Practical Considerations When Protecting Mutually Coupled Lines

Craig Holt and Michael J. Thompson
Schweitzer Engineering Laboratories, Inc.

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Practical Considerations When Protecting Mutually Coupled Lines

Craig Holt and Michael J. Thompson, *Schweitzer Engineering Laboratories, Inc.*

Abstract—**Mutual coupling between parallel lines continues to be problematic for protection engineers. Ground distance and directional overcurrent elements are susceptible to mutual coupling, whether it is due to the impact on the apparent impedance or due to incorrect directional decisions during specific system configurations.**

This paper first provides insights into how mutual coupling affects ground distance, ground overcurrent, and directional elements in different system configurations. Next, it offers practical advice for identifying situations where mutual coupling must be considered using a case study. Finally, the paper provides step-by-step guidance for setting ground distance and directional overcurrent elements on transmission lines that are affected by mutual coupling.

I. Introduction

Mutually coupled lines are prevalent in urban areas or where right of way is limited. They exist due to multiple circuits on the same tower or a shared right of way for towers with individual circuits, allowing for mutual induction.

Many papers have been written on mutual coupling. Most discuss what happens, or why it happens, in hopes of educating the reader so that they can apply the lessons learned. This paper hopes to build on these thought-provoking papers, such as [1], and provide step-by-step analysis that gives practical guidance on how protection engineers can design and set reliable protection schemes when mutual coupling is present. The consequences of mutual coupling ripple through ground-fault-related protection, whether it is simple ground overcurrent, distance, directional, or directional comparison pilot protection. There are specific cases where mutual coupling can cause misoperations. Many engineers have adopted negative-sequence directional control due to its immunity to mutual coupling. But what happens if there is not sufficient negative-sequence current or voltage signals to enable the element? Later in the paper, we analyze a case study where this happened and what could have been done to prevent the misoperation.

The goal of this paper is to give the engineer practical guidance on the following:

- Determining to what extent the mutual coupling will affect the protection.
- Reviewing of system operating conditions that lead to dilemmas and tradeoffs, with evaluation of the impedances of the zero-sequence network.
- Evaluating different methods, schemes, and protective elements and analyzing strengths and weaknesses in various scenarios.

II. Mutual Coupling and Apparent Impedance

Mutual coupling can be visualized as a simple transformer. Two lines that are inductive are mutually coupled by the air. Due to the distance between the lines, the ability of the "transformer" to replicate the voltage is drastically reduced. The voltage drops across the mutually coupled lines are actually much more complicated when applied to a system with multiple sources because each circuit is mutually dependent on the other.

Consider Fig. 1, which shows a mutually coupled system. Equations (1) and (2) represent the voltage drops across the lines in this system. Both voltage drops across Lines 1 and 2 are dependent on the current flow in the other line. This complicated codependence creates the need for a simplified equivalent. Equivalents are analyzed in more detail in the Appendix.

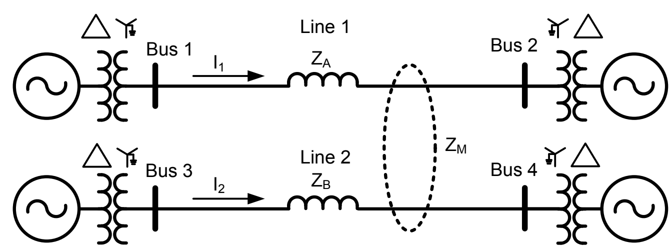

Fig. 1. Mutually coupled systems

$$V_{12} = I_1 \bullet Z_A + I_2 \bullet Z_M \quad (1)$$

$$V_{34} = I_2 \bullet Z_B + I_1 \bullet Z_M \quad (2)$$

Throughout this paper, mutual coupling refers to the zero-sequence network and simplified electrical equivalents. These electrical equivalents result in currents and voltages that appear to relays as infeed and outfeed, affecting the magnitude of currents and the apparent impedance measured by the relays.

Two different cases are analyzed throughout the paper where the change in zero-sequence apparent impedance is of interest to the engineer. The first case is the change of zero-sequence source impedance that pertains to directional elements. This change affects impedance-based directional elements like $Z0S_{APP}$ in (3) [2], which measures the apparent zero-sequence source impedance behind the relay.

$$Z0S_{APP} = \frac{\text{Re}\left[3V_0 \bullet \left(I_G \bullet 1\angle Z0ANG\right)^*\right]}{\left|I_G\right|^2} \quad (3)$$

The second case is the change in zero-sequence impedance that affects the impedance measured by the distance elements. This change is commonly referred to as Z_{APP}. Equation (4) uses the conversion k0 in (5) [3] to relate faults involving ground current to the positive-sequence line impedance because of the differences in positive- and zero-sequence line impedances.

$$Z_{APP} = \frac{V_A}{I_A + k0 \bullet 3I0} \tag{4}$$

$$k0 = \frac{Z0 - Z1}{3 \bullet Z1} \tag{5}$$

The apparent impedance changes that affect (3) and (4) are the result of a voltage that is impressed in series with the mutually coupled lines. This voltage is developed by the zero-sequence mutual impedance, $Z0_M$. The impedance $Z0_M$ directly relates to the coupling strength between circuits.

III. Coupling Strength

Coupling strength is determined by the magnitude of $Z0_M$. Equation (6), which directly relates the strength to the zero-sequence impedance of the line in question, is one way to quantify its possible effect on protection. The effect of mutual coupling can be significant if two lines with mutual coupling result in a large %M value or more than two mutually coupled lines with a lower %M value total to a similar effect. Regardless of the condition in which the lines are mutually coupled, the protective elements must be evaluated similarly.

$$\%M = \left| \frac{Z0_M}{Z0_L} \right| \bullet 100 \tag{6}$$

The percent strength given by (6) is a function of the distance between the mutually coupled conductors (proximity) and the distance two or more mutually coupled lines share the proximity (length of shared right of way).

The practical upper limit of percent strength is considered to be 70 percent [4]. We evaluate this condition later in the paper. Typically, if (6) does not exceed 10 percent, the effect of the mutual coupling can be ignored. Results will show little effect up to a larger percentage, but these results are based on specific system values and should not be assumed the same every time. Ten percent offers a threshold that typically does not affect protection and is below most security margins used when setting protective elements.

A. Two Mutually Coupled Lines

Table I illustrates the effect of proximity. The results are first derived from the tower configuration shown in Fig. 2 and then further evaluated with separation between the transmission lines, which decreases proximity. The conductor is "Drake," the line is 50 miles long, and complete transposition is assumed with a soil resistivity at 100 ohm-meters.

Table I
Coupling Strength

Scenario	Proximity (ft)	$Z0_M/Z0_L$ (%)
1	14 (shared tower)	69
2	114	44
3	214	36

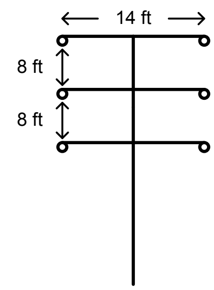

Fig. 2. Tower configuration

Results from Table I show that there is significant mutual coupling, even as the proximity decreases. The mutual coupling effect drops proportionally with the reduction in length of the shared right of way in the mutually coupled line. The effect on Z_{APP} also reduces but not linearly due to differences in the zero- and positive-sequence line impedances (5).

Fig. 3 shows a system where the percent strength changes depending on the length the lines that share the same right of way. Line 2 shares the same right of way for a variable distance. This can be due to the location of Bus 3 or because the Line 2 route diverges at some point.

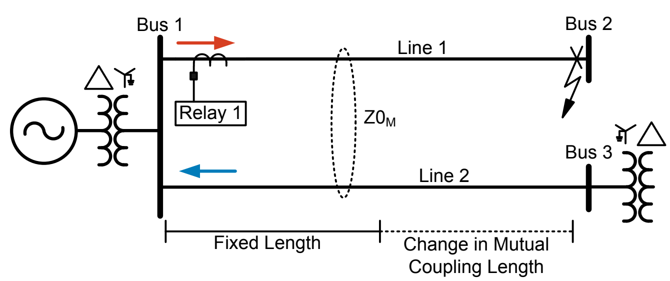

Fig. 3. Variable mutual coupling length

Table II illustrates the Relay 1 Z_{APP} change for the different mutual coupling percentage strength values for the system in Fig. 3. The results demonstrate that the effect of mutual coupling is small at best when below 30 percent coupling strength. However, the percentage change at the extreme condition of 70 percent coupling strength is significant. Factors such as line length, mutual coupling voltage levels, current flow in the mutually coupled ground loop, and source values can affect the results.

TABLE II
RELAY 1 Z_{APP} VARIATION WITH PERCENT STRENGTH OF MUTUAL COUPLING FOR THE EXAMPLE SYSTEM SHOWN IN FIG. 3

%	System Normal Z_{APP} (Primary Ω)	System Normal ($Z_{APP}/Z1_L$)
5	34.3	1.0
10	34.1	1.0
30	32.5	0.95
50	29.7	0.87
70	25.8	0.76

B. Three Mutually Coupled Lines

When a protected line has more than two lines in close proximity to it, Z_{APP} is impacted similarly to a single line in close proximity to the protected line, just less severely. Consider the example shown in Fig. 4, where two different transmission lines are mutually coupled to the transmission line in question.

