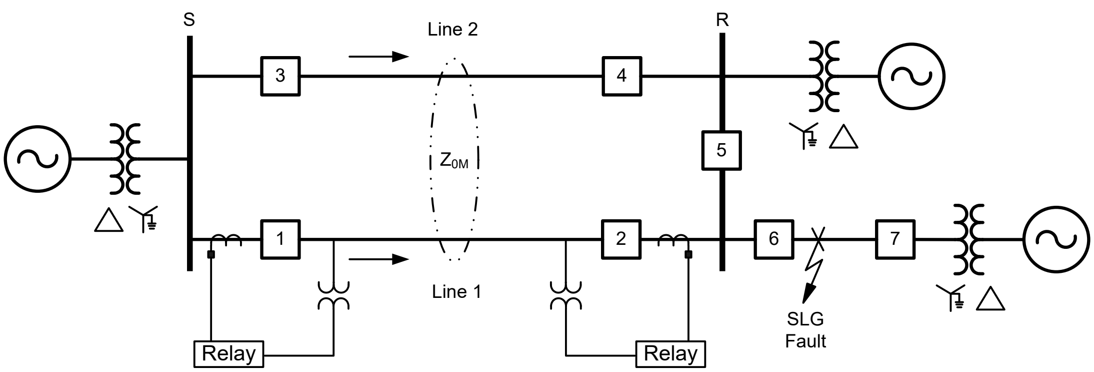

Fig. 8. Mutually coupled lines bused together at Bus S and Bus R.

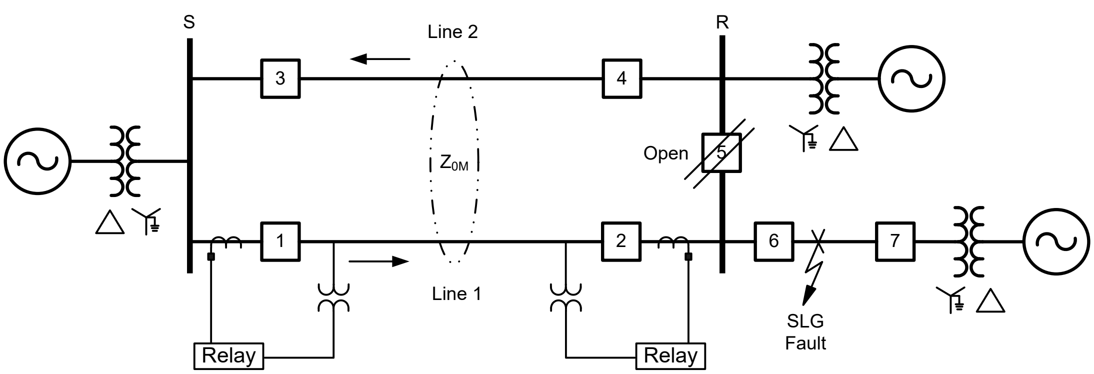

Fig. 9. Mutually coupled lines bused together with bus-tie breaker open at Bus R.

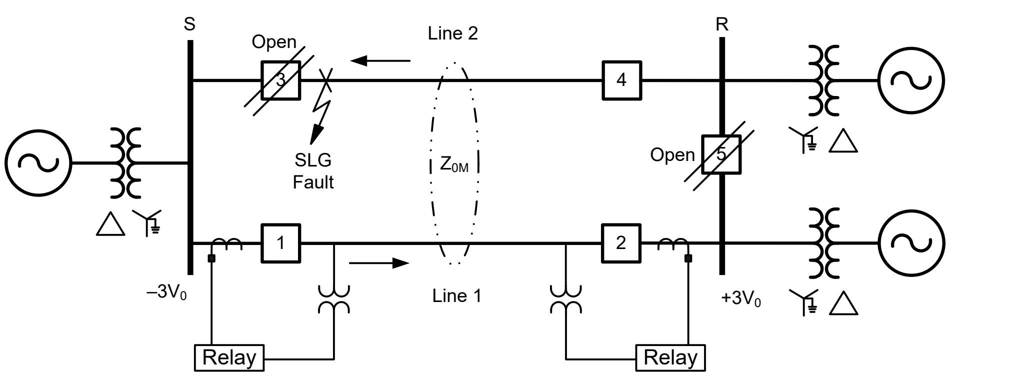

Fig. 10. Breaker 3 tripping with tie Breaker 5 open causes zero-sequence network isolation and results in a zero-sequence polarizing quantity reversal.

Fig. 11 shows another network arrangement where mutually coupled lines are bused at one end, Bus S, and terminate at two different substations, Bus R and Bus T. The lines are mutually coupled for only a portion of the line length (i.e., from S to M on Line 2 and S to N on Line 1). This configuration, which is more common than the one shown in Fig. 10, may also lead to zero-sequence polarizing quantity reversal, depending on system parameters. Furthermore, sequential fault clearing can cause isolation of zero-sequence networks, as shown in Fig. 11, for a line-end fault in front of Breaker 3, which causes this breaker to trip before Breaker 4.

When the lines are mutually coupled for only part of their length, as in Fig. 11, the correct way to model the zero-sequence mutual coupling in a short-circuit program is to create two additional buses (Points M and N in Fig. 11), instead of distributing the mutual coupling from Bus R to Bus S and from Bus S to Bus T. Distributing the mutual coupling incorrectly can produce erroneous short-circuit currents. Making relay settings based on short-circuit study results that did not properly take into consideration the fact that the lines were only mutually coupled for a portion of their total length can cause misoperations of instantaneous ground directional overcurrent elements.

3) Mutually Coupled Lines in Looped Systems

Looped network configurations are also susceptible to zero-sequence quantity reversals. Fig. 12 shows an example of such a network configuration. This network provides a weaker electrical connection between Bus S and Bus R than the parallel line configuration of Fig. 8. Hence, polarizing quantity reversals are possible even with all breakers closed. In addition, sequential clearing of line-end faults (e.g., the fault shown in Fig. 12 causing Breaker 3 to open first) increases the likelihood of zero-sequence polarizing quantity reversals. Finally, operating the Fig. 12 system with one line open creates a configuration similar to those in Fig. 10 and Fig. 11, which further increases the likelihood of polarizing quantity reversals.

4) Mutually Coupled Lines Operating at Different Voltages

Two or more transmission lines at different voltage levels may share the same right of way or may even share the same towers. This results in a strong zero-sequence mutual coupling between the two voltage systems. Typically, these two voltage systems are electrically connected to each other via power transformers. However, this connection is weak when compared with the magnetic coupling between the lines.

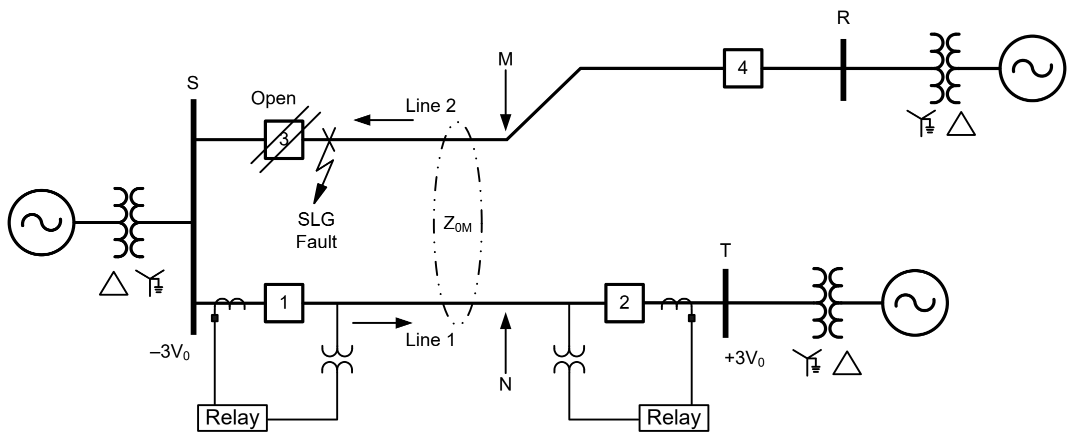

Fig. 11. Mutually coupled lines bused at one end and terminating at different substations.

