Improving Ground Fault Sensitivity for Transmission Lines Near Inverter-Based Resources

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***Abstract*—In this paper, we provide recommendations to enhance the ground fault sensitivity of communications-assisted directional comparison schemes when inverter-based resources are connected to mutually coupled lines. This includes permissive overreaching transfer trip (POTT) and directional comparison block (DCB) schemes.**

To provide sensitive ground fault protection on transmission lines, a sensitively set directional ground overcurrent element (67G) is often used in conjunction with a directional comparison scheme to provide selective clearing for high-resistance ground faults. The 67G element typically uses one of the following elements for directional control: negative-sequence voltage and current (32Q), zero-sequence voltage and current (32V), or zero-sequence current only (32I). To prevent security concerns related to mutual coupling, 32Q is preferred. However, transmission lines near inverter-based resources (IBRs) create security challenges with 32Q. To mitigate these security challenges, the negative-sequence overcurrent supervision of the directional element is desensitized such that it only declares a fault direction when the $3I_2$ current exceeds the maximum IBR output level. This reduces the sensitivity of a 67G element that uses 32Q supervision for ground faults, especially for high output IBRs.

The zero-sequence overcurrent supervision elements for the 32V and 32I do not need to be set as a function of IBR output, and these elements improve ground fault protection sensitivity in many applications, especially when the transmission line is not mutually coupled.

However, using zero-sequence directional elements in the presence of mutual coupling requires additional considerations to maintain security near an IBR. In this paper, we will review these considerations and offer guidance, as well as other techniques, to improve directional element sensitivity and maintain security in mutually coupled lines near an IBR.

I. INTRODUCTION

Directional ground overcurrent elements (67G) are typically used in conjunction with directional comparison schemes to improve protection dependability and sensitivity for high-resistance faults in transmission lines. To provide directional control to the ground overcurrent elements, we use negative-sequence and/or zero-sequence quantity-based directional elements.

In conventional systems, directional elements have worked well and provided the necessary sensitivity for high-resistance faults. The overcurrent supervision pickup settings for the directional elements in conventional systems are selected above the system's standing unbalance (i.e., unbalanced loads or untransposed lines). These unbalances typically produce low levels of $3I_2$ and $3I_0$. In most cases, directional element overcurrent supervision settings are left at default values, which are a fraction of the nominal current rating of the relay.

Often, a negative-sequence directional element (32Q) provides 67G directionality. One of the benefits of using 32Q is that it is simpler to apply than zero-sequence directional elements (32V or 32I) in transmission lines with mutual coupling. No detailed studies are required to apply 32Q.

However, in transmission lines near inverter-based resources (IBRs), a sensitively set negative-sequence directional element may not be secure during external faults because of the active I_2 injection by the IBR, which often creates an incoherent relationship between I_2 and V_2. In such systems, the protection engineer needs to desensitize the negative-sequence directional element by increasing the pickup of 32Q overcurrent supervision settings (50QF and 50QR) [1] [2] to improve the security for external faults fed by an IBR-only source. This reduces the sensitivity of the negative-sequence directional elements near the IBRs and has led to a renewed interest in using zero-sequence directional elements in these applications.

In some new installations, an IBR is connected to an existing double-circuit line with mutual coupling, and this is shown in Fig. 1.

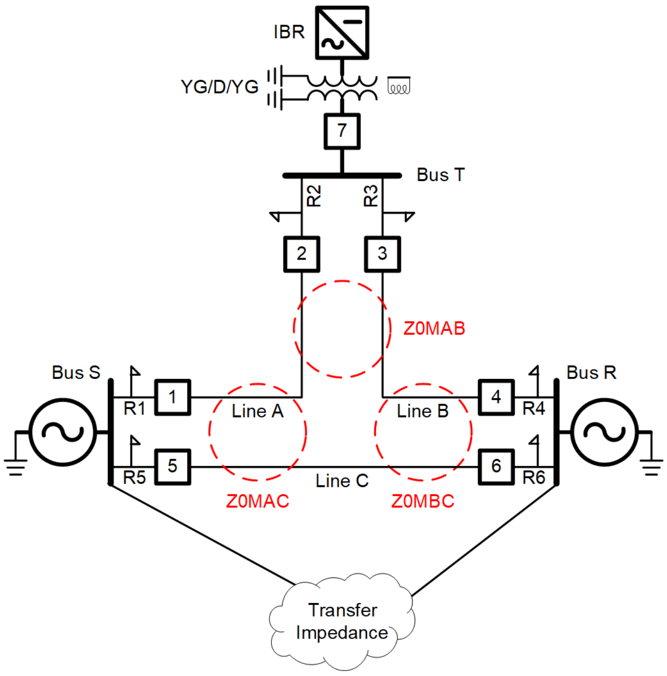

Fig. 1 IBR cut into an existing transmission line with mutual coupling.