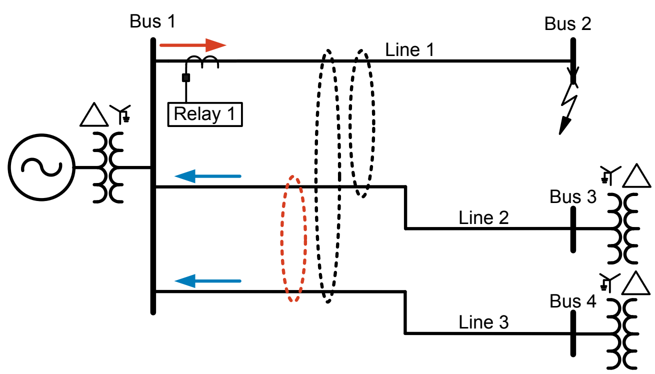

Fig. 4. More than two mutually coupled lines

The mutual coupling effects result in Relay 1 seeing an increase in current and a decrease in measured impedance, regardless of whether Lines 2 and 3 are mutually coupled. The mutual coupling effect is more pronounced when Lines 2 and 3 are only mutually coupled with Line 1 and are not mutually coupled together.

Practically, any two lines that are mutually coupled with a third line will share some amount of coupling strength. For example, Line 2 from Fig. 4 may share close coupling strength with both Lines 1 and 3, but Lines 1 and 3 may share a reduced coupling strength due to a greater distance between the two lines.

Referring to Fig. 4, a fault at Bus 2 will result in current flow from each ground source toward the fault. Because the contribution from the ground sources at Buses 3 and 4 flows toward the fault, the mutually induced voltages result in an increase in overall fault current. However, if there is significant coupling strength between Lines 2 and 3, a counteracting mutual voltage will be induced in Lines 2 and 3, reducing the total fault current through Relay 1.

Table III shows both the current and impedance measured by Relay 1 for the fault at Bus 2 in Fig. 4, for the following scenarios:

1. Mutual coupling not in effect.
2. Lines 2 and 3 mutually coupled between themselves as well as Line 1.
3. Lines 2 and 3 only mutually coupled with Line 1.

TABLE III
MUTUAL COUPLING WITH MULTIPLE LINES

Scenario	Relay 1 Amperes	Relay 1 Z_{APP} (Ω)
1	757	34.4
2	849	30.7
3	873	30.0

In Fig. 4, positive-sequence sources are not included at Buses 2, 3, and 4 for simplification. Current flow in Lines 2 and 3 is strictly zero-sequence current due to mutual coupling and the ground sources at Buses 3 and 4. Lines 2 and 3 are the same electrically in terms of line and mutual impedance.

Table III shows that Z_{APP} in the faulted line is reduced, regardless of how the mutually coupled lines are coupled. Scenario 3 has a slightly greater impact on relaying because of the reduced coupling strength between Lines 2 and 3.

C. Comparison

The scenario with three mutually coupled lines was derived from the scenario with two mutually coupled lines. The mutual value $Z0_M$ was cut in half to 35 percent coupling strength, so Lines 2 and 3 each share a coupling strength of 35 percent with Line 1. Comparing the 70 percent strength value in Table II (25.8 Ω) to Scenario 3 in Table III (30.0 Ω) shows that the two lines that are mutually coupled have a greater effect on protection.

When three lines exist with reduced coupling strength, the mutual coupling voltage induced in each line is much less than when compared to two lines with 70 percent coupling strength. The combination of reduced mutual voltage and an additional ground loop results in less total current in the faulted line, reducing the adverse effects on the protection. If mutual coupling is present between Lines 2 and 3, the effect is reduced even further.

IV. SYSTEM CONFIGURATION

The following four system configurations should be analyzed:

1. Single common bus.
2. No common bus (systems that are electrically isolated in the zero-sequence network).
3. Common buses.
4. Mutually coupled line out of service and ungrounded.

Note that Configuration 4 is the same as if mutual coupling is not present and is not addressed in this paper, but it should be considered during system analysis.

Each of these system configurations can take various forms. These conditions can exist naturally, or they can develop due to field switching for maintenance or from a protective device isolating a faulted circuit. The engineer must identify each potential configuration when setting a protective relay. Short-circuit (SC) programs should not solely be relied upon to determine potential configurations. Actual switches and tie breakers may not be modeled, depending on the practice of the system in question.

These potential configurations determine if and to what extent a protective element may fail in terms of dependability or security. Once this is identified, the engineer can make the appropriate adjustments to the relay settings, preventing unintentional outages and preserving system integrity.

A. Configuration 1: Single Common Bus

Configuration 1 can exist as a natural system configuration or from a breaker or switch isolating a second common bus. Fig. 5 shows a natural Configuration 1. Fig. 6 shows an example of how a portion of the system can be isolated to become Configuration 1.

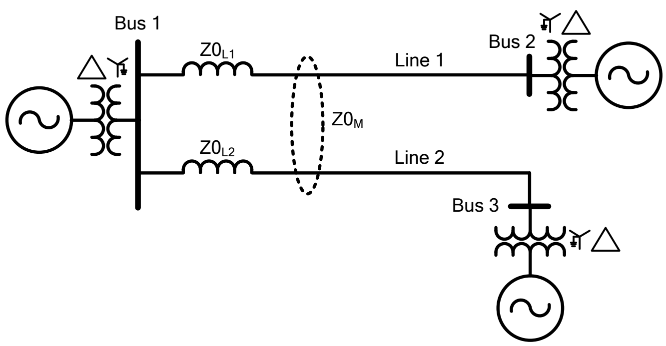

Fig. 5. Natural system with single shared bus

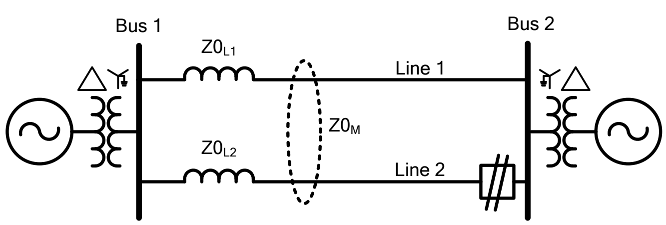

Fig. 6. Operation creating single shared bus

The scenario shown in Fig. 5 can cause an increase or decrease in current, depending on the ground sources in the system, location of the fault, strength of the mutual coupling, and which terminal is being analyzed. This means that overcurrent and distance elements are at risk of underreaching or overreaching, depending on the system configuration. The scenario shown in Fig. 6 will cause an increase in current and a decrease in impedance for a relay looking into Line 2 from Bus 1.

Fig. 7 shows how a relay can experience different underreaching and overreaching conditions from two different faults. Relay 1 experiences a decrease in overall fault current for Fault F1 because the mutually induced voltage produces a voltage drop in the zero-sequence network, reducing the current. The reduced current flow results in Relay 1 measuring a larger Z_{APP}. The opposite effect is present for Fault F2 at Bus 3. The fault current from each line produces a mutually induced voltage that increases the zero-sequence voltage, resulting in an increase in total fault current flowing through Relay 1. A distance element would measure a reduced impedance.

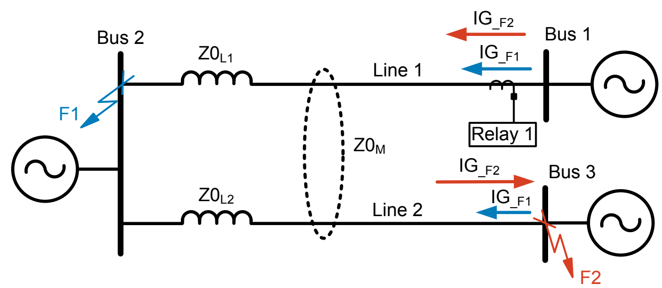

Fig. 7. Local and remote mutually coupling effects

B. Configuration 2: No Common Buses

Configuration 2 occurs when there is a discontinuity in the zero-sequence network caused by delta-wye transformers, as shown in Fig. 8 or when there is no electrical connection between the two mutually coupled lines. Like Configuration 1, this can exist as the natural system configuration or by switching from maintenance or relay action. Fig. 9 shows this scenario.

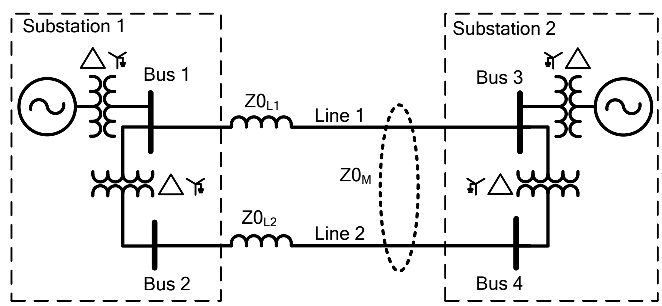

Fig. 8. Naturally electrically isolated zero-sequence networks

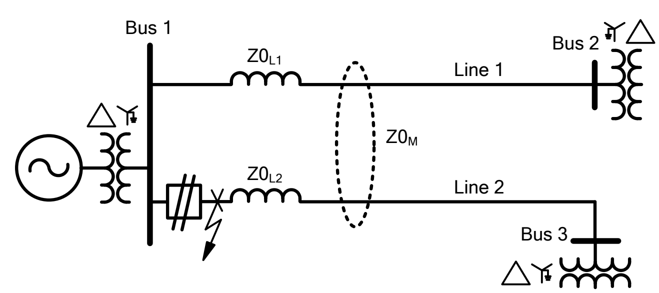

Fig. 9. Breaker operation resulting in isolation of the zero-sequence networks

Configuration 2 will result in a decrease in measured impedance and an increase in current in the faulted line. The induced mutual voltage in the mutually coupled line is always additive in these scenarios, increasing the fault current.

Two systems that are not completely isolated can appear electrically isolated due to a large impedance between the two systems and the fault location. This configuration is shown in Fig. 10.