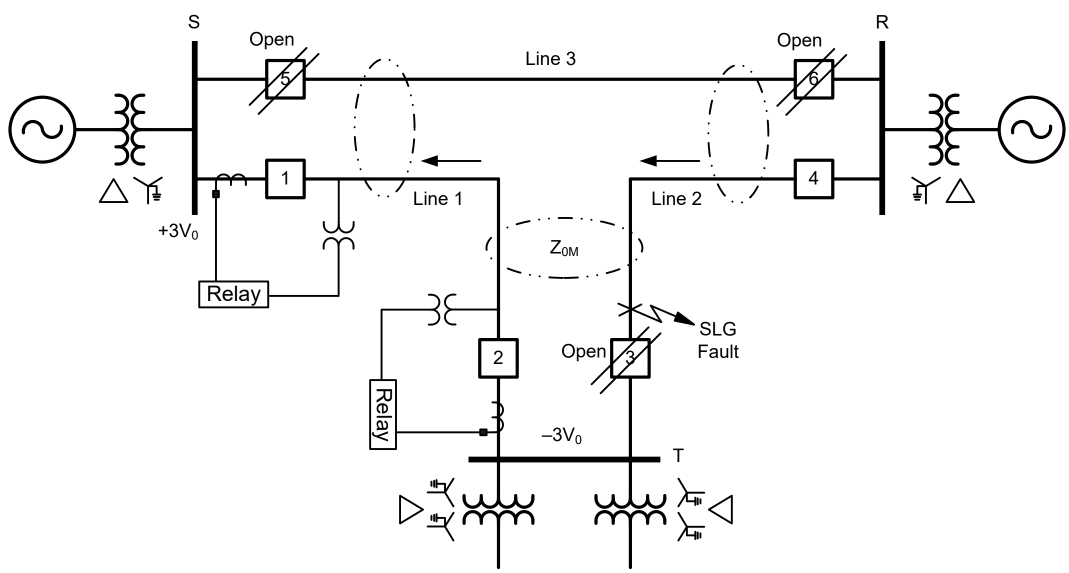

Fig. 12. Mutually coupled lines in a looped network configuration.

Therefore, the magnetic coupling is dominant. As a result of this mutual coupling, any ground fault on one power system will influence the zero-sequence current flow in the other circuit. Typically, the higher voltage system will have higher fault currents, and as a result, ground faults on the high-voltage system will have a pronounced effect on the lower voltage system.

In some countries, high-voltage and distribution voltage lines often share the same towers, and there is a strong zero-sequence mutual coupling between the two lines. When the high-voltage power system experiences a ground fault, the strong zero-sequence mutual coupling does not result in large current flow in the distribution system if the distribution system is either high-impedance grounded, resonant (Petersen coil) grounded, or even ungrounded.

If both systems are effectively grounded, then zero-sequence polarized protection elements should be avoided. The integrity of the zero-sequence elements cannot be guaranteed because a ground fault on one power system will induce zero-sequence currents, and as a result, zero-sequence voltage into the other system. This may result in relays on the healthy power system operating for a fault on the faulted power system. As was shown in Fig. 7, a voltage reversal is not uncommon for systems that are electrically isolated from one another. Proper modeling of zero-sequence mutual coupling in short-circuit programs is essential to analyze these configurations.

C. Solutions

Incorrect directional element performance caused by zero-sequence polarizing quantity reversals can be avoided using the following methods [13] [14] [15] [16] [17] [18]:

- Applying negative-sequence directional elements.
- Using negative-sequence overcurrent elements to supervise ground directional comparison schemes.
- Applying ground distance elements.
- Applying current differential schemes.

1) Applying Negative-Sequence Directional Elements

Negative-sequence voltage-polarized directional elements have the following advantages when compared with zero-sequence voltage-polarized directional elements:

- Negative-sequence directional elements are insensitive to zero-sequence mutual coupling. They are suitable for systems with isolated zero-sequence networks.
- If the bus behind the relay location is a strong zero-sequence source, the negative-sequence voltage available at the relay location is typically higher than the zero-sequence voltage.

There are, however, system network configurations where both the negative- and zero-sequence sources are very strong, which makes the negative-sequence directional elements performing phase comparison ineffective. The scalar quantity calculated by these elements is very small when the polarizing voltage is low (Section IV, Subsection A). Negative-sequence directional elements that measure impedance (Section IV, Subsection A) are more secure and reliable than negative-sequence directional elements performing phase comparison [17]. Faults at the end of long lines provide very low negative-sequence voltage for systems with strong negative-sequence sources, and for that reason, the directional elements measuring impedance are preferred.

While a negative-sequence directional element measuring impedance should be the preferred choice for most transmission line ground fault protection applications, one directional element may not be sufficient for all operating conditions, as discussed in Section IV, Subsection A. An adaptive ground directional element [12] automatically selects between three directional elements based on different polarizing methods for each ground fault.

There are cases where the negative-sequence quantities are not available. For example, some utilities install station bypass switches to accommodate breaker maintenance, as shown in Fig. 13. For this analysis, we assume that negative-sequence directional elements are applied to the looped system of Fig. 13. We also assume that there is no generation source at the low-side bus of the transformers connected at Bus T.

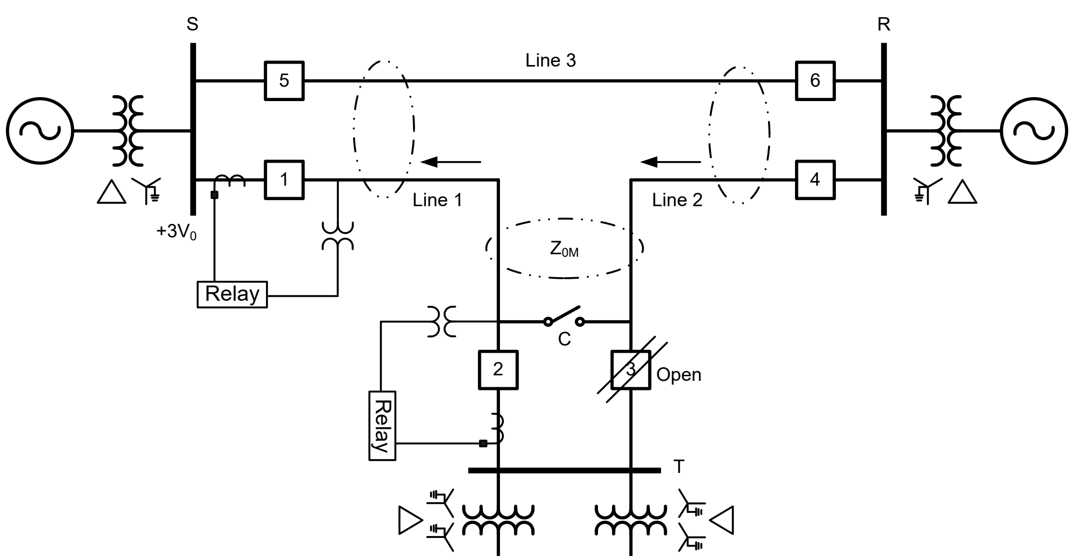

Fig. 13. Breaker maintenance at Bus T creates additional ground fault protection challenges.

Closing the station bypass Switch C to accommodate maintenance of Breaker 3 at Bus T creates a three-terminal line, which presents additional protection challenges that will not be addressed here as they are beyond the scope of this paper. Note, however, that using any type of negative-sequence directional element at Bus T cannot provide adequate ground fault protection because there is no positive- or negative-sequence source behind Breaker 2. The protection engineer should then select the most appropriate polarizing quantity for the Fig. 13 switching arrangement. A possible solution is to apply zero-sequence voltage or current for polarization and use a different settings group for the Breaker 2 relay. If zero-sequence current polarization is not available, or zero-sequence voltage polarization is not adequate based on the results of a short-circuit study, then other protection principles may be more appropriate (e.g., line current differential protection or ground distance protection). In any case, the protection engineer must always evaluate all available polarizing quantities and select the most appropriate one for the particular application.