In a networked system, there is likely an equivalent transfer impedance between the existing Bus S and Bus R representing an electrical connection between the two buses; this is shown in Fig. 1 as a cloud. Connecting the IBR to an existing transmission line will split the line into two new lines (Line A and Line B), which are both mutually coupled to Line C. If Bus T is far from the tap point, then Line A and Line B may also be mutually coupled. Typically, there is a ring bus configuration at the point of interconnection, which is not shown in Fig. 1 for simplicity.

The IBR is isolated from the protected line in the zero-sequence network because of the delta/wye transformer connection between the low-voltage generation and the medium-voltage collector system [1] [2] (not shown in Fig. 1). Therefore, the IBR does not contribute zero-sequence current to the fault. However, the wye-grounded winding of the medium- to high-voltage step-up transformer (shown in Fig. 1) provides a zero-sequence path for $3I_0$ to flow from the conventional sources at Bus S and Bus R connected to the line. Therefore, zero-sequence-based directional elements can be set sensitively near the IBRs as the IBR does not "corrupt" the $3I_0$ signal.

The introduction of mutual coupling complicates the application of 32V. In this paper, we will focus on improving ground fault sensitivity using 32V for the configuration shown in Fig. 1, but the method can be applied to any line with mutual coupling.

II. DIRECTIONAL ELEMENTS NEAR IBRS

The poor security of negative-sequence directional elements near IBRs is well documented [1] [2] [3] [4] [5]. The generalized recommendation to maintain directional security is to desensitize the overcurrent supervision of the negative-sequence directional elements. Reference [2] assumes an IBR with a maximum negative-sequence fault current output of 1.3 times the full-load amperes with a 1.25 margin factor to arrive at a 50QF setting of 1.63 times the full load current of the IBR. We refer to this setting value as $3I2_{PU}$ throughout the rest of this paper. This value can vary based on the maximum fault current output level of the IBR, but this multiplier serves as a general recommendation to maintain security for faults fed by an IBR [2]. As a result, the negative-sequence directional element sensitivity becomes a function of the generation capacity of nearby IBRs, rather than the very low standing unbalance considered in conventional systems.

A. *High IBR MVA Ratings*

Higher megavolt-ampere (MVA) ratings of the inverters will result in higher 50QF pickup settings and 32Q desensitization for any relay that can measure only IBR current under credible system contingencies. In Fig. 1, this means R1, R2 (Line B out of service), and R3, R4 (Line A out of service) will have 50QF set as a function of the IBR output. Because 32Q often provides directional supervision for ground overcurrent elements (67G), 32Q can become the limiting factor in ground fault sensitivity.

For example, one regional operator mandates that a relay must detect at least 600 A of ground fault current ($3I_0$) [6]. Considering a 230 kV system, if the IBR size exceeds 146 MVA, then negative-sequence overcurrent supervision will be set greater than 600 A ($3I_2$). If we assume $3I_2 = 3I_0$ for a single-phase-to-ground fault, then any IBR above 146 MVA will result in less fault resistance coverage for single-phase-to-ground faults for relays that rely on 32Q supervision of 67G. Because 32V overcurrent supervision is not a function of the IBR size, it is possible to use 32V to improve ground fault resistance coverage.

We refer to the 600 A ground fault pickup limit as $3I0_{PU}$ throughout the rest of this paper and use it to illustrate fault resistance coverage for ground faults. While a 600 A pickup for $3I_0$ is the maximum allowed by one regional operator, it is still beneficial to strive for the highest level of sensitivity you can get while still being secure. Reference [7] has guidance on practical limits to sensitivity of ground directional overcurrent elements.

B. *Fault Resistance Coverage for IBR Fed Faults*

While assuming $3I_2 = 3I_0$ for a phase-to-ground fault helps understand the loss of 67G sensitivity when supervised by 32Q, it does not take into account the current distribution for an internal fault on a two-terminal line. Using [8], we modeled a simple two-source, single-line system in which Bus S is a conventional strong source, and Bus T is an IBR source, with no transfer impedance between Bus S and Bus T. We assume the IBR at Bus T is capable of producing 300 MVA, which is large enough to lead to the desensitization of 32Q. This model approximates the N-1 condition from Fig. 1 in which Line B is out of service.

Throughout this paper, we refer to an N-1 contingency as one element of the system is out of service and will influence the relay behavior of the subject transmission line. Examples of an element out of service include a generation source, a transmission line, or an open breaker prior to the occurrence of a fault. An N-2 contingency means two elements of the system are out of service.