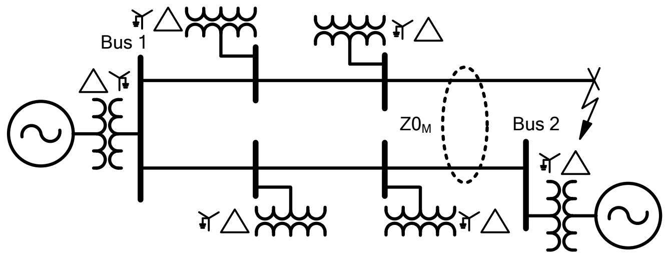

Fig. 10. Electrical isolation due to a large series impedance

Fig. 11 shows a mutually coupled line that is out of service for maintenance and grounded at both ends. In this case, the isolated network consists of two open breakers that isolate the two zero-sequence networks. With both ends of the line grounded, the mutually coupled network is short circuited through the ground path. This causes no issue with the out-of-service line. However, the low-impedance path coupled to the in-service path lowers the Z_{APP} of the in-service line similar to a parallel-impedance circuit.

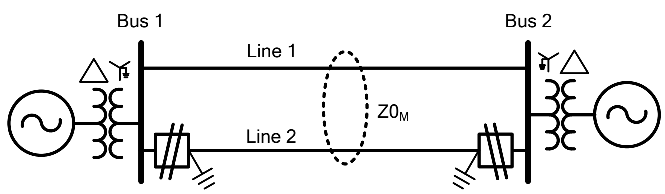

Fig. 11. Maintenance resulting in line out of service and grounded

In Configuration 2, where the mutually coupled lines are isolated, such as Fig. 8, Fig. 9, and sometimes Fig. 10, all zero-sequence voltage and current polarized directional elements can declare forward in the unfaulted isolated system. The cause is commonly referred to as zero-sequence voltage reversal [5]. Typically, V0 quantities are measured as negative values. This is because the zero-sequence network is defined by voltage drops, without a voltage source.

In referring to Fig. 12, Relay 1 measures +V0 while Relay 2 measures –V0. The current flow in the line is measured as negative in Relay 1 and positive in Relay 2. Because the relay expects a negative zero-sequence voltage (approximately 180 degrees) and a positive zero-sequence current (lags by the line angle), both Relays 1 and 2 declare forward.

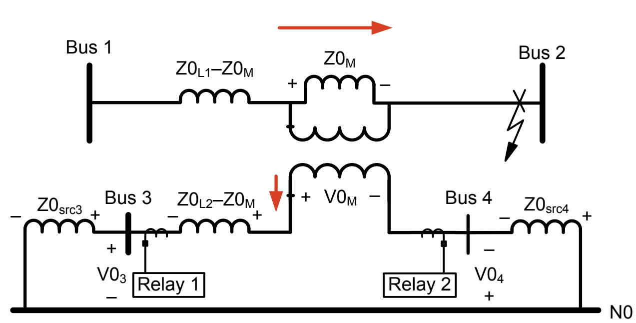

Fig. 12. Voltage reversal

The term *zero-sequence voltage reversal* is useful in understanding the configuration illustrated by Fig. 10, where the voltage from the electrical connection to the fault is smaller than the voltage caused by the mutual coupling. It can be said that the polarizing voltage is dominated by the voltage induced by the mutual coupling, which results in a voltage that is reverse, which is not expected. The term is not particularly descriptive for configurations with mutually coupled lines that are completely isolated in the zero-sequence network. Reversal implies a point of reference, and if the unfaulted system is electrically isolated from the faulted system, the location of the fault on the adjacent system is an abstract concept for the line in the unfaulted system.

Another way of explaining why zero-sequence directional relays always declare forward on the unfaulted system in Configuration 2 is as follows. As previously mentioned, V0 in the zero-sequence network is the result of the voltage drop caused by the I0 current flow through the Z0 impedance. Because the voltage drop is caused by the V0 voltage induced in series with the line and not by a short circuit, the current and polarizing voltage will appear out of phase (forward for voltage-polarized elements) and the current and polarizing current will appear in phase (forward for current-polarized elements) at all relay terminals on the unfaulted system.

Engineers often have difficulty visualizing the effect of mutual coupling because they are used to analyzing shunt unbalances (short circuits) on the power system. Mutual coupling, on the other hand, causes series unbalance. The zero-sequence voltage from the mutual coupling is induced in series with the line. A similar case of series unbalance that is difficult to visualize is when single-pole trip and reclose is applied. During the single-pole-open (SPO) interval, directional elements on the SPO line also always declare forward because of the relationship of the unbalanced voltage drop to the unbalanced load flow [6].

Because zero-sequence directional elements always declare forward if the induced 3I0 current meets the element's qualifying thresholds, there are only two practical solutions if the systems can ever become isolated in the zero-sequence network. Those solutions are to raise the supervisory fault detectors above the worst-case induced current or to disable the zero-sequence elements and use negative-sequence elements exclusively. Raising the fault detectors can reduce the sensitivity of the protection scheme to high-resistance ground faults.

The negative-sequence elements are relatively immune to this phenomenon because the negative-sequence currents are balanced and little negative-sequence current is induced in the unfaulted isolated system. Further, in the Fig. 8 scenario, the negative-sequence network is not electrically isolated between the two mutually coupled lines. A strong electrical connection results in correct polarization of the directional element. Isolation of the negative-sequence networks can only happen in the Fig. 9 scenario.

C. *Configuration 3: Common Buses*

Configuration 3 can exist due to parallel lines or two stations being very close together, as shown in Fig. 13 and Fig. 14, respectively. Configuration 3 results in an increase in impedance and a decrease in current. Both lines carry fault current in the same direction, resulting in opposing mutually induced voltage. In Fig. 14, Buses 2 and 3 have little impedance between them and therefore Buses 2 and 3 resemble one common bus.

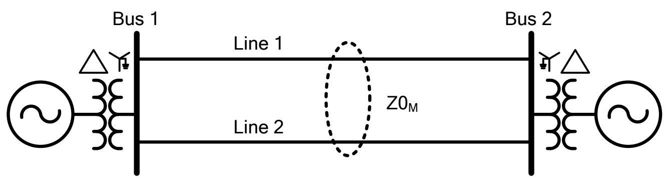

Fig. 13. Shared buses

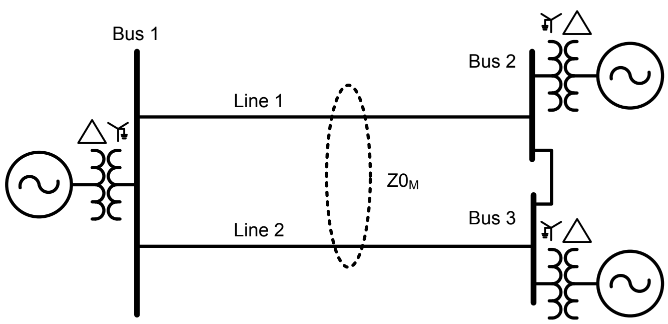

Fig. 14. Electrically shared buses

D. *Configurations Summary*

The configurations discussed dictate how the protective settings will be adjusted. One, two, or all three of these configurations may exist for any given mutually coupled line, depending on how the system can be broken apart. The engineer must anticipate these configurations by evaluating system one-line diagrams or system switching maps.

V. Directional Decisions

Correct directional decisions improve security for all tripping elements that are supervised by the directional element. Many misoperations are caused by the directional element's inability to correctly identify a forward or reverse fault because of the influence of mutual coupling. This is why the recommended practice is to solely use negative-sequence elements on lines with significant mutual coupling. Some misoperations of zero-sequence voltage polarized directional elements can be prevented, but this requires detailed analysis and may not be effective in all cases (such as the Configuration 2 cases shown in Fig. 8, Fig. 9, and sometimes Fig. 10). Zero-sequence current polarization should not be used on mutually coupled lines because there are no settings that can be adjusted to mitigate the effects of mutual coupling [7].

A. *Impedance-Based Directional Elements*

Mutual coupling can fool impedance-based directional elements due to its effect on $Z0S_{APP}$ measured by the relay. Impedance-based directional elements are unique and provide superior resistive fault coverage when automatic settings [8] are used, which set the forward threshold to half of the protected line impedance. Equation (3) shows how the relay, per [2], would calculate the zero-sequence impedance.

Equation (3) uses the thresholds in (7) and (8) to determine if the fault is forward or reverse, respectively. Z0F is a setting and is typically set at half of the protected line's zero-sequence impedance, while the reverse threshold is offset by 0.1 ohm secondary from the forward threshold. Because the directional element will measure the zero-sequence impedance behind the relay, the theory is that a forward fault will always result in a negative impedance measurement that reflects the source impedance behind the relay and a reverse fault will always be the positive line impedance plus the remote source impedance.

$$Z0FTH = 1.25 \cdot Z0F - 0.25 \cdot \left| \frac{3V_0}{I_G} \right| \quad (7)$$

$$Z0RTH = 1.25 \cdot Z0R + 0.25 \cdot \left| \frac{3V_0}{I_G} \right| \quad (8)$$

Fig. 15 shows a typical zero-sequence network. The directional element works extremely well in most cases. The problem arises when mutual coupling is introduced.

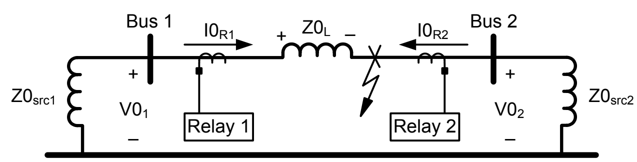

Fig. 15. Typical zero-sequence network

B. *Configuration 1 Analysis*

Fig. 16 shows a system that naturally resides in Configuration 1. The mutual coupling results in an increase in current in both Lines 1 and 2. Equation (9) can be used to calculate the $Z0S_{APP}$ seen by Relay 1 because of the fault in Fig. 16 with Breaker 4 open. Equation (9) is derived in the Appendix and was first introduced in [9].