Digital relays offer flexibility in the selection of directional elements and in using the directional elements to supervise the ground overcurrent elements. Forward or reverse directional elements can be used for supervision. Application of reverse directional elements requires careful analysis because they can impact relay coordination in ways that are not readily apparent. Reference [18] provides excellent examples from a large utility company of misoperations of zero-sequence voltage-polarized directional elements. It also provides recommendations for directional supervision of digital ground overcurrent elements.

2) Applying Negative-Sequence Overcurrent Supervision

The zero-sequence network isolation conditions shown in Fig. 6 and Fig. 10 cause zero-sequence quantity reversals, making zero-sequence voltage- or current-polarized ground directional elements unreliable. A solution to avoid misoperation of a pilot protection scheme on Line 1 is to apply negative-sequence directional elements measuring impedance available in some modern digital relays.

Another solution to this problem is to supervise the ground directional overcurrent element with a nondirectional negative-sequence overcurrent element. For example, Fig. 14 shows that there is no negative-sequence current on Line 1 for the specific switching conditions of Fig. 6. Therefore, a sensitive negative-sequence overcurrent element can be used to supervise the voltage-polarized zero-sequence directional elements of Breaker 1 and Breaker 2 and prevent a misoperation of Line 1 relays during an external ground fault.

3) Applying Ground Distance Elements

When zero-sequence and negative-sequence quantities are not reliable for polarizing ground directional elements, ground distance elements may be considered for ground fault protection [15]. Before applying ground distance elements for these cases, a thorough understanding of distance elements is required. For instance, quadrilateral ground distance elements may be polarized either by zero- or negative-sequence current, and if that is the case, these elements may not be useful. For such a case, a self-polarized quadrilateral ground distance element may become an option. In most cases, a system has at least either a strong zero-sequence source (suggesting zero-sequence current polarization) or a strong negative-sequence source (suggesting negative-sequence current polarization).

Ground distance elements have limited sensitivity to detect high-resistance faults. The voltage measured by the relay is the sum of the line voltage drop to the fault and the voltage drop across the fault resistance. The voltage drop across the fault resistance depends on the current infeed from the other line terminal(s). On looped transmission systems with tapped substations, there are several sources of ground current feeding the fault, which causes an amplification of the fault resistance. As the total fault current increases with respect to the relay current, the apparent fault resistance also increases [1].

Application of ground distance elements is discussed in more detail in Section V.

4) Applying Current Differential Schemes

Application of modern digital current differential schemes provides high-speed line protection and the best selectivity and solves most of the zero-sequence polarization problems discussed earlier in this paper. Application of line current differential protection is discussed in more detail in Section VI.

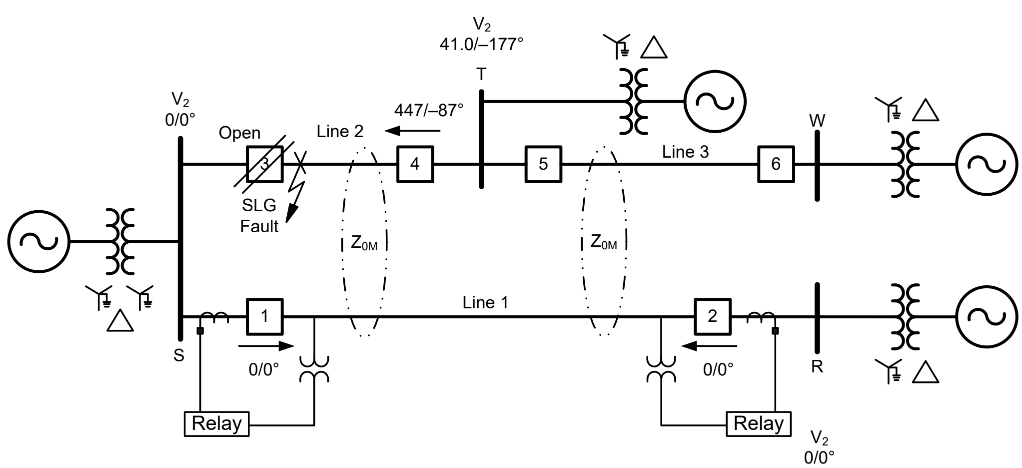

Fig. 14. No negative-sequence current flows in the isolated Line 1 loop.

D. Ground Instantaneous Overcurrent Element Settings

The fundamental criterion for setting ground instantaneous overcurrent elements is to provide instantaneous protection for the majority of the line length without tripping on external ground faults. The settings calculation goal is to determine the maximum current in the relay under consideration by assuming abnormal but realistic switching changes.

The first step is to apply SLG faults at the remote bus, removing one ground source at a time from the remote bus. Ground sources can be transformers or other transmission lines. Maintaining the strongest system behind the relay under consideration and removing one ground source at a time from the remote bus would suffice in most systems. Some protection engineers may also consider removing two ground sources from the remote bus to simulate reclosing the line into a permanent SLG fault while another line or transformer is out of service at the remote bus.

The most common condition that generates the maximum ground fault current is the removal of a parallel line. However, this may not always be true, and other SLG faults should be considered. One such case would be a line-end SLG fault on a parallel line that is mutually coupled with the line protected by the relay under consideration.

Fig. 15 shows the zero-sequence currents from a short-circuit study used to set a ground instantaneous overcurrent element at Breaker 1, taking into consideration the switching conditions discussed previously. Note from Fig. 15 that the maximum current for the relay under consideration is a line-end fault in the parallel mutually coupled line. The instantaneous overcurrent element should be set to at least 125 percent of the maximum $3I_0$ current. In this example, the instantaneous element should be set at 1.25 • 2,800 = 3,500 amperes.