The positive- and negative-sequence impedance values for the IBR located at Bus T are different and difficult to quantify, vary with time, and are beyond the scope of this paper [9]. For analysis purposes, we assume that the incremental change in voltage (ΔV) is equal to the system voltage for a close-in three-phase fault at the IBR terminal. Assuming that the IBR was at full generation capacity prior to the fault (1 per unit current), the maximum fault current output is 1.3 per unit current, and there is little difference in the fault current angle and the load angle, then the incremental change in current (ΔI) is 0.3 per unit current. Dividing ΔV by ΔI provides for a "ball park" value of the IBR positive-sequence source impedance (Z_{1T}), which we assume is equal to the negative-sequence impedance(Z_{2T}). In reality, Z_{2T} may be larger than Z_{1T} as IBRs may limit negative-sequence current contribution to unbalanced faults [10]. Regardless, Z_{1T} and Z_{2T} will be quite large and the IBR can be characterized as a weak source in the positive- and negative-sequence networks as compared to conventional generation sources. In systems with high penetration of IBRs, more detailed modeling is required to determine the fault resistance coverage.

The zero-sequence impedance value at the IBR terminal equals the step-up transformer zero-sequence impedance value. We assume a 9 percent transformer impedance at a 210 MVA base, which is 70 percent of the full output capacity of the IBR we consider (300 MVA). The transformer will make Z_{0T} much smaller than Z_{2T} and Z_{1T} at the IBR terminal.

Two examples follow that show fault resistance coverage. Case 1 is for a relay that uses common overcurrent supervision for 32Q and 32V. Based on the MVA rating of the IBR (300 MVA) and 230 kV system voltage, the forward directional overcurrent supervision for 32Q (50QF) and 32V (50GF) will be set at 1228 A. Case 2 is for a relay that allows separate overcurrent supervision for 32Q and 32V. In this case, 50QF remains set at 1228 A, while 50GF is set at 600 A. If either 32Q or 32V declare a forward direction, 67G is permitted to operate. We also show fault resistance coverage of 67Q (set at 1228 A), which is a negative-sequence directional overcurrent element supervised by 32Q.

In Fig. 2 and Fig. 3, a fault located at Bus S has a fault location of 0 per unit (pu), while a fault located at Bus T has a fault location of 1 pu. A relay element will operate for fault resistance values below its respective line plotted in Fig. 2 and Fig. 3. The 67Q element of R2 has no coverage for phase-to-ground faults because the negative-sequence current contribution from the IBR does not exceed the 67Q set point. As such, no line for 67Q (R2) is plotted.

Case 1: Relay With Common Overcurrent Supervision for 32V and 32Q

Fig. 2 shows the fault resistance coverage of 67G and 67Q elements of R1 (solid lines) and the fault resistance coverage of the 67G element of R2 (dotted lines) with 32V and 32Q overcurrent supervision set at 1228 A.

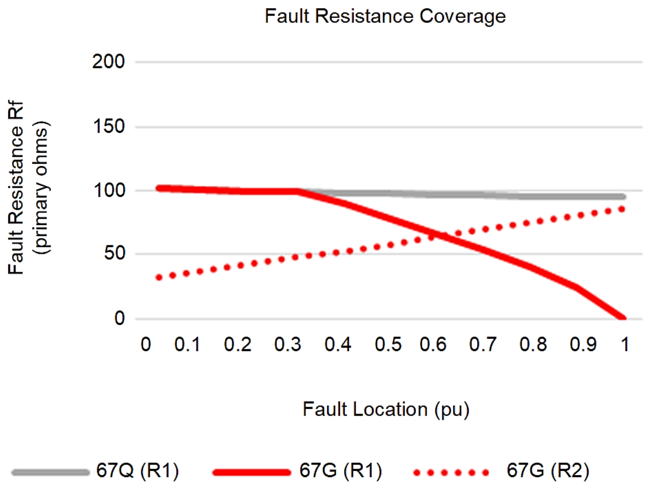

Fig. 2 Fault resistance coverage when 32V and 32Q overcurrent supervision is set based on IBR output.

As shown in Fig. 2, we can see that the 67G (R2) still has fault resistance coverage for faults along the line, even with 32V overcurrent supervision set based on the IBR output. This is because of the low impedance path in the zero-sequence network from the IBR step-up transformer at Bus T. However, 67G (R2) has decreasing fault resistance coverage as the fault location is moved from Bus T to Bus S. This is because the current distribution in the zero-sequence network becomes less favorable for 67G (R2) the further the fault is from Bus T.

We can see that 67Q (R1) has improved fault resistance coverage over 67G (R1) for faults closer to Bus T. The IBR is a large impedance in the negative-sequence network relative to Source S. The current distribution in this two-source system highly favors Bus S because we essentially have an open circuit in the negative-sequence network at Bus T. This means that the 67Q (R1) has good fault resistance coverage for faults along the entire length of the line. In contrast, the fault resistance coverage of 67G (R1) declines as the fault moves closer to Bus T as the zero-sequence current distribution becomes less favorable.

Case 2: Relays With Separate Overcurrent Supervision for 32V and 32Q

Fig. 3 shows the fault resistance coverage of 67G and 67Q of R1 (solid lines) and the fault resistance coverage of R2 (dotted lines) with 32Q overcurrent supervision still set at 1228 A, but the 32V overcurrent supervision set more sensitively at 600 A.