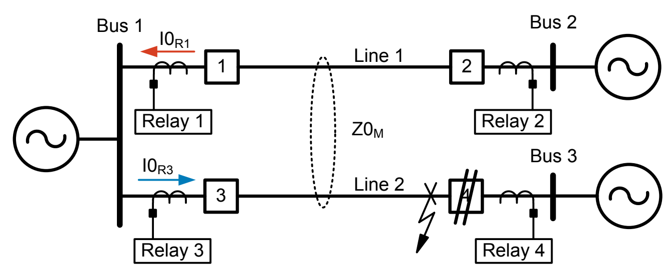

Fig. 16. Faulted Configuration 1

$$Z0S_{APP} = \frac{Z0_{src2} - Z0_M + Z0_{L2}}{Z0_{src1} + Z0_M} \cdot Z0_{src1} \quad (9)$$

Fig. 17 shows how $Z0S_{APP}$ for Relay 1 in Fig. 16 varies as the fault location moves from close-in to the remote end. The Z0F threshold (horizontal line in Fig. 17) is set to 50 percent of the line Z0 impedance, neglecting $Z0_M$. The measured reverse $Z0S_{APP}$ for Relay 1 significantly decreases as the fault moves toward the Bus 3 end of the line, which results in an incorrect directional decision for any fault located more than approximately 25 percent down the line.

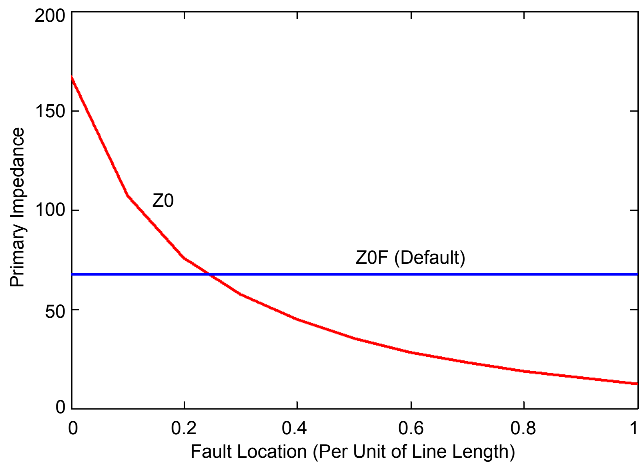

Fig. 17. Z0 change per fault location

The cause of the misoperation for faults beyond 25 percent of Line 1 is that the default setting assumes that the $Z0S_{APP}$ for any reverse fault has to be, at a minimum, equal to the line impedance. So setting the boundary between forward and reverse at half of the line is reasonable. But, due to the reduction in $Z0S_{APP}$ caused by the mutual coupling, $Z0S_{APP}$ is positive (indicating a reverse fault) but not positive enough to be higher than the boundary between reverse and forward.

To further illustrate the point, consider a simple example using (9) and Fig. 16. Consider two lines that are highly mutually coupled [i.e., (6) equals 70 percent] in Configuration 1 with source impedances that are 10 percent of the line impedance. The impedance angles are all assumed to be the same for simplicity. If everything is evaluated in per unit of the line impedance, (9) results in (10):

$$Z0S_{APP} = \frac{0.1 - 0.7 + 1}{0.1 + 0.7} \cdot 0.1 = 0.05 \tag{10}$$

Table IV provides the results for four scenarios.

TABLE IV
VARIABILITY OF $Z0S_{APP}$ ZERO-SEQUENCE SOURCE IMPEDANCE FOR RELAY 3

Scenario	**$Z0_{src1}$**	**$Z0_{src2}$**	**$Z0S_{APP}$ Per Unit of Line Z0**
Both sources strong	0.1	0.1	0.050
Source 1 strong	0.1	1.0	0.163
Source 2 strong	1.0	0.1	0.235
Both sources weak	1.0	1.0	0.765

The resulting reverse $Z0S_{APP}$ is highly variable. The reduction in $Z0S_{APP}$ is greatest when the currents are high (sources are strong). $Z0S_{APP}$ is only 5 percent of the line impedance. The next worst case is where there is a strong zero-sequence source at the local bus because it makes the current in the faulted line relatively greater than the current in the Relay 3 line. The case where the system is weak and results in low-magnitude current has much less of an effect on $Z0S_{APP}$ for Relay 3.

The worst-case reverse $Z0S_{APP}$ will always occur for a fault at the location where the mutual coupling ends with the remote breaker open. This is where the mutual coupling is in full effect and the remote source has been removed. To use a Z0 impedance-based directional element for a line with this configuration, the engineer must find the case where the source impedances have the lowest magnitude (current in the coupled line is highest) and set the Z0F threshold at 50 percent of the resulting $Z0S_{APP}$ instead of 50 percent of $Z0_L$.

C. Configuration 2 Analysis

For the Configuration 2 scenario of power systems isolated in the zero-sequence network, as discussed in Section IV, Subsection B, directional elements on the unfaulted line will declare forward.

Equation (11) represents the apparent zero-sequence line impedance for a reverse fault right behind the relay in question for Configuration 2 where the mutually coupled line is out of service and grounded. A detailed derivation of (11) is found in the Appendix.

$$Z0L_{APP} = Z0_{L1} - \frac{Z0_M^2}{Z0_{L2}} \tag{11}$$

Assuming the maximum mutual coupling strength of 70 percent (practical limit of coupling strength) and that the line impedances ($Z0_{L1}$ and $Z0_{L2}$) are equal, the result is 0.51 per unit. This indicates that a practical rule of thumb for setting the Z0F threshold to account for the reduction in $Z0S_{APP}$ for a double circuit line with the parallel circuit out and grounded is 25 percent of $Z0_L$ instead of 50 percent.

D. Configuration 3 Analysis

The equivalent measured zero-sequence line impedance for two lines that share two common buses is shown in (12), and the derivation can be found in the Appendix. This assumes that the two mutually coupled lines are of the same impedance. The result of (12) is an increase in apparent zero-sequence line impedance. When (12) is used to evaluate a zero-sequence impedance-based directional element, an increase in $Z0S_{APP}$ makes the element more secure, ensuring that the measured impedance is more than half of the zero-sequence line impedance for a reverse fault.

$$Z0L_{APP} = Z0_L + Z0_M \tag{12}$$

E. Summary of Directional Decisions

With hard-to-predict changes in the zero-sequence network, the zero-sequence directional element is very difficult to set securely. This has led to philosophies that strictly use the negative-sequence directional element Z2 in (13). This works for many applications and provides much better security, as discussed in Section IV, Subsection B.

$$Z2 = \frac{\mathrm{Re}\left[V_2 \cdot \left(I_2 \cdot 1\angle Z1ANG\right)^*\right]}{\left|I_2\right|^2} \tag{13}$$

There are certain circumstances where negative-sequence directional elements may not have sufficient polarizing quantities. If and when the engineer identifies a situation where the negative-sequence element qualifying checks are not satisfied or system-specific practice is to use two different polarizing methods, the engineer can assign the negative-sequence directional element priority, with zero sequence as a backup, and apply the thresholds in (14) or AUTO2 from [10]. AUTO2 places the forward and reverse thresholds at ±0.3 ohms secondary on either side of the origin on the impedance plane. This reduces the likelihood of a reduced reverse-measured zero-sequence impedance that results in a forward-directional decision, as illustrated in Table IV.

If primary impedance values are used in (14), they must be converted to secondary ohms when setting the relay. The reverse threshold may then be offset by 0.1 ohms secondary.

$$Z0F = 0.5 \cdot \frac{Z0_{src2} - Z0_{M} + Z0_{L1}}{Z0_{src1} + Z0_{M}} \cdot Z0_{src1} \quad (14)$$

The engineer should keep in mind that it may be better to have no decision on the unfaulted line than to have an incorrect decision. For applications where there is concern about a lack of negative-sequence quantities to enable the negative-sequence directional element to trip for an internal fault, echo keying (permissive schemes) [11], direct underreaching transfer trip, and weak-feed protection schemes can be used to improve dependability and mitigate the security risk of including zero-sequence directional elements on a mutually coupled line.

VI. Case Study

The impedance-based directional element described in [2] has been around for years but continues to be misapplied. This is typically due to unanticipated operating conditions in combination with trust in elements that were designed to work for most operating conditions.

An anonymous utility provided an event that took place on their system in hopes of educating other engineers. The relay in question used best-choice logic [8], which assigns priority when multiple methods for determining direction are used. The relay logic qualifies measured values against thresholds, and then the element that is qualified and first in order makes the directional decision. The relay was set for negative-sequence impedance priority first and zero-sequence impedance priority second. The lack of I2 current coupled with increased I0 current caused by mutual coupling resulted in the relay using the zero-sequence impedance-based directional element instead of the negative-sequence impedance-based element.

A. System Event Overview

At first glance, the case study system shown in Fig. 18 resembles Configuration 3, as introduced in Fig. 14, assuming that Line 3 is short in comparison with Lines 1 and 2. The engineer would expect fault current to flow from Bus 1, out through Lines 1 and 2 toward the fault. Line 3 is much shorter than Lines 1 and 2. Lines 1 and 2 have approximately the same impedance values. The current in Line 2 flows opposite of what would be expected when contributing to a fault. For the location of the fault along Line 1, Line 2 would be electrically neutral without mutual coupling. The current from the source behind Bus 3 wants to flow through Line 3 and the current from the source behind Bus 1 wants to flow through Line 1, leaving a very small current in Line 2. However, due to the current flowing in Line 1 from the source behind Bus 1 to the fault, the effect of mutual coupling increases the current in Line 2 from what would have been less than 100 amperes flowing toward Bus 3 to 760 amperes flowing toward Bus 1.