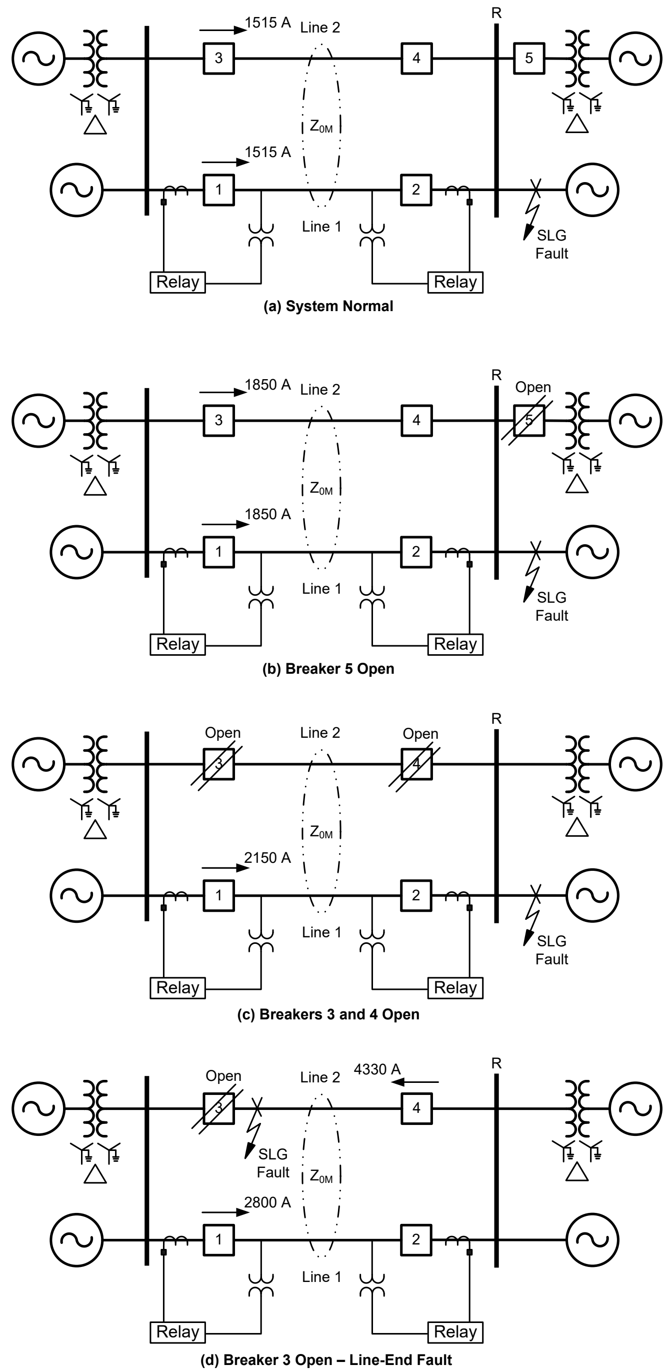

Fig. 15. Fault simulations for setting a ground instantaneous overcurrent element at Breaker 1.

V. Ground Distance Protection Considerations

A. Ground Distance Elements

1) Ground Distance Element Input Signals

Table I summarizes the input signals to traditional ground distance elements. Reference [19] and other books provide the mathematical derivation of these input signals. For bolted faults, phase and ground elements that receive only faulted-phase information (referred to as the fault loop elements) measure the positive-sequence impedance of the faulted line section.

TABLE I
VOLTAGE AND CURRENT INPUT SIGNALS TO TRADITIONAL GROUND DISTANCE ELEMENTS

Element	Voltage	Current
AG	V_a	$I_a + k_0 I_r$
BG	V_b	$I_b + k_0 I_r$
CG	V_c	$I_c + k_0 I_r$

Ground distance elements require the phase currents to be compensated by residual current I_r [see (13)] times a multiplying factor k_0 [see (14)].

$$I_r = I_a + I_b + I_c \tag{13}$$

where:

I_a is the measured A-phase current.

I_b is the measured B-phase current.

I_c is the measured C-phase current.

$$k_0 = \frac{Z_{0L} - Z_{1L}}{3Z_{1L}} \tag{14}$$

where:

Z_{0L} is the line zero-sequence impedance.

Z_{1L} is the line positive-sequence impedance.

2) Ground Distance Element Characteristics

Distance elements make a phase or amplitude comparison of signals derived from the measured voltages and currents to create operating characteristics [1] [20] [21]. Electromechanical relays compare torques. Most solid-state analog relays use time-coincidence phase comparison techniques. Digital relays use torque-like products and other methods to create their operating characteristics [1] [10].

Mho distance elements are widely used for line phase and ground fault protection [1]. Mho distance elements are easier to set than quadrilateral distance elements because mho elements require fewer settings. The dynamic characteristic expansion of a mho element using positive-sequence voltage polarization with memory improves its fault resistance coverage [10].

Quadrilateral distance elements are often used for line ground fault protection and for phase fault protection of short lines [1]. Quadrilateral distance elements are preferred over mho distance elements for ground fault protection of resistance-grounded systems [22].

B. Impact of Mutual Coupling on Ground Distance Elements

Fig. 16 shows two parallel, mutually coupled lines. For a bolted A-phase-to-ground fault on Line 1, the input signals to the A-phase ground distance element are the current $I = I_a + k_0 I_r$ and the voltage $V = V_a$ given by (15).

$$V_a = mZ_{1L}\left(I_a + k_0 I_r\right) + mZ_{0M} I_{0M} \tag{15}$$

where:

I_{0M} is the zero-sequence current in the coupled line.

Z_{0M} is the zero-sequence mutual coupling impedance between both lines.

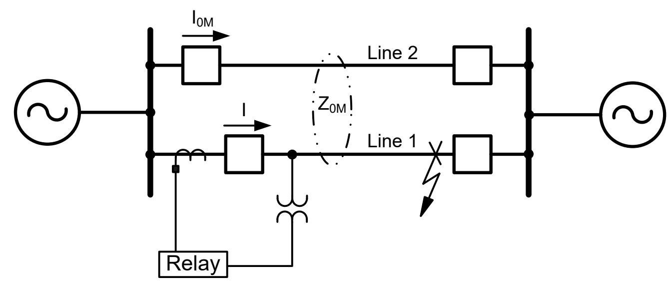

Fig. 16. Mutual coupling affects the impedance measured by ground distance elements.

Equation (16) gives the impedance Z_{APP} measured by the AG ground distance element on Line 1.

$$Z_{APP} = \frac{V_a}{I_a + k_0 I_r} = mZ_{1L} + mZ_{0M}\frac{I_{0M}}{I_a + k_0 I_r} \tag{16}$$

The measured or apparent impedance Z_{APP} includes an error term, which is positive when currents I_{0M} and I_0 flow in the same direction (underreach) and negative when these currents flow in opposite directions (overreach).

A distance element overreaches when the measured impedance is smaller than the actual impedance to the fault location. The element underreaches when the measured impedance is greater than the actual impedance to the fault location.

For the fault condition shown in Fig. 16, Z_{APP} is greater than mZ_{1L} (the ground distance element underreaches). For system configurations and fault locations that cause currents I_{0M} and I_0 to flow in opposite directions, the error term in (16) is negative and ground distance elements overreach.

These impedance measurement errors affect ground distance elements of both lines and also affect impedance-based single-ended fault locating algorithms using zero-sequence quantities. Section V, Subsections D and E show ways to prevent Zone 1 element overreach and Zone 2 element underreach and to reduce fault locating errors.

C. Complex Mutual Coupling Problems

The relative directions of the currents in mutually coupled lines (which determine ground distance element overreaching or underreaching conditions) depend on the existing mutual couplings, the system topology, and the fault location. Mutual couplings and system topologies can be very complex [15] [23]. In addition, the system topology can change during a fault because of sequential breaker tripping.

For example, based on the network configurations presented in Section IV, the following can be concluded:

- In a network with two mutually coupled lines connected in parallel (Fig. 8), the currents flow in the same direction on both lines for an external ground fault. All the zones of the Breaker 1 ground distance elements underreach. Zone 1 underreaching is not a problem, but Zone 2 underreaching is undesirable.
- In applications where parallel lines are served from a single zero-sequence source, the percentage of underreach and overreach is more pronounced than those of parallel lines where zero-sequence sources exist at both line ends [5] [23] [24]. This switching arrangement arises when only load is served at the remote Bus R (Fig. 8) or when breakers to the right of this remote bus are open for maintenance.
- In a network with the mutually coupled lines bused together at only one end (Fig. 9), the currents flow in opposite directions for an external ground fault. This configuration is a result of opening the tie Breaker 5. The Breaker 1 ground distance elements overreach, which is a problem for Zone 1 elements [25]. This configuration is similar to that in Fig. 11, except that the lines in Fig. 11 are mutually coupled for only part of their length, which requires careful modeling of the mutual coupling in short-circuit programs.
- When the zero-sequence networks are electrically isolated (Fig. 10), the currents flow in opposite directions for a line-end ground fault on the coupled line. This configuration is a result of tripping Breaker 3 first to clear the fault with the tie Breaker 5 open. The Breaker 1 ground distance elements measure load impedance (slightly modified by I_{0M}) and have no problem.

Ground distance elements can also overreach when the coupled line is out of service for maintenance and is grounded at both ends. Fig. 17 shows that, for a phase-to-ground fault at Bus R, the zero-sequence current induced in the grounded Line 2 flows in the opposite direction as the Line 1 zero-sequence current.