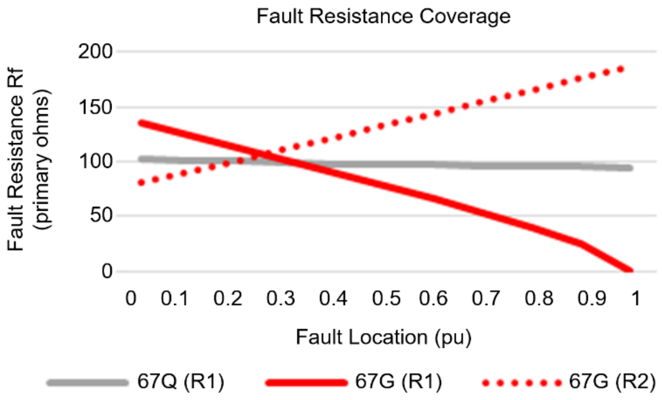

Fig. 3 Fault resistance coverage when 32V overcurrent supervision is set independently of IBR output.

For close-in faults at Bus S, 67G (R1) provides better fault resistance coverage than 67Q (R1) with the more sensitive settings. 67G (R2) provides a significant sensitivity improvement for faults along the entire length of the line.

C. *Communications-Assisted Tripping Scheme Sensitivity*

The communications-assisted tripping scheme in service on the line is often selected based on the communication medium. If the communication medium has high availability (i.e., fiber), then a permissive overreaching transfer trip scheme (POTT) is typically implemented. If the communication medium has low availability, especially during an internal fault (i.e., power line carrier), then directional comparison blocking (DCB) is typically implemented.

Most POTT schemes implemented are hybrid POTT schemes that include additional dependability features like echo keying and weak infeed tripping. For an internal fault, if one terminal is weak and unable to have an overreaching element assert, high-speed tripping at the weak and strong terminals is still possible. The strong terminal detects the internal fault and sends permission to the weak terminal. If the weak terminal sees a voltage that indicates a fault is on the system, but not enough current to activate the local protection, the permission is echoed back to the strong terminal and both terminals trip.

The use of echo logic requires reverse reaching elements that are set to coordinate with remote overreaching elements to prevent echoing for reverse faults [11]. In both POTT and DCB schemes, if one terminal declares forward, the other terminal *must* declare reverse for out-of-zone faults for security to be maintained.

In a POTT scheme with weak infeed tripping enabled, the addition of 67Q at the strong terminal (Bus S) allows each terminal to trip and will improve fault resistance coverage [12], especially for faults near the IBR terminal. Further, sensitivity improvements in 67G (R1) and 67G (R2) by using 32V with more sensitive overcurrent supervision are also beneficial in improving fault resistance coverage.

In a DCB scheme, the weak terminal is tripped only if it can detect a fault. This makes the sensitivity improvement for 67G (R2) particularly beneficial, especially for ground faults near Bus S.

D. *Improving 21G Dependability Using Voltage-Based Fault Identification Selection (VFIDS)*

Raising the overcurrent supervision for 32Q also affects the sensitivity of current-based FIDS logic (CFIDS) in some relays. CFIDS logic enables the appropriate distance loops based on the angle relationship of I_2 and I_0 [13] [14]. For a ground loop to operate (21G), the $3I_0$ measured must be above the forward overcurrent supervision setting (50GF) or the reverse overcurrent supervision setting (50GR). Additionally, $3I_2$ must be above the 50QF or 50QR overcurrent supervision settings. 50QR is recommended to be set at 1.3 times the full load current of the IBR [2]. Therefore, CFIDS will not enable 21G elements for faults fed by an IBR-only source. VFIDS is preferred to enable 21G near IBR sources [2].

The voltage-based FIDS logic typically compares the phase voltage magnitude against an undervoltage setting and enables the proper distance loops. For example, for the A-phase-to-ground loop to be enabled, the A-phase-to-ground voltage must be lower than 70 percent of nominal, and the unfaulted phase voltages must still be near or above nominal voltage. Reference [3] covers multiple ways VFIDS can be implemented.

We plot the sensitivity of VFIDS relative to the fault resistance coverage of a memory-polarized Zone 2 ground distance element at R2 set to 120 percent of the Line A impedance (Fig. 4). The undervoltage threshold for VFIDS was set at 0.7 pu.

As we can see from Fig. 4, the fault resistance coverage provided by VFIDS is better than that of the Zone 2 element for this system, which means that VFIDS is not a limiting factor in 21G sensitivity.

Using VFIDS can also be useful for Zone 1 21G at R2 to provide fast and selective clearing for low-resistance ground faults on Line A in N-1 conditions. However, in these cases, exercise care when setting the Zone 1 reach as the effective source-to-impedance ratio (SIR) may be quite high [15]. If VFIDS is not available in the relay, there is more reliance on directional overcurrent elements to provide dependability for internal line faults under N-1 conditions.