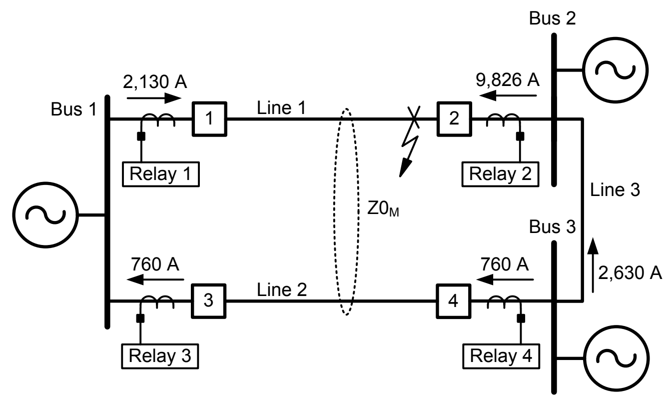

Fig. 18. Case study system and ground current flow

B. Event Analysis

This event consisted of a single-line-to-ground fault on the system, illustrated in Fig. 18, and both the SC study values and the event data are shown in Table V. The event took place on an extra-high voltage (EHV) system that was protected by a directional comparison blocking scheme. The fault was close-in to a generating station located at Bus 2. Bus 3 also had significant generation, while Bus 1 was fed by EHV lines. Large currents flowed in Lines 1 and 3 with small current in Line 2 in the opposite direction of what would normally be expected when mutual coupling is not present.

TABLE V
FAULT CURRENT FLOW

Line Designation	Current Flow From SC Study (I1/3I0)	Current Flow From Event (I1/3I0)
Line 2	40 A/760 A	1,588 A/735 A
Line 3	1,566 A/2,630 A	No data
Bus 1, Line 1	886 A/2,130 A	1,063 A/2,770 A
Bus 2, Line 1	3,099 A/9,826 A	2,841 A/7,387 A

The event contained almost 1,600 amperes of load current on Line 1 and approximately 1,400 amperes of load current on Line 2.

Relay 3 from Fig. 18 misoperated during the event, declaring forward instead of blocking, and Relays 3 and 4 both operated their respective breakers. Relays 3 and 4 were set to use negative-sequence impedance as first priority and then switch to zero-sequence impedance if the negative-sequence current was too low to qualify. For this fault, Relays 3 and 4 used the zero-sequence impedance-based directional element. This was due to the relatively low negative-sequence current available to the negative-sequence directional element.

Now we evaluate the zero-sequence impedance measured behind the relay. The relay was quantifying (3) against (8) to determine if the fault was in the forward direction. If the settings were left as default, which would automatically calculate the forward-impedance threshold as half of the line impedance, the problem arose when the apparent impedance behind the relay dropped below half of the line impedance.

The actual measured impedance from the event data was approximately 71 ohms primary, which was well below the anticipated threshold based on the default setting of approximately 115 ohms. The system was not electrically isolated by a breaker, and the fault current flowed mostly through Lines 1 and 3, leaving mostly mutually induced current in Line 2. If the system acted like Configuration 3, fault current would have flowed from Bus 1 to the fault in both Lines 1 and 2. Because the current flow was the opposite of what was expected, the system appeared as Configuration 1.

These results reinforce the previous concepts in that heavily mutually coupled lines are very susceptible to misoperation from zero-sequence directional elements. Fig. 19 illustrates the resulting impedance for the directional element at Relay 3. The typical reverse $Z0S_{APP}$ represents a reverse fault at Bus 2 that would be expected for a system without mutual coupling. A reverse fault results in the line impedance behind the relay plus the equivalent source behind the line. The typical forward $Z0S_{APP}$ is the result for a forward fault, where mutual coupling is not present and the relay measures the source impedance behind the relay. The resulting apparent impedance $Z0S_{APP}$ is caused by mutual coupling, in this case study, which is dependent on the location of the fault, configuration of the system, and value of the source impedances (which influence the magnitude of the current in the mutually coupled line). We can see that the impedance measured was clearly reverse (positive impedance) but much less than the boundary between forward and reverse.

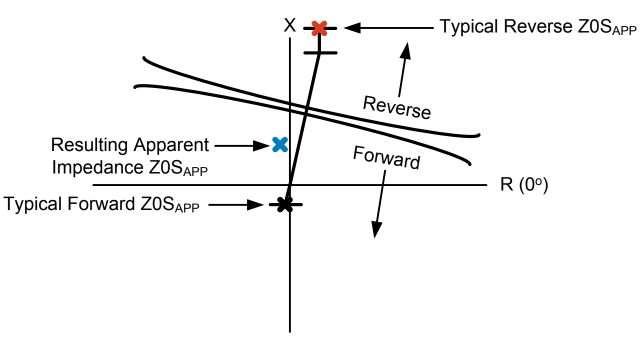

Fig. 19. Directional impedance values

C. SC Study Analysis

Table VI shows the resulting $Z0S_{APP}$ from the SC study for the system in Fig. 18. The apparent impedance was evaluated with Breaker 2 closed (Configuration 3) and open (Configuration 1) for comparison while sliding a fault along Line 1.

TABLE VI
Z0 IMPEDANCE FROM SLIDING FAULT BEHIND RELAY 3

Fault Location From Bus 1 (%)	Breaker 2 Closed, Z0 (Ω Primary)	Breaker 2 Open, Z0 (Ω Primary)
0	318	233
20	270	135
40	215	90
60	152	64
80	81	48
100	96	**43.4**

The $Z0S_{APP}$ measured by Relay 3 when the breaker was closed is significantly larger than when the breaker was open. This was due to the ground source at Bus 2 reducing the current flow from Bus 1 to Bus 2. This resulted in less ground current in Relays 1 and 3. When the breaker opens, the ground current redistributes through the system, resulting in more current in Lines 1 and 2 (flowing in opposite directions) and reducing the measured impedance for Relays 1 and 3.

D. Determining Settings for Event Application

To determine the settings for the application, the engineer would first establish the coupling strength. Applying (6) with the values in Table VII, we find that the coupling strength is approximately 36 percent and enough to warrant further evaluation. Note that Lines 1 and 2 are assumed to have the same zero-sequence impedance because they were so close in value.

TABLE VII
SYSTEM IMPEDANCE VALUES

Impedance Identifier	Impedance Values From Model (Ω)
$Z0_{src1}$	$29.96\angle 77°$
$Z0_{src3}$	$9.63\angle 82.4°$
$Z0_M$	$83.9\angle 58.5°$
$Z0_L$	$231.7\angle 76.1°$

The system values in Table VII can be used to find the worst-case $Z0S_{APP}$ for a fault behind Relay 3 in Fig. 18. As discussed in Section V, Subsection B, Configuration 1 will result in the worst-case $Z0S_{APP}$, and therefore, (9) should be utilized. Inserting the system values into (9) results in approximately 43.4 ohms primary, which is consistent with the worst-case value (100 percent, breaker open) in Table VI. The results from (9) could have been used in (14), resulting in a Z0F setting of approximately 22 ohms, or the AUTO2 solution could have been incorporated to make the zero-sequence directional element more secure. Because the $Z0S_{APP}$ measured by the relay during the event was 71 ohms, a setting of 22 ohms or lower would have allowed the relay to declare the fault as reverse and prevented the misoperation.

However, when setting relays, it is necessary to ensure that the protection maintains reliability under N-1 conditions and high probability under N-2 conditions [7]. For this case study, the most problematic N-1 condition is Line 3 out of service.

This changes the system to Configuration 1, with Bus 1 as the single common bus. In the previous analysis, we used Configuration 1 to determine the worst-case $Z0S_{APP}$ to determine the relay setting.

Now the worst case for the relays on Line 2 becomes the relatively high probability of a ground fault on Line 1 that is successfully cleared, followed by Breaker 2 reclosing first into a permanent fault. We identify this as Configuration 2. Line 2 is an unfaulted line mutually coupled to a faulted line that is electrically isolated. We know from Section IV, Subsection B, that the zero-sequence directional elements at both terminals on Line 2 will declare forward and the pilot scheme will incorrectly trip if the magnitude of the induced current is above the pickup of the pilot ground tripping elements. From this we conclude that for highly mutually coupled lines (36 percent, in this case), enabling zero-sequence directional elements, even as a second priority and with careful analysis to determine the settings, is very risky. If Relay 3 from the case study had been set for negative-sequence directional supervision only instead of allowing zero-sequence directional as second priority, even though the 3I0 magnitude was above the pickup of the pilot tripping element, the negative-sequence directional element would not have permitted the element to assert and trip the line.

VII. Protective Elements

Each protective element has advantages and disadvantages. Overcurrent, ground instantaneous, and ground time-overcurrent elements operate on the magnitude of the measured ground current and are typically supervised by a directional element. Distance elements are inherently directional and operate based on V/I principles. Distance elements are normally much more secure when mutual coupling is not present because they are not susceptible to source changes. Ground overcurrent elements are influenced by the change in sources over time, especially the instantaneous element. However, the ground time-overcurrent element is much more dependable because of its sensitive pickup setting, and it provides greater resistive fault coverage [12]. For these reasons, overcurrent elements are typically applied in conjunction with distance elements, capitalizing on the benefits of both.

A. Ground Overcurrent

The instantaneous element is susceptible to overreach, and mutual coupling increases the chances of overreach in Configurations 1 and 2. The time-overcurrent element does not suffer from overreach, and underreaching is typically not a concern because of the ability to set the element to be very sensitive. However, it does present very complex coordination issues.