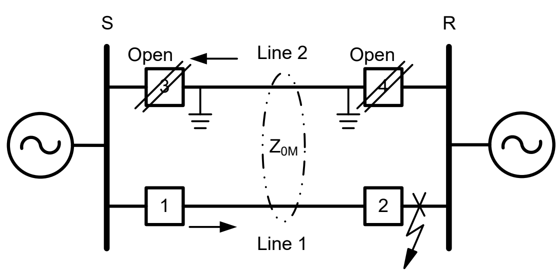

Fig. 17. An out-of-service line grounded at both ends may cause overreach of ground distance elements on the adjacent coupled line.

Other configurations may include tapped lines (sources of zero-sequence current), which are fairly common in subtransmission systems. Reference [15] proposes a methodology to account for the influence of the tapped loads. It consists of calculating equivalent positive- and zero-sequence impedances at different line locations with a short-circuit program and using these values to determine the k_0 compensation factors to use in ground distance element settings.

These examples show that applying ground distance elements requires careful and extensive short-circuit studies. This fact, combined with the limited fault resistance coverage of ground distance elements, significantly limits their application.

D. Mutual Coupling Compensation Methods

As mentioned previously, the impedance measurement errors caused by mutual coupling affect ground distance elements and zero-sequence single-ended fault locating algorithms. This subsection describes methods to mitigate ground distance element errors. Section V, Subsection E discusses fault locating algorithm problems and solutions.

1) Applying Reach Settings That Consider Mutual Coupling Effect

This method consists of carefully determining ground distance element reach settings by calculating the apparent impedance considering mutual coupling for all practical system configurations and fault locations. Settings calculations require many contingency evaluations and extensive study of the power system under faulted conditions.

We use the system shown in Fig. 18 as an example. This system includes two mutually coupled lines connected in parallel. Considering the ground distance elements of Breaker 1 (Line 1), Zone 1 must be set to not overreach Bus R under any system configurations and fault conditions; similarly, Zone 2 must not underreach Bus R and should cover faults like F_2 in Fig. 18. Hence, overreaching caused by mutual coupling must be considered when setting Zone 1, and underreaching must be considered when setting Zone 2 and other overreaching zones, which are typically used in directional comparison schemes (e.g., permissive overreaching transfer trip [POTT]).

To illustrate the effect of the system configuration, Table II shows the different switching states of the coupled line and the measured impedances in each case for a fault at the end of the parallel line at Bus R (Fig. 8 and Fig. 18) [24]. The measured impedances were derived from (16) with the following assumptions:

- The phase current and the residual current of the protected line are equal ($I_a = I_r$).
- The coupled line residual current is equal to the residual current of the protected line ($I_r = 3I_{0M}$).

TABLE II
MEASURED IMPEDANCES FOR DIFFERENT SWITCHING STATES OF THE COUPLED LINE

State of Coupled Line	Measured Impedance
In service	$Z_{APP} = Z_{1L} + \frac{Z_{0M}}{3(1+k_0)}$
Out of service and grounded at one point only or not grounded	$Z_{APP} = Z_{1L}$
Out of service and grounded at both line ends	$Z_{APP} = Z_{1L} - \frac{Z_{0M}^2}{3Z_{0L}(1+k_0)}$

The first scenario in Table II is an underreaching condition, the second scenario represents a correct impedance measurement, and the third scenario is an overreaching condition. One alternative to deal with these scenarios is for the user to select reach settings values that accommodate all three scenarios. Another alternative is to use different settings groups.

In the fixed settings alternative, Zone 1 reach should be set smaller than the measured impedance for the third scenario. Zone 2 reach should be set greater than the measured impedance for the first scenario, with a safety multiplier of at least 120 percent. Of course, the user must also evaluate other possible fault locations.

There is a lower limit to the Zone 1 reach setting: Zone 1 must detect ground faults at least up to 60 percent of the line length. Theoretically, 50 percent line coverage would be enough, but then there would be no safety margin. With 60 percent line coverage, ground faults on 20 percent of the line (middle part between 40 and 60 percent) can be cleared from both line terminals simultaneously. Ground faults on the remaining 80 percent of the line (0 to 40 and 60 to 100 percent) will normally be cleared instantaneously by the pilot scheme or sequentially by the distance scheme.

Another alternative to deal with the scenarios in Table II is to assign and adapt individual settings groups to different operating conditions (parallel line in service, out of service, or out of service and grounded) by considering the effective mutual coupling of the different operating conditions [24]. The state of the coupled line can change dynamically from in service to switched off and not grounded because of a breaker opening at one or both line ends. Ground element reach settings of the protected line may be too slow to adapt in real time, and for this reason, the user needs to find a common settings group that would serve both scenarios (e.g., the coupled parallel line in service or out of service and ungrounded). The third scenario, where the coupled line is out of service and grounded at both ends, can be addressed with a different settings group that is manually activated during line maintenance conditions. Some electric utilities apply single-point grounding methods during line maintenance activities. In such cases, the user may introduce an additional settings group corresponding to the second scenario in Table II.

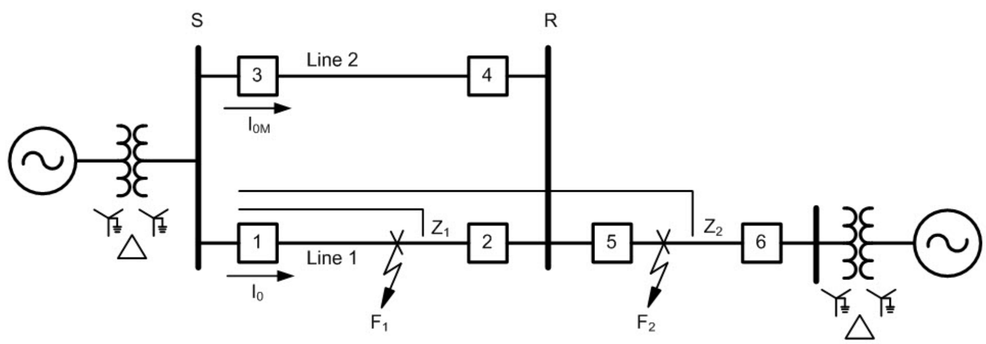

Fig. 18. Example power system that illustrates Zone 1 and Zone 2 reach settings.

As mentioned previously, the user must consider other fault locations and system conditions. For example, a fault on the coupled line may cause coordination problems in pilot schemes because the direction and magnitude of the residual current in the healthy line will change during the course of sequential fault clearing. The ground distance element at Breaker 2 in Fig. 8 will overreach and detect ground faults throughout the whole length of the coupled line, especially if the source behind Bus S is weaker than the source behind Bus R. This overreaching effect should also be considered for the reverse-looking zones of the ground distance elements at Breaker 1 in Fig. 8 when a POTT or directional comparison blocking (DCB) scheme is applied. These reverse-looking zones must reach further that the pilot forward overreaching zone of the ground distance elements at Breaker 2 for all ground faults in Line 2 in order to avoid tripping the healthy Line 1.

2) Using the Zero-Sequence Current From the Coupled Line

Equation (17), derived from (15), shows a theoretical way to eliminate the impedance measurement error caused by mutual coupling.

$$V_a = mZ_{1L}\left(I_a + k_0\, I_r + \frac{Z_{0M}}{Z_{IL}} I_{0M}\right) \tag{17}$$

The term in parentheses in (17) is the current required to eliminate the impedance measurement error. This current includes an additional compensation term that contains I_{0M}. Hence, the ground distance element requires zero-sequence current information from the coupled line.

This method has the following problems:

- The method requires wiring between the protection panels of the mutually coupled lines. In many system configurations, current information from the coupled line is not locally available because the lines terminate at different substations (e.g., see Fig. 11 and Fig. 12).
- It is not possible to obtain the zero-sequence current from the coupled line when the line is out of service for maintenance and is grounded at both ends.
- The method only eliminates the impedance measurement errors on the faulted line relays and may increase the errors on the adjacent healthy line relays [19]. For example, the unfaulted line relay may lose directionality for a close-in reverse SLG fault on the coupled line, because the zero-sequence compensation current may overcome the actual line current.
- Protection engineers prefer not to mix currents from different line terminals into one relay panel because of the possibility of incorrect installation, for safety considerations, and to avoid testing mistakes.