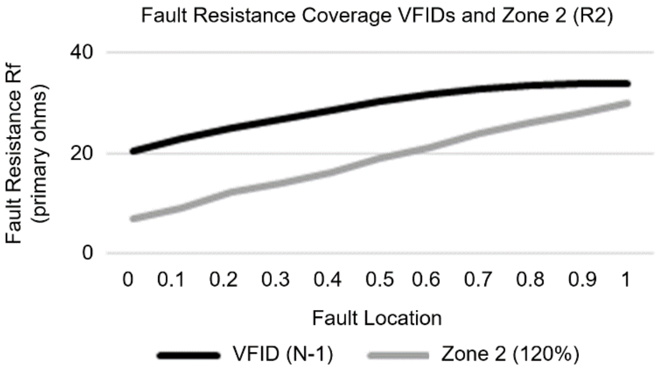

Fig. 4 VFIDS is more sensitive than Zone 2 ground distance element for single-phase-to-ground faults.

III. DIRECTIONAL ELEMENT OVERVIEW

In this paper we will discuss impedance-based directional elements that have threshold settings to bias the element towards dependability or security [16] [17] [18]. From a very high level, these elements can be summarized as follows: for forward faults, the element calculates a negative scalar impedance value, and, for reverse faults, the element calculates a positive scalar impedance value. The calculated impedance is compared to settable impedance thresholds. If the calculated signed scalar impedance is less than the forward impedance directional threshold, the relay declares a forward fault. If the calculated signed scalar impedance is greater than the reverse impedance directional threshold, the relay declares a reverse fault.

Generally, the impedance thresholds are set such that a negative impedance must be calculated for a forward fault and a positive impedance must be calculated for a reverse fault. If the calculated impedance is near zero, no directional decision is made. This general setting method is often referred to as AUTO2 [17] [18].

We will also discuss a zero-sequence current-polarized directional element that performs a phase comparison of two currents. This element has no settings to balance dependability and security, but was a popular option before impedance-based elements were available.

A reliable directional decision requires that the polarizing quantity's phase angle (a voltage or a current) is similar regardless of the direction of the fault. The operating quantity (a current) must have a significantly different phase angle relative to the polarizing quantity for forward and reverse faults.

A. *Impedance-Based Negative-Sequence Voltage-Polarized Element (32Q)*

A negative-sequence voltage-polarized element uses V_2 as its polarizing quantity and I_2 as its operating quantity. For forward faults, the negative-sequence current leads the V_2 voltage. For reverse faults, the negative-sequence current lags V_2. Based on this relationship, the 32Q element calculates a signed scalar impedance value. As shown in Fig. 5, for forward faults, the scalar impedance value is negative and equal to the source impedance (Z_{2S}); for reverse faults the signed scalar impedance value is positive and equal to the sum of the line and remote source impedances ($Z_{2L} + Z_{2R}$).

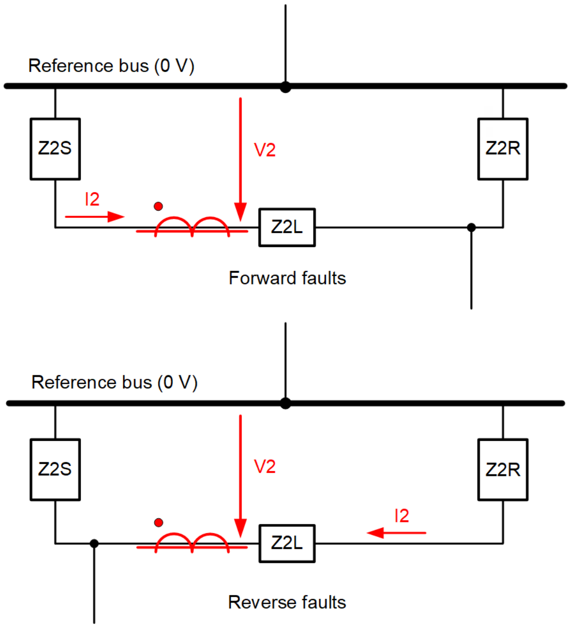

Fig. 5 Negative-sequence network for forward and reverse faults.

Because there is no voltage source in the negative-sequence network, the measured negative-sequence voltage at any point in the circuit is negative. Therefore, the direction of current flow determines the sign of the scalar impedance value, where forward current flow is positive and reverse current flow is negative.

B. *Impedance-Based Zero-Sequence Voltage-Polarized Element (32V)*

A zero-sequence voltage-polarized element uses V_0 as its polarizing quantity and I_0 as its operating quantity. For forward faults, the zero-sequence current leads the V_0 voltage. For reverse faults, the zero-sequence current lags V_0. Based on this relationship, the 32V element calculates a signed scalar impedance value. For forward faults, the scalar impedance value is negative and equal to the source impedance (Z_{0S}); for reverse faults the signed scalar impedance value is positive and equal to the sum of the line and remote source impedances ($Z_{0L} + Z_{0R}$).