Mutual coupling presents unique problems for the overcurrent elements, depending on which configuration is encountered. Configuration 1 presents complex problems for both instantaneous and time-overcurrent elements. Configuration 2 results in an increased current in the faulted line. Configuration 3 is subject to reduced fault current and typically does not provide worst-case coordination times. It is the events that occur after Configuration 3 changes to Configuration 1 that lead to complex coordination.

Consider Fig. 20, which shows Breaker 4 opening instantaneously due to a fault in front of it. Prior to Breaker 4 opening, both lines contributed to the fault as if it were a bus fault at Bus 2. This resulted in reduced current being seen by both Relays 1 and 3 when compared with other configurations.

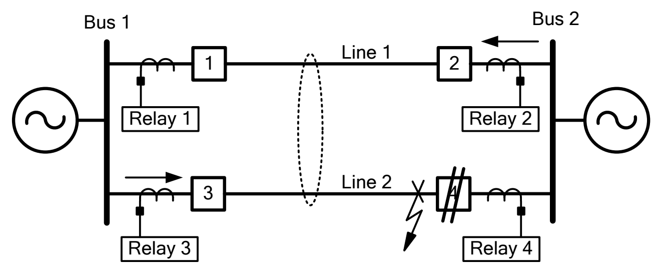

Fig. 20. Resulting current flow from Configuration 1

Fig. 21 shows the resulting current if Breaker 4 is open and the fault location is moved along the length of Line 2. The Relay 3 current is exactly what we would expect: the current decreases as the fault moves further down the line. But the Relay 2 current is the opposite of what we expect. As the fault moves along Line 2, the coupling strength grows, causing an increase in current flow through Relay 2. As expected, for a close-in fault on Line 2, Relay 3 sees considerably more current than Relay 2. This aids the coordination of instantaneous elements and improves the coordination of inverse-time elements. However, for an end-of-line fault, the difference in current magnitude in the two relays is much less, resulting in the critical coordination point for instantaneous and inverse timing elements being for an end-of-line fault instead of a close-in fault.

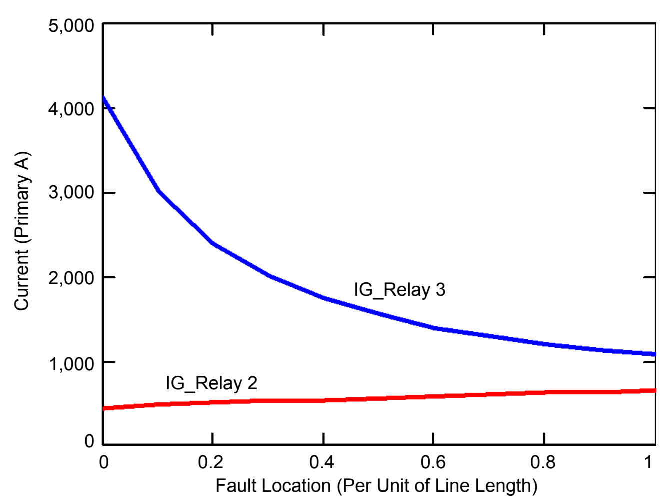

Fig. 21. Resulting ground current per fault location

The fault currents shown in Fig. 21 also cause concerns for instantaneous elements. Consider Fig. 20 with Breaker 4 still closed. An engineer's first inclination for setting the instantaneous element for Relay 2 would be to consider Line 2 out of service and grounded. However, depending on the strength of the ground sources at Bus 1, the fault current for a fault at Bus 1 may be less than when the breaker is open. This occurs because the ground source that was causing less current to flow from Bus 2 toward the fault contributes significantly to a fault in front of the open Breaker 4. This increases the fault current through Line 1 because of the mutual coupling and may be the greatest fault current Relay 2 will see for an out-of-zone fault.

Fig. 22 shows the results from the system in Fig. 20 except that the mutual coupling only exists for 50 percent of the line. The original results are displayed as well for comparison. As the fault location moves out from 50 percent of the line, the relay current begins to decrease for Scenario 2, placing the worst-case coordination in the middle of the line, assuming the instantaneous element does not reach that far. This scenario now requires Relays 2 and 3 to be coordinated for a fault at 50 percent of the line.

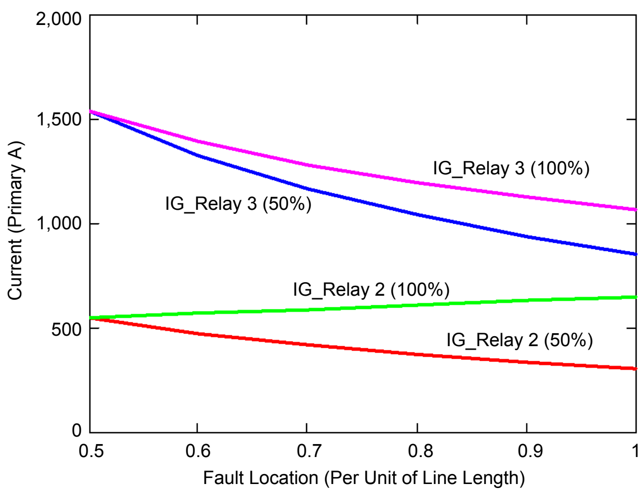

Fig. 22. Currents for 50 percent shared right of way vs. 100 percent shared right of way

Automated SC programs are highly encouraged to check results and assist with coordination. The “brute force” method may be used [7]. This method has the SC program run through various contingencies and system configurations to find the worst-case current and coordination issues. Once the program runs the various scenarios, the engineer may use the minimum and maximum results to set the relay.

B. Ground Step Distance

Step distance elements are more secure than the overcurrent elements because what is measured in front of the relay is not affected by source changes. However, the underreaching element, typically Zone 1, is just as susceptible to overreach as the instantaneous overcurrent element. The overreaching element, typically Zone 2, is very susceptible to underreaching conditions.

Now consider Fig. 20, in which a large ground source has been inserted at Bus 2, resulting in Fig. 23. The Relay 1 Zone 1 element is analyzed for overreaching concerns and compared to the instantaneous overcurrent underreaching element for the following scenarios:

1. System normal.
2. N-1, strong ground source out at the remote bus.
3. Line 2 out of service and grounded.
4. Fault in front of Breaker 3, and Breaker 3 is open.
5. Fault in front of Breaker 3, and Breaker 3 is open with the new strong ground source out.

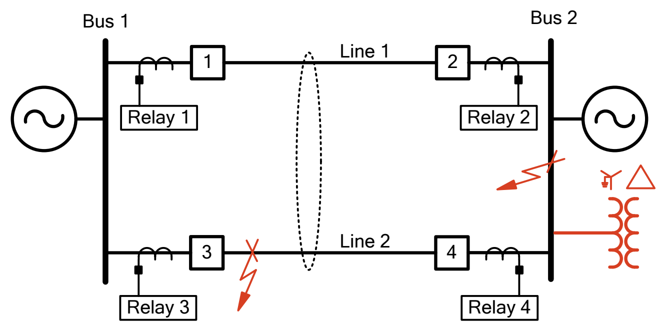

Fig. 23. Overreaching concerns with a strong remote ground source

According to Table VIII, Zone 1 must be set for Scenario 3, which results in the worst-case apparent impedance. The worst-case overreaching condition for the ground instantaneous element is Scenario 5 with the strong remote ground source out. The engineer should not assume that the same worst-case overreaching conditions exist for both overcurrent and distance elements.

TABLE VIII
FAULT CURRENT FLOW AND APPARENT IMPEDANCE FOR FIG. 23

Scenario	Relay 1 Z_{APP} (Ω)	Relay 1 Current (3I0) (A)
1	39.4	143
2	46.2	348
3	29.2	363
4	51.1	651
5	46.0	661

There are conditions where a single ground source may reside at a substation, and during the outage of that ground source currents may redistribute around the zero-sequence network, resulting in a significant apparent impedance reduction.

Fig. 24 shows the possible redistribution of ground current throughout a network when a single large ground source is removed. The change in voltage at the station does not change proportionally to the change in current when the ground source is removed.

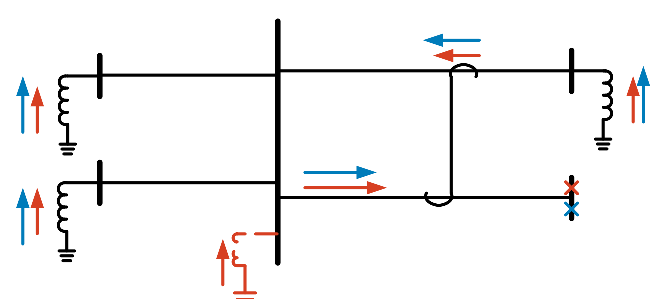

Fig. 24. Ground current redistribution

The Zone 2 ground should be checked for an increase in Z_{APP} at the remote terminal. A reduction in impedance at one terminal may result in an increase in impedance at the remote terminal, and vice versa.

An SC program can be used to validate or find the worst-case apparent impedance conditions. The automated program allows the engineer to simulate an outage on all equipment associated with the protected line, minimizing the chance of missing a worst-case configuration and contingency.

C. Comparison of Overcurrent and Distance Elements

Table IX shows a comparison of changes in the overcurrent and distance elements for Relay 1 in Fig. 23 under various operating conditions. It shows to what extent each element is affected by the different configurations.

TABLE IX
CHANGE IN OVERCURRENT AND DISTANCE ELEMENTS

System Configuration	IFault/IRef	$Z1_L/Z_{APP}$
Breaker 3 open	1.49	1.44
System normal	0.42	0.76
Line 2 out of service and grounded, Breaker 2 closed	0.49	1.16
Line 2 out of service and grounded, Breaker 2 open	1.32	1.44

A common reference is needed for comparison to quantify the change. The resulting current for each system configuration is compared to the current (IRef = 747 A) when the mutually coupled line is out of service and the remote breaker opens. The remote breaker is opened to remove the split in-ground fault current between the two zero-sequence sources at Buses 1 and 2.