For all these reasons, it is not recommended to use the zero-sequence current from the coupled line for mutual coupling compensation.

3) Applying k_0 Settings That Consider Mutual Coupling Effect

For a line-end, bolted A-phase-to-ground fault in the Fig. 16 system, *m* = 1 in (15). Assuming that the coupled line residual current is equal to the residual current of the protected line ($I_r = 3I_{0M}$), (15) takes the form that is shown in (18).

$$V_a = Z_{1L}\left(I_a + \left(k_0 + \frac{Z_{0M}}{3Z_{IL}}\right) I_r\right) \tag{18}$$

The term in parentheses preceding I_r in (18) is the modified k_0 value (k_0') required to eliminate the impedance measurement error when both lines are in service (the first scenario in Table II), which is shown in (19).

$$k_0' = k_0 + \frac{Z_{0M}}{3Z_{IL}} = \frac{Z_{0L} - Z_{1L} + Z_{0M}}{3Z_{IL}} \tag{19}$$

For a line-end, bolted A-phase-to-ground fault in the Fig. 17 system, the coupled line residual current is shown in (20).

$$I_{0M} = -\frac{Z_{0M}\, I_r}{3Z_{0L}} \tag{20}$$

Equation (21) substitutes (20) into (15) and makes *m* = 1.

$$V_a = Z_{1L}\left(I_a + \left(k_0 - \frac{Z_{0M}^2}{3Z_{IL} Z_{0L}}\right) I_r\right) \tag{21}$$

The term in parentheses preceding I_r in (21) is the modified k_0 value (k_0'') required to eliminate the impedance measurement error when the coupled line is out of service and grounded at both ends (the third scenario in Table II), which is shown in (22).

$$k_0'' = k_0 - \frac{Z_{0M}^2}{3Z_{IL} Z_{0L}} = \frac{Z_{0L} - Z_{1L} - \dfrac{Z_{0M}^2}{Z_{0L}}}{3Z_{IL}} \tag{22}$$

Table III shows the required k_0 values for the different switching states of the coupled line for a line-end ground fault. These k_0 values are also valid for external phase-to-ground faults.

Modern digital line protection relays allow the assigning of different k_0 values to different zones of the ground distance elements. One alternative is for the user to select k_0 values that accommodate all three scenarios in Table III. Another alternative is to use different settings groups.

TABLE III
K_0 VALUES FOR DIFFERENT SWITCHING STATES OF THE COUPLED LINE

State of Coupled Line	k_0 Value
In service	$k_0' = \dfrac{Z_{0L} - Z_{1L} + Z_{0M}}{3Z_{IL}}$
Out of service and grounded at one point only or not grounded	$k_0 = \dfrac{Z_{0L} - Z_{1L}}{3Z_{IL}}$
Out of service and grounded at both line ends	$k_0'' = \dfrac{Z_{0L} - Z_{1L} - \dfrac{Z_{0M}^2}{Z_{0L}}}{3Z_{IL}}$

In the fixed settings alternative, the user can apply the k_0'' value to Zone 1 to avoid overreaching and the k_0' value to Zone 2 to avoid underreaching. The user must also evaluate other possible fault locations.

In the settings group alternative, the user can apply the k_0 value to Zone 1 and the k_0' value to Zone 2 when the coupled line is in service. Then, when the coupled line is out of service and grounded at both ends, the user can apply the k_0'' value to Zone 1 and the k_0' value to Zone 2. Alternatively, the user can apply the k_0 value to Zone 1 and Zone 2 if the coupled line is out of service and grounded at only one point.

E. Errors in Single-Ended Fault Locating Algorithms

Modern line protection relays include fault location functions. The absence of I_{0M} from the coupled line in single-ended fault locating algorithms that use zero-sequence information causes fault location errors. Mutual coupling compensation using the zero-sequence current from the coupled line (Section V, Subsection D) eliminates these errors. However, this type of compensation is not typically used, so the zero-sequence current from the coupled line is not available for the fault locating algorithms.

Fault locating algorithms do not have the high-speed processing requirement of distance protection functions. These algorithms typically process the fault signals recorded after the relay issued a breaker tripping signal and before the breaker opens to clear the fault. For this reason, it has been suggested to provide the relay with information on the zero-sequence current of the coupled line using direct relay-to-relay communication or the IEC 61850 standard analog value messaging [23].

A better solution for fault locating in mutually coupled lines is to apply multi-ended, negative-sequence, fault locating algorithms [26] or traveling wave fault locating algorithms [27].

VI. CURRENT DIFFERENTIAL PROTECTION CONSIDERATIONS

Line current differential protection schemes use a communications channel to compare current information from the line terminals. Today, digital microwave and fiber-optic channels support line current differential schemes.

A. Line Current Differential Elements

Traditional line current differential schemes use percentage differential elements [1] [28], which compare operating current (I_{OP}) with restraining current (I_{RT}). The element generates a tripping signal if I_{OP} is greater than a percentage of I_{RT} and is also greater than a minimum pickup current. The element operating characteristic is typically a plot of I_{OP} as a function of I_{RT}.

Fig. 19 shows the alpha plane differential element characteristic [2] that is available in some modern line protection relays. The restraining region includes the point $1\angle180°$, which represents ideal through-current conditions (load or external faults without CT saturation). Setting 87LANG determines the angular extent of the restraining region. Setting 87LR determines the restraining region outer radius. The inner radius is the reciprocal of 87LR. The differential element operates when the current ratio I_R / I_L (where I_R is the remote-end current and I_L is the local-end current) leaves the restraining region and the differential current magnitude $|I_L + I_R|$ is above a minimum pickup value (a relay setting).

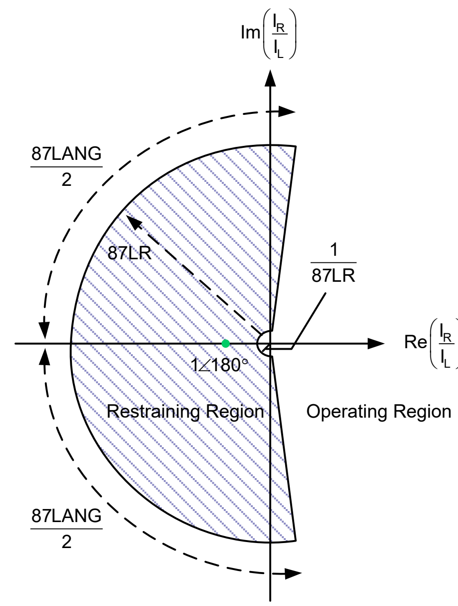

Fig. 19. Alpha plane differential element characteristic.

References [28] and [29] describe an advanced differential protection scheme for multiterminal lines. Some characteristics of this scheme are as follows:

- Uses generalized phase, negative-sequence, and zero-sequence alpha plane differential elements for multiterminal line applications.
- Consolidates all the currents in each line terminal into one partial differential current and one partial restraining current for optimum usage of the channel bandwidth. The partial currents feed into the generalized alpha plane calculations.
- Provides external fault detection logic at each line terminal for higher security.
- Provides line charging current compensation for higher sensitivity.
- Accommodates in-line transformers without sacrificing sensitivity.
- Can use direct or multiplexed fiber-optic channels and also wide-area synchronous optical network (SONET) or Ethernet networks.
- Provides channel-based and/or external-time-reference-based data synchronization.