When no zero-sequence mutual coupling is present, there is no voltage source in the zero-sequence network, and the measured zero-sequence voltage at any point in the circuit is negative. The direction of current flow determines the sign of the scalar impedance value, where forward current flow is positive and reverse current flow is negative.

However, when mutual coupling is present, the line includes a voltage source (see Fig. 6) that can produce a voltage rise or a voltage drop. In Fig. 6, V_{MUTUAL} produces a voltage rise (positive) in the direction of current flow, which is reverse (negative). The voltage rise of V_{MUTUAL} leads to a zero-sequence voltage measured at the relay location that is less negative than if mutual coupling was not present. This in turn means the relay will calculate an impedance that is smaller than ($Z_{0L} + Z_{0R}$) for reverse faults.

In some extreme cases in lines with zero-sequence mutual coupling, the voltage rise in the zero-sequence network may overcome other voltage drops in the circuit and create a positive zero-sequence voltage measurement at the relay location. We discuss this in more detail in Section IV.

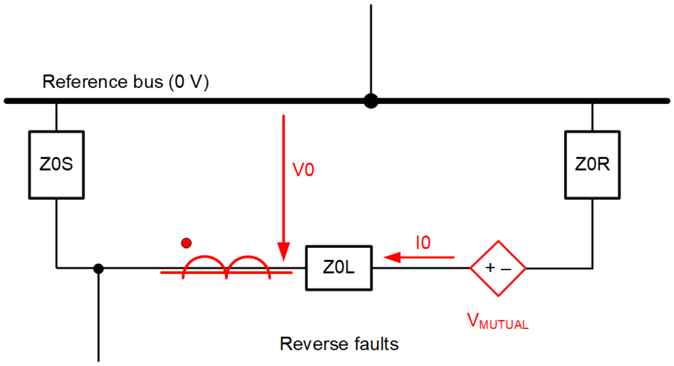

Fig. 6 Zero-sequence network for reverse fault with mutual coupling.

C. *Zero-Sequence Current-Polarized Element (32I)*

A zero-sequence current-polarized element uses IN as its polarizing quantity (i.e., a transformer neutral or circuit transformers [CTs] inside a delta winding) and $3I_0$ (from the line current transformers) as its operating quantity. For forward faults, $3I_0$ and IN are in phase. For reverse faults, $3I_0$ and IN are out of phase. The 32I element is reliable if IN does not change direction for forward and reverse faults. Like 32V, 32I elements can be challenged in systems with mutual coupling (see Section IV.C).

32I elements are not commonly applied because they require an unrelated piece of equipment to the protected line to be in service (a power transformer), require complex CT connections, and provide no settings to bias the element towards security or dependability.

IV. EFFECT OF MUTUAL COUPLING ON ZERO-SEQUENCE DIRECTIONAL ELEMENTS

There are many excellent papers on mutual coupling that describe the effects of mutual coupling on ground directional elements, ground overcurrent coordination, ground distance element performance, and fault locating [19] [20]. In this paper, we focus on directional element performance of 32V for lines with mutual coupling and explore methods to aid in security issues that can arise, specifically in directional comparison schemes.

A. *System Configurations*

Section IX of this paper details circuit analysis used to quantify the effects of mutual coupling for various system configurations. Here, we start with a sample system that helps illustrate the challenges of maintaining 32V security for relays on Line B. Fig. 7 shows a zero-sequence network in which only Lines B and C only are mutually coupled.

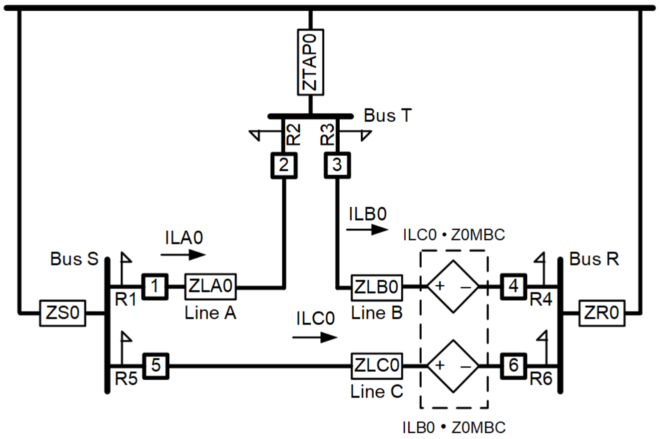

Fig. 7 Zero-sequence network with mutual coupling between Lines B and C.