The distance element is compared to $Z1_L$, which the relay should measure when the mutually coupled line is out of service and the remote breaker opens.

The change is similar, and overreaching scenarios for overcurrent elements create overreaching concerns for distance elements, and vice versa for underreaching scenarios. The change compared to the reference is not the same due to the voltage change and k0 factor influence on the distance element.

D. Directional Comparison Pilot Schemes

Pilot schemes mitigate stability and coordination concerns when in service but are very unforgiving during security failures. Pilot schemes act instantly and do not allow protection outside of their own zone to clear faults first. Security failures begin with the directional element's inability to discriminate between an internal and external fault. This occurs when an unexpectedly low apparent source impedance occurs, systems become isolated in the zero-sequence network, or a polarizing quantity reverses polarity.

1) Configuration 1 (Apparent Source Impedance Changes)

A change in $Z0S_{APP}$ for reverse-looking zero-sequence directional elements in Configuration 1 can be accounted for by using (9), except during Configuration 2 when two power systems are isolated or practically isolated in the zero-sequence network. This ensures correct directional decisions for Configurations 1 and 3 but not Configuration 2, except when the mutually coupled line is out of service and grounded. Negative-sequence directional elements are still the preferred choice for mutually coupled lines.

2) Configuration 2 (Isolated Systems)

a) Configuration 2 Negative-Sequence Directional Element

The negative-sequence directional element will not qualify in the line relays of the unfaulted line. This is due to the lack of negative-sequence current flowing to enable the element. If the engineer is using best-choice logic or two directional elements that run in parallel, misoperation is still likely.

b) Fault Detectors

Fault detector supervision works on the premise that the mutually coupled line will experience current values for true faults that greatly exceed those induced by the mutually coupled line. However, raising the fault detector settings reduces sensitivity when fault impedance is encountered.

c) Distance Elements Only in Pilot Schemes

Pilot schemes using a ground distance element for local trip instead of a directional overcurrent element provide better security. Pilot schemes require a correct directional decision at both terminals, otherwise a blocking scheme will fail to a send block and a permissive scheme will fail to block echo keying [11]. Using the overreaching ground distance element for the local trip reduces the likelihood of misoperation.

Referring to (4), V_A will be high on the unfaulted line and I_0 and I_A will be reduced, compared to if the line was faulted. Z_{APP} will result in an impedance much larger than any typical Zone 2 value. This solution greatly increases security because of the fixed reach, but it reduces resistive fault coverage. Luckily, high-speed clearing for ground faults with fault impedance is not a stability concern; however, it does impact public safety [7].

d) Negative-Sequence Supervision

Negative-sequence supervision requires the engineer to qualify a zero-sequence directional element with a negative-sequence overcurrent element. This solution has merit when individual fault detectors for the zero- and negative-sequence directional elements are not available or the two directional elements run in parallel.

VIII. CONCLUSION

Mutual coupling creates a vast array of problems for engineers. Understanding when and to what extent mutual coupling influences a relay's set points can greatly assist engineers. Engineers must go through system checks to validate concerns and mitigate problems. The authors of this paper feel that an understanding of the consequences of mutual coupling is needed to minimize the chance that worst-case contingencies are missed.

The configuration in Fig. 20 was only for illustration purposes and was used because all three potential configurations existed in a single example. When mutual coupling is present, each system can be broken down into the three possible configurations mentioned previously. Contingencies affect to what extent each configuration impacts the protection settings.

SC programs should be heavily relied on to check results, but they should not be depended upon to set the relay. Automated checks by these programs require an understanding of the system implications, not only at the local bus but at the remote bus and mutually coupled line. Many SC programs allow for contingency checks for the local terminal but provide an option for the engineer to specify their own contingencies outside of the local zone of protection. If the engineer is able to identify troublesome configurations, it becomes much easier to correctly set up the automated routines in the SC programs.

Engineering analysis allows engineers to do the following:

- Identify to what extent the mutual coupling effects will influence the protective elements.
- Understand and identify system configurations that worsen the mutual coupling effect for a given element.
- Identify and evaluate the security and dependability requirements of the directional element, based on Section V.
- Perform rigorous checks to mitigate missed system configurations using an SC program.

Key takeaways from this paper include the following:

- Configuration 1 can result in extreme apparent zero-sequence source impedance ($Z0S_{APP}$) changes, depending on system source impedances, which impact zero-sequence impedance-based directional elements when these are set to half of the line impedance.
- Configuration 2 results in zero-sequence directional element misoperation in the unfaulted line, except for in Configuration 2 where the mutually coupled line is out of service and grounded.
- Worst-case scenarios for overcurrent and distance elements should not be assumed to be the same.
- Fault current in the unfaulted line rises in Configuration 1 as the fault moves away from the shared bus on the mutually coupled line.
- Using negative-sequence directional elements exclusively on lines with significant (greater than 10 percent) mutual coupling reduces the risk of security failures during unexpected or unidentified Configuration 1 and 2 scenarios.
- Removing sensitive directional ground overcurrent pilot tripping elements from high-speed pilot schemes can mitigate the risk of misoperation caused by mutual coupling. Ground distance elements provide high-speed protection for significant ground faults, while high-impedance ground faults, which have little impact on stability, can be cleared with time delay.
- Because the variation in apparent impedance caused by mutual coupling is very dependent upon current in the other circuit, small inaccuracies in the SC model that affect current distribution can affect the accuracy of the results. Use larger-than-normal security and dependability margins.

IX. Appendix

A. Overview

Equations (15) and (16) derived from Fig. 25 are written in terms of zero sequence because the mutual coupling (assuming transposition) shows up predominately in the zero-sequence network. The following analysis shows how we arrive at the zero-sequence network shown in Fig. 26. The line current contribution is added and subtracted from (17), which is shown in [13], for a net zero result but allows for a simplified equivalent network.

$$V0_{21} = I0_{21} \cdot \left(Z0_{L1} - Z0_M\right) + Z0_M \cdot \left(I0_{21} + I0_{1F}\right) \tag{15}$$

$V0_{1F}$ is solved similarly to (17).

$$V0_{1F} = I0_{1F} \cdot \left(Z0_{L1} - Z0_M\right) + Z0_M \cdot \left(I0_{21} + I0_{1F}\right) \tag{16}$$

$$V0_{21} = I0_{21} \cdot Z0_{L1} + I0_{1F} \cdot Z0_M - I0_{21} \cdot Z0_M + I0_{21} \cdot Z0_M \tag{17}$$

Each line equation, (15) and (16), has a mutual term subtracted from the line current, and the mutual impedance is multiplied by the sum of the two currents. $I0_{1F}$ can be considered the total fault current, while $I0_{21}$ is less than the Bus 1 contribution and opposite in polarity. The fact that $I0_{21}$ and $I0_{1F}$ are opposite in polarity is key. So $I0_{21}$ flows from Bus 2 to Bus 1, and $I0_{1F}$ flows from Bus 1 to the fault. The mutual impedance is still multiplied by the sum of the two currents, which is actually the source contribution from Bus 1.

The bus voltage reference remains the same (notice that the potential transformer (PT) in Fig. 26 is connected to Bus 1 and not where the current divides), but we have created a current divider that satisfies (15) and (16). The sequence network results show that the faulted line impedance and the mutual impedance reduce linearly with the fault location, while the Line 1 zero-sequence impedance remains fixed. This all assumes that the breaker is open.