B. *Advantages of Line Current Differential Protection*

The advantages of line current differential protection schemes are that they:

- Do not require voltage information, thereby avoiding problems for close-in faults, blown potential fuses, ferroresonance in voltage transformers, transients in coupling capacitor voltage transformers, and voltage inversion. However, if the differential element sensitivity for long lines or cables must be improved, calculating the charging current using the line voltage is advantageous.
- Are almost immune to unbalances, current reversals on parallel lines, power swings, and zero-sequence mutual coupling.
- Perform well for evolving, intercircuit, and cross-country faults.
- Tolerate high line loading.
- May handle outfeed conditions, depending on the operating characteristic.

These advantages make line current differential protection the best solution for mutually coupled transmission line applications.

VII. Double-Circuit Transmission Lines Operated as a Single Circuit

Occasionally, a situation arises where there is no room in a substation to add a new bay. The utility planning engineer may decide to free one of the bays by operating the double-circuit transmission line that connects the local substation to a remote substation as a single circuit. Fig. 20a illustrates two mutually coupled lines operating in parallel as independent circuits from each other, and Fig. 20b illustrates two mutually coupled lines operating as a single circuit with jumpers placed between the two circuits in front of their respective breakers.

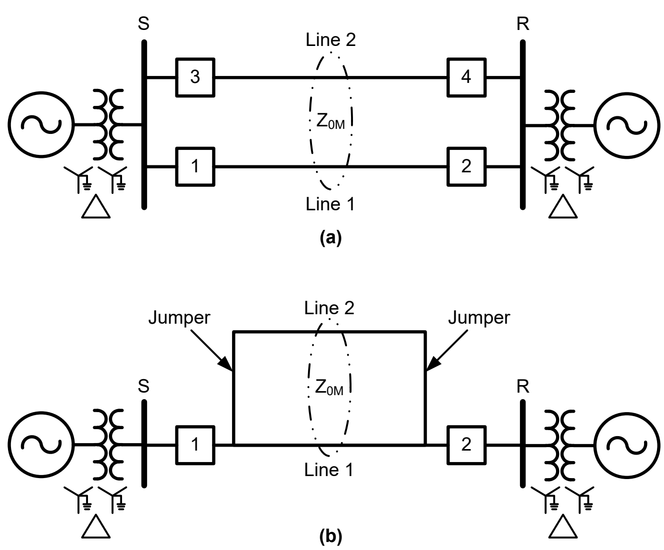

Fig. 20. (a) Mutually coupled lines operated independently; (b) mutually coupled lines operated in a single-circuit configuration.

The protection engineer must decide whether the double-circuit line can be operated in a single-circuit configuration with jumpers between the lines only in front of the breakers or whether additional jumpers between the two lines are necessary to avoid Zone 1 or Zone 2 underreaching. In this section of the paper, this problem is analyzed and suggestions are offered for solving it. The lines in Fig. 20a are 50-mile 230 kV lines with the following impedances:

$Z_{1L} = 6.90 + j\ 38.45$ ohms

$Z_{0L} = 21.20 + j\ 121.75$ ohms

$Z_{0M} = 14.30 + j\ 74.85$ ohms

First, apply three-phase faults along Line 2, assuming the sources behind Bus S and Bus R to be of equal strength. Table IV shows the impedances measured from Bus S and Bus R for faults along Line 2 (0 percent represents a fault in front of Breaker 2, and 100 percent represents a fault in front of Breaker 1).

Table IV
Impedances Measured From Bus S and Bus R for Three-Phase Faults Along Line 2

Distance From Bus R (Percent of Line Length)	Impedance Measured From Bus S (Ohms)	Impedance Measured From Bus R (Ohms)
100	0.00	19.55
90	4.24	25.22
85	6.31	33.22
80	8.35	26.22
70	12.29	25.00
60	16.00	22.71
50	19.42	19.42

Assume that the Zone 1 phase distance element is set at 90 percent of the equivalent positive-sequence impedance of the two lines. The Zone 1 setting is 17.50 ohms. Table IV shows that for a three-phase fault at 85 percent from Bus R, the impedance measured from Bus R is 33.22 ohms (approximately 190 percent of Zone 1 setting). This result implies that the Zone 1 phase distance element cannot detect this three-phase fault. Therefore, the protection engineer should request additional jumpers to be placed between the two circuits in order to maintain adequate protection using industry-acceptable Zone 1 and Zone 2 reach settings. The question is: what is the minimum number of jumpers that must be placed along the line so that Zone 1 and Zone 2 phase distance elements do not underreach for phase faults along the lines?

Fig. 21 shows an even more challenging fault in computing the Zone 1 underreach. Here it is assumed that two of the conductors broke at a transmission line tower and caused a phase-to-phase fault. This event may seem unlikely; however, these complex faults occasionally occur (e.g., during severe storms, earthquakes, or airplanes flying through transmission lines in agricultural areas during crop spraying). More often, one conductor would fall from a transmission tower to ground because of a faulty splice connector. In such cases, ground distance elements may underreach.

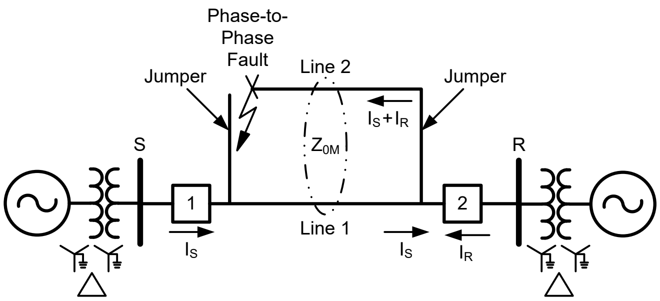

Fig. 21. Phase-to-phase fault at the end of Line 2 with phase conductors open toward Breaker 1.

Equation (23) gives the impedance measured from Bus S for the fault shown in Fig. 21. Equation (24) gives the impedance measured from Bus S for this fault, with no infeed from Bus R ($I_R = 0$). The impedance measured from Bus S is more than 400 percent of the equivalent positive-sequence impedance ($Z_{1L}/2$) with no infeed from Bus R. Therefore, Zone 1 and Zone 2 phase distance elements would severely underreach for this fault.

$$Z_{APP} = Z_{1L}\left(2+\frac{I_R}{I_S}\right) \tag{23}$$

$$Z_{APP} = 4\frac{Z_{1L}}{2} \tag{24}$$

Now assume that an additional jumper is placed at 50 percent of the line, as shown in Fig. 22. Equation (25) gives the impedance measured from Bus S for the fault shown in Fig. 22. Equation (26) gives the impedance measured from Bus S for this fault, with no infeed from Bus R. The measured impedance is 250 percent of $Z_{1L}/2$.

$$Z_{APP} = Z_{1L}\left(\frac{5}{4}+\frac{2}{4}\frac{I_R}{I_S}\right) \tag{25}$$

$$Z_{APP} = 2.5\frac{Z_{1L}}{2} \tag{26}$$

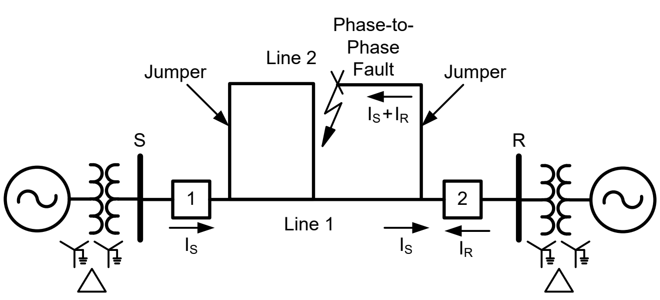

Fig. 22. One additional jumper placed at 50 percent of the line.