We represent the voltage induced on Line B, due to the current flow on Line C, as a lumped current-dependent voltage source. This voltage source is in series with the lumped impedance of the line. We use the same representation on Line C. We can represent voltage from R3 to R4 and R5 to R6, as shown in (1).

$$\begin{aligned} V34 &= ILB0 \bullet ZLB0 + ILC0 \bullet Z0MBC \\ V56 &= ILC0 \bullet ZLC0 + ILB0 \bullet Z0MBC \end{aligned} \tag{1}$$

where:

V34 is the voltage measured at R3 minus the voltage measured at R4.

V56 is the voltage measured at R5 minus the voltage measured at R6.

ILx0 is the zero-sequence current flowing on the respective line.

ZLx0 is the actual zero-sequence impedance of the line.

Z0Myz is the zero-sequence mutual coupling impedance between line y and Line z.

Note: x, y, and z are replaced with the line letter (A, B, or C) under consideration.

In (1), ILB0 and ILC0 are signed values. From (1), the voltage is defined as V34 and V56 (rather than V43 and V65), so the current flow from left to right in Fig. 7 is positive current. The following conditions are applicable:

- If ILB0 and ILC0 both flow from left to right, then the induced voltage on Line B (ILC0 • Z0MBC) and Line C (ILB0 • Z0MBC) is a voltage drop in the direction of the current flow.
- If ILB0 and ILC0 are both flowing from right to left, then the induced voltage on Line B (–ILC0 • Z0MBC) and Line C (–ILB0 • Z0MBC) is still a voltage drop in the direction of the current flow.
- If ILB0 current is flowing from right to left and ILC0 current is flowing from left to right, the induced voltage on Line B (ILC0 • Z0MBC) and Line C (–ILB0 • Z0MBC) becomes a voltage rise in the direction of the current flow.

In summary, if ILB0 and ILC0 are flowing in the same direction, then the mutually coupled voltage simply becomes another voltage drop in the zero-sequence circuit. However, if ILB0 and ILC0 are flowing in opposite directions, then the mutually coupled voltage becomes a voltage rise.

If we divide (1) by the respective line current, we can define the apparent impedance of each line (2) and see how the direction of current flow affects the apparent impedance of the line.

$$\begin{aligned} Z34 &= ZLB0 + \frac{ILC0}{ILB0} \bullet Z0MBC \\ Z56 &= ZLC0 + \frac{ILB0}{ILC0} \bullet Z0MBC \end{aligned} \tag{2}$$

where:

Z34 is the apparent zero-sequence impedance between R3 and R4 (Line B).

Z56 is the apparent zero-sequence impedance between R5 and R6 (Line C).

From observation of (2), we can see that if there is no mutual coupling between the lines (Z0MBC = 0), then the apparent impedance of Line B and Line C (Z34 and Z56) is equal to the actual impedance of the line (ZLB0 and ZLC0).

If we assume that mutual coupling exists between Line B and Line C (Z0MBC > 0), we can make additional observations:

1. If ILC0 and ILB0 currents are flowing in the same direction, the apparent impedance of each line becomes larger than the line impedance (Z34 > ZLB0 and Z56 > ZLC0).
2. If ILC0 and ILB0 currents are flowing in opposite directions, then the apparent impedance of each line becomes smaller than the line impedance (Z34 < ZLB0 and Z56 < ZLC0).

Below, we define fault locations and system configurations that will produce the two relationships in Fig. 7. We specify one system configuration when ILB0 and ILC0 flow in the same direction (Configuration 1). We specify four separate system configurations (Configurations 2a, 2b, 2c, and 2d) when ILB0 and ILC0 are flowing in opposite directions.

- Configuration 1: All breakers closed, fault on Bus R.
- Configuration 2a: Breaker 6 open, fault on Line C near Breaker 6.
- Configuration 2b: Configuration 2a with Line B out and grounded.
- Configuration 2c: Configuration 2a with Line A out of service.
- Configuration 2d: Configuration 2a with a variable transfer impedance between Bus T and Bus S (discussed in Section V).

We consider Configuration 2a to be an N-1 contingency. This would commonly occur when a fault is cleared on Line C and Breaker 5 recloses into a permanent fault. We consider Configuration 2b, 2c, and 2d to be credible N-2 contingencies [19]. Regarding Configuration 2c, this would occur when Line A is out of service, a fault is cleared on Line C, and Breaker 5 recloses into a permanent fault on Line C.

B. 32V Security Analysis for System Configurations

We analyze how the impedance-based 32V element in the R3 and R4 relays of Line B respond to faults in each of these configurations. We focus on relays that should declare a reverse fault direction based on the system configuration to identify security concerns. In the figures below, we highlight when the direction of current flow is opposite of the conventions established in Fig. 7. This in turn leads to a change in the polarity of the associated voltage source, which is also highlighted. Section IX offers more in-depth circuit analysis for each configuration.