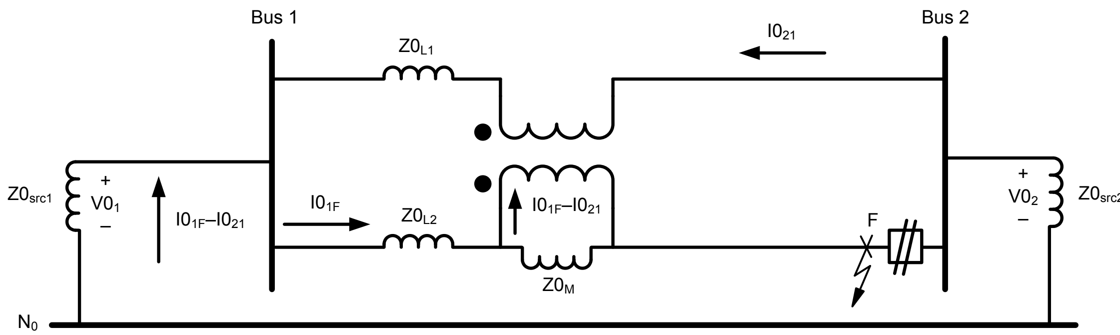

Fig. 25. Configuration 1 system

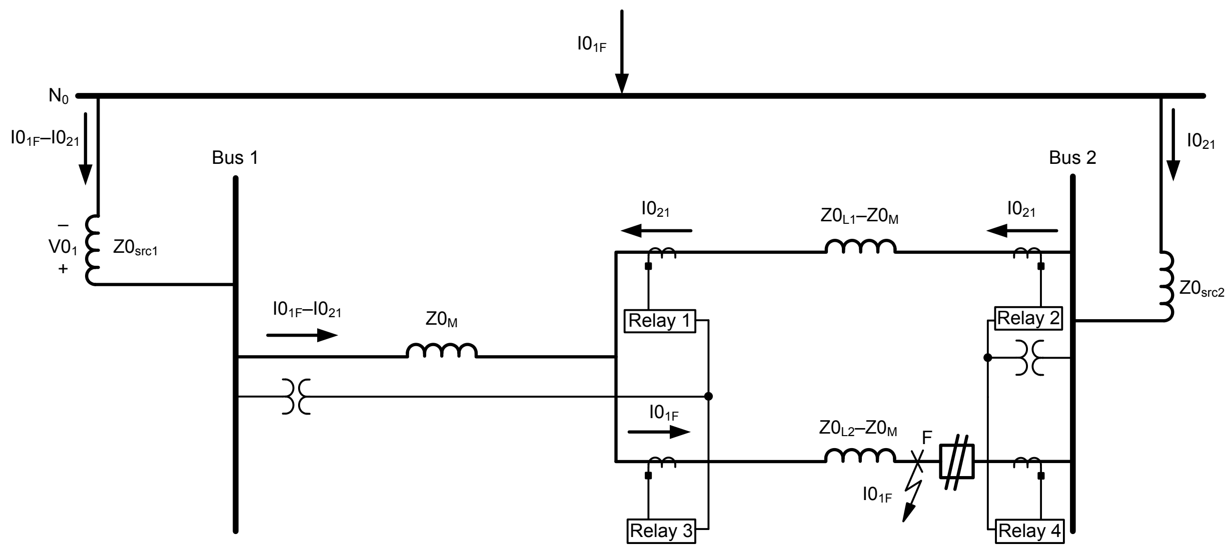

Fig. 26. Equivalent zero-sequence network

B. Configuration 1 Reverse

Because of the directional element design [2], the thresholds reside on the positive side of the impedance plane. Because of this, the reverse element is most susceptible to misoperation.

Consider Relay 1 in Fig. 26, which is at risk of misoperation. Equation (18) is the zero-sequence impedance measured by the relay. The voltage and current for (18) are identified by a current divider shown in (19) and the voltage drop across the source impedance shown in (20).

The voltage in (20) is represented by the PT connected to Bus 1 in Fig. 26 and calculated by the known current ($I0_{1F}$–$I0_{21}$) through the zero-sequence source impedance behind the relay at Bus 1.

$$Z0_{R1} = \frac{V0_{R1}}{I0_{R1}} \tag{18}$$

$$I0_{R1} = I0_{1F} \bullet \frac{\left(Z0_{src1} + Z0_M\right)}{\left(Z0_{src1} + Z0_M\right) + \left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]} \tag{19}$$

$$V0_{R1} = I0_{1F} \bullet \frac{\left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]}{\left(Z0_{src1} + Z0_M\right) + \left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]} \bullet Z0_{src1} \tag{20}$$

Inserting (19) and (20) into (18) results in (21). Further simplification results in (22).

$$\frac{V0_{R1}}{I0_{R1}} = \frac{I0_{1F} \bullet \frac{\left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]}{\left(Z0_{src1} + Z0_M\right) + \left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]} \bullet Z0_{src1}}{I0_{1F} \bullet \frac{\left(Z0_{src1} + Z0_M\right)}{\left(Z0_{src1} + Z0_M\right) + \left[\left(Z0_{L1} - Z0_M\right) + Z0_{src2}\right]}} \tag{21}$$

$$Z0_{R1} = \frac{\left[\left(Z0_{12} - Z0_M\right) + Z0_{src2}\right]}{\left(Z0_{src1} + Z0_M\right)} \bullet Z0_{src1} \tag{22}$$

Equation (22) is used to find the worst-case $Z0S_{APP}$, which could cause a security failure.

C. Configuration 1 Forward

Configuration 1 for the forward direction is at much less risk of a dependability failure than the reverse element is of a security failure. Forward faults result in a negative impedance, and because the directional thresholds are positive, a forward-measured impedance would need to become positive to be at risk of being declared reverse. Equation (23) defines the forward impedance measured by Relay 3 in Fig. 26. The current and voltage are defined by (24) and (25), respectively. The current has changed from (19), which was the result of a current divider, and is now the total fault current shown in (24). The measured relay voltage is the same as measured in (20), as shown in (25).

$$Z0_{R3} = \frac{V0_{R3}}{I0_{R3}} \tag{23}$$

$$I0_{R3} = I0_{1F} \tag{24}$$

$$V0_{R3} = V0_{R1} \tag{25}$$

Substituting (24) and (25) into (23) results in (26), which is the forward $Z0S_{APP}$. Equation (27) is the result of the canceling currents, and (28) is the final simplified forward $Z0S_{APP}$.

$$\frac{V0_{R3}}{I0_{R3}} = \frac{I0_{Total} \bullet \frac{\left[\left(Z0_{L1} - Z0_{M}\right) + Z0_{src2}\right]}{\left(Z0_{src1} + Z0_{M}\right) + \left[\left(Z0_{L1} - Z0_{M}\right) + Z0_{src2}\right]} \bullet Z0_{src1}}{I0_{Total}} \tag{26}$$

$$Z0_{R3} = \frac{\left[\left(Z0_{L1} - Z0_{M}\right) + Z0_{src2}\right]}{\left(Z0_{src1} + Z0_{M}\right) + \left[\left(Z0_{L1} - Z0_{M}\right) + Z0_{src2}\right]} \bullet Z0_{src1} \tag{27}$$

$$Z0_{R3} = \frac{Z0_{L1} - Z0_{M} + Z0_{src2}}{Z0_{src1} + Z0_{L1} + Z0_{src2}} \bullet Z0_{src1} \tag{28}$$

D. Configuration 2

Equations (29) and (30) are derived from Configuration 2 in Fig. 27. When Line 2 is out of service and grounded, the voltage on Line 2 is zero. When there is a ground fault, the voltage impressed on the out of service and grounded line (Line 2) is equal to the Line 1 current (flows in the opposite direction of the Line 1 current) and then is multiplied by the mutual impedance, as shown in (31).

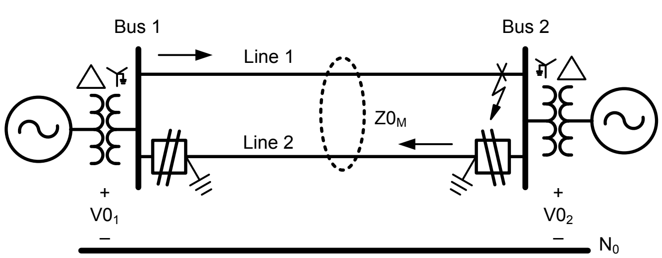

Fig. 27. Configuration 2 system derivation

$$V0_{12} = I0_{L1} \bullet Z0_{L1} + I0_{L2} \bullet Z0_{M} \tag{29}$$

$$V0^{*}_{12} = I0_{L2} \bullet Z0_{L2} + I0_{L1} \bullet Z0_{M} \tag{30}$$

$$-I0_{L2} \bullet Z0_{L2} = I0_{L1} \bullet Z0_{M} \tag{31}$$

Solving for $I0_{L2}$ in (31) yields (32). Equation (32) is then inserted into (29), resulting in (33). Rearranging (33) and solving for Z_{APP} of the line results in (34).

$$I0_{L2} = \frac{-I0_{L1} \bullet Z0_{M}}{Z0_{L2}} \tag{32}$$

$$V0_{12} = I0_{L1} \bullet Z0_{L1} + \left[\frac{-I0_{L1} \bullet Z0_{M}}{Z0_{L2}}\right] \bullet Z0_{M} \tag{33}$$

$$\frac{V0_{12}}{I0_{L1}} = Z0_{L1} - \frac{Z0_{M}^{2}}{Z0_{L2}} \tag{34}$$

E. Configuration 3

Configuration 3 shown in Fig. 28 is similar to Configuration 2 in Fig. 27, except that the induced currents are now flowing in the same direction (subtractive). Equation (31) is used to find $I0_{L2}$ in (35). Equation (35) is substituted into (29), resulting in (36).

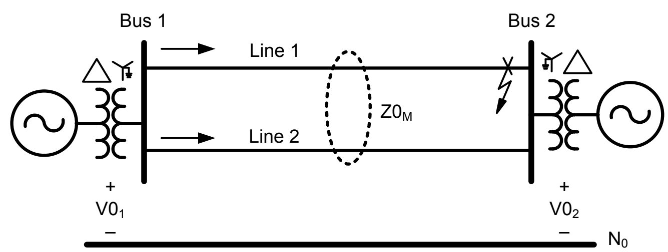

Fig. 28. Configuration 3 system derivation

$$I0_{L2} = \frac{V0_{12} - I0_{L1} \bullet Z0_{M}}{Z0_{L2}} \tag{35}$$

$$V0_{12} = I0_{L1} \bullet Z0_{L1} + \left[\frac{V0_{12} - I0_{L1} \bullet Z0_{M}}{Z0_{L2}}\right] \bullet Z0_{M} \tag{36}$$

Equation (37) is the result of rearranging (36). Solving for the impedance results in (38), which further reduces to (39).

$$V0_{12} \bullet \left[1 - \frac{Z0_{M}}{Z0_{L2}}\right] = I0_{L1} \bullet \left[Z0_{L1} - \frac{Z0_{M}^{2}}{Z0_{L2}}\right] \tag{37}$$

$$\frac{V0_{12}}{I0_{L1}} = \frac{\left[Z0_{L1} - \frac{Z0_{M}^{2}}{Z0_{L2}}\right]}{\left[1 - \frac{Z0_{M}}{Z0_{L2}}\right]} \tag{38}$$

$$Z0_{L1} + Z0_{M} \tag{39}$$

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XI. References

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XII. Biographies

Craig Holt received his B.S. in electrical engineering from California State University of Fresno in 2006 and an M.E. from the University of Idaho in 2011. Upon graduating in 2006, he worked at Southern California Edison for over six years. He joined Schweitzer Engineering Laboratories, Inc. in 2013 as a protection engineer.

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

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