Now assume that three jumpers, in addition to the two jumpers at the line ends, are placed at intervals of 25 percent of the line length, as shown in Fig. 23. Equation (27) gives the impedance measured from Bus S for the fault shown in Fig. 23. Equation (28) gives the impedance measured from Bus S for this fault, with no infeed from Bus R. The measured impedance is 175 percent of $Z_{1L}/2$.

$$Z_{APP} = Z_{1L}\left(\frac{7}{8}+\frac{2}{8}\frac{I_R}{I_S}\right) \tag{27}$$

$$Z_{APP} = 1.75\frac{Z_{1L}}{2} \tag{28}$$

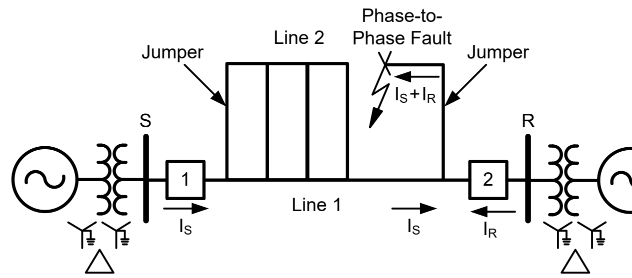

Fig. 23. Three additional jumpers placed at 25 percent line length intervals.

Equation (29) shows a generalized formula that describes the impedance measured from Bus S for the phase-to-phase faults shown in Fig. 23, with *n* jumpers placed at equidistant points along the line, in addition to the two jumpers at the line ends. Equation (30) gives the impedance measured from Bus S with no infeed from Bus R.

$$Z_{APP} = Z_{1L}\left(\frac{(n+4)}{2(n+1)}+\frac{2}{2(n+1)}\frac{I_R}{I_S}\right) \tag{29}$$

$$Z_{APP} = \frac{Z_{1L}}{2}\frac{(n+4)}{(n+1)} \tag{30}$$

To find the minimum number of jumpers required to clear an internal phase-to-phase fault sequentially ($I_R = 0$) with a Zone 2 setting of 130 percent of $Z_{1L}/2$, use (30), substitute Z_{APP} with $1.3Z_{1L}/2$, and solve for *n*. This gives us *n* = 9. For a Zone 2 setting of 150 percent of $Z_{1L}/2$, *n* = 5.

Table V gives the impedances measured at Bus S for phase-to-phase faults along Line 2 (Fig. 23), with *n* = 9.

TABLE V
IMPEDANCES MEASURED FROM BUS S AND BUS R FOR PHASE-TO-PHASE FAULTS ALONG LINE 2

Distance From Bus R (Percent of Line Length)	Impedance Measured From Bus R (Ohms)	Impedance Measured From Bus S (Ohms)	Impedance Measured From Bus S With $I_R = 0$ (Ohms)
10	4.72	45.60	25.40
20	7.06	36.98	23.52
30	9.46	31.26	21.57
40	11.94	26.88	19.61
50	14.54	23.24	17.66
60	17.28	20.04	15.70

Assume that Zone 1 is set at 90 percent of $Z_{1L}/2$ (17.60 ohms) and Zone 2 is set at 130 percent of $Z_{1L}/2$ (25.40 ohms). From the results shown in Table V, the following can be concluded:

- The Zone 1 distance element at Bus R will operate for faults up to 60 percent of the line.
- The Zone 1 and Zone 2 distance elements at Bus S underreach and will not operate for faults in Sections 1 through 4.
- The Zone 2 distance element at Bus S will operate sequentially after the breaker at Bus R is tripped by its Zone 1 distance element.
- Application of an overreaching pilot scheme (POTT or DCB) is necessary to clear faults instantaneously if sequential tripping is not acceptable.
- Settings for overreaching distance elements should be carefully selected using (29) by taking into consideration the worst-case fault current contribution from the remote end ($IR \neq 0$).

A similar analysis can be performed for ground distance elements at Bus S and Bus R. Underreaching of Zone 2 ground distance elements occurs for faults in a portion of the jumpered parallel lines. Line-to-ground fault clearing depends on sequential breaker opening, similar to the phase-to-phase fault scenario discussed previously.

This analysis assumes equidistant spacing of jumpers between similar phases along the transmission lines. Better results could be achieved by placing jumpers in nonequidistant spacing along the lines (e.g., placing jumpers closer together near the line ends and farther away near the middle of the line). Placing seven jumpers at 7, 13, 19, 22, 19, 13, and 7 percent along the lines might be one such choice. Other choices may provide even better results. The protection engineer should study each application, taking into consideration the source strength, to make sure the lines are adequately protected.

VIII. Conclusion

This paper discusses the protection problems of mutually coupled transmission lines and provides guidelines for solving them. We can conclude the following:

- Magnetic mutual coupling affects ground directional overcurrent elements polarized with zero-sequence quantities, which compromises directional comparison scheme security.
  - Mutual coupling may cause zero-sequence polarizing quantity reversals when this coupling is strong enough to dominate over the electrical connection between lines. An extreme case is when the zero-sequence network of the protected line is electrically isolated from the zero-sequence network of the faulted line.
  - Zero-sequence polarized directional elements can misoperate for reverse faults under certain system configurations and breaker switching conditions.
  - A solution to this problem is to use negative-sequence polarized directional elements.
- Magnetic mutual coupling affects ground distance elements and compromises distance and directional comparison scheme security and dependability.
  - Ground distance elements overreach (a concern for Zone 1) when the zero-sequence currents in the protected line and the coupled line flow in opposite directions and underreach (a concern for Zone 2) when these currents flow in the same direction.
  - Solutions to this problem include applying reach or k_0 settings that consider the mutual coupling effect and providing the relay with information on the zero-sequence current of the coupled line.
  - These mutual coupling compensation methods are complex to apply, require extensive short-circuit studies, and generally provide only partial solutions. For this reason, it is not recommended to use ground distance elements in mutually coupled lines.
- Current differential protection is an excellent solution for mutually coupled lines.
- Mutual coupling also causes errors in single-ended zero-sequence fault locating algorithms. Multi-ended negative-sequence fault locating algorithms and traveling wave algorithms are not affected by mutual coupling.
- Operating a double-circuit transmission line as a single circuit with jumpers placed across similar phases along the line causes phase and ground distance element underreaching. Applying current differential schemes solves this problem.

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X. Biographies

Demetrios A. Tziouvaras received his BSEE from the University of New Mexico and MSEE from Santa Clara University. He is an IEEE senior member and a member of the Power System Relaying Committee (PSRC) and CIGRE. He previously worked at Pacific Gas and Electric Company, where he held various protection engineering positions, including principal protection engineer for 18 years. In 1998, he joined Schweitzer Engineering Laboratories, Inc., where he currently holds the position of senior instructor at SEL University. He holds four patents and has authored and coauthored more than 50 technical papers. He served as the convener of CIGRE working group B5.15 on "Modern Distance Protection Functions and Applications" and is a member of several IEEE PSRC and CIGRE working groups.

Héctor J. Altuve received his BSEE degree in 1969 from the Central University of Las Villas in Santa Clara, Cuba, and his Ph.D. in 1981 from Kiev Polytechnic Institute in Kiev, Ukraine. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School at the Central University of Las Villas. From 1993 to 2000, he served as professor of the Graduate Doctoral Program in the Mechanical and Electrical Engineering School at the Autonomous University of Nuevo León in Monterrey, Mexico. In 1999 through 2000, he was the Schweitzer Visiting Professor in the Department of Electrical Engineering at Washington State University. Dr. Altuve joined Schweitzer Engineering Laboratories, Inc. (SEL) in January 2001, where he is currently a distinguished engineer and dean of SEL University. He has authored and coauthored more than 100 technical papers and several books and holds four patents. His main research interests are in power system protection, control, and monitoring. Dr. Altuve is an IEEE senior member.

Fernando Calero received his BSEE in 1986 from the University of Kansas, his MSEE in 1987 from the University of Illinois (Urbana-Champaign), and his MSEPE in 1989 from the Rensselaer Polytechnic Institute. From 1990 to 1996, he worked in Coral Springs, Florida, for the ABB relay division in the support, training, testing, and design of protective relays. Between 1997 and 2000, he worked for Itec Engineering, Florida Power and Light, and Siemens. In 2000, Mr. Calero joined Schweitzer Engineering Laboratories, Inc. and presently is a senior automation systems engineer.

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