In Configuration 1 (Fig. 8), R3 will see this fault in the forward direction, and R4 will see this fault in the reverse direction. Because of the apparent impedance of Line B (Z34) being larger than the actual line impedance (ZLB0), R4 will see a larger positive zero-sequence impedance than if no mutual coupling was present for this fault. In Configuration 1, the 32V element will remain secure for reverse faults.

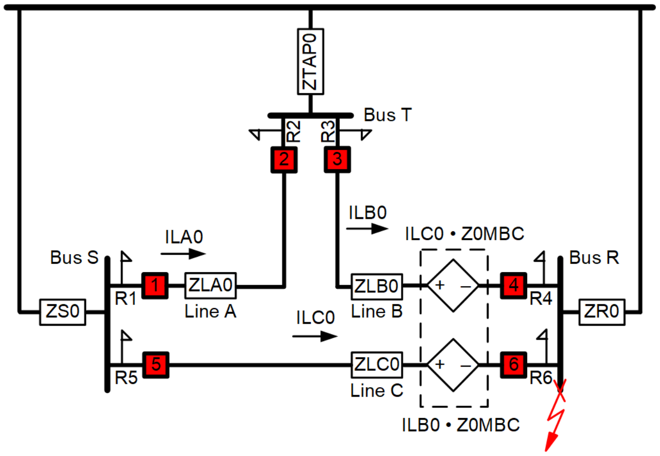

Fig. 8 Configuration 1 zero-sequence network.

In Configuration 2a (Fig. 9), R4 will see the fault in the forward direction and R3 will see the fault in the reverse direction. Because of the apparent impedance of Line B (Z34) being smaller than the actual line impedance (ZLB0), R3 will see a reduced (but still positive) apparent zero-sequence impedance. This could be a security concern but can be mitigated by using impedance-based thresholds that are set below the zero-sequence impedance seen by R3 for this fault. In general, directional thresholds that do not include 0 ohms in the forward operating region are still secure for Configuration 2a.

In Configuration 2b (Fig. 10), the relay response of R3 and R4 is of no importance because Line B is out of service. There is no electrical connection between Line B and Line C. However, we do note that there is current circulating on Line B because of the coupled voltage ILC0 • Z0MBC. This coupled voltage on Line B results in ILB0 current flow through the ZLB0 impedance, which will produce the voltage (ILB0 • ZLB0). Because each side of the line is grounded, a closed loop is present where the voltages in the loop must sum to zero. The induced voltage (ILC0 • Z0MBC) will be a voltage rise because it is the only available source in the closed loop, and ILB0 • ZLB0 will be a voltage drop. Referring to Fig. 10, this means current is flowing from right to left on Line B.

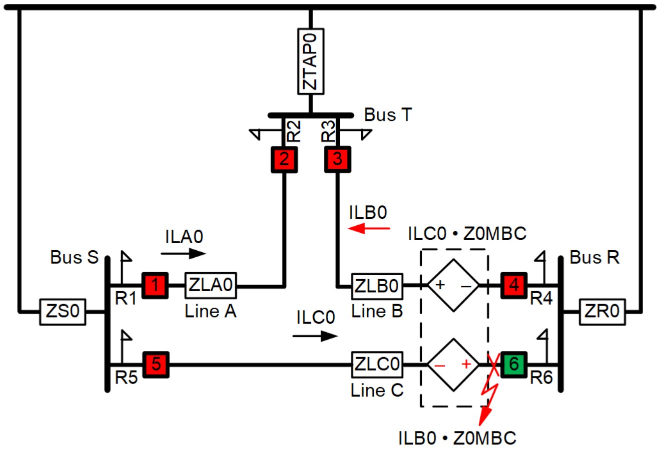

Fig. 9 Configuration 2a zero-sequence network.

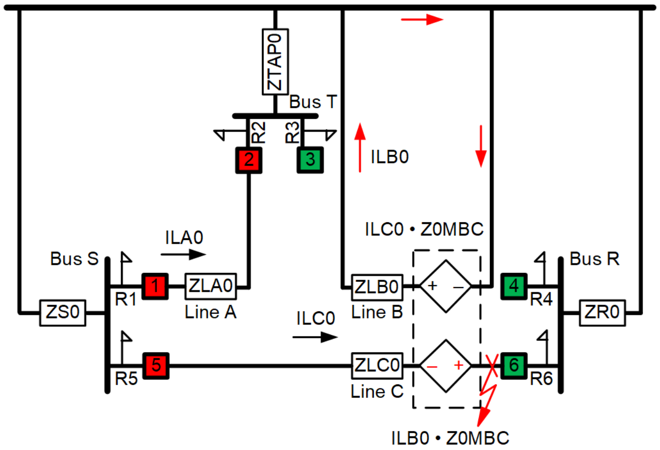

Fig. 10 Configuration 2b zero-sequence network.

In Configuration 2c (Fig. 11), there is again no electrical connection between the faulted Line C and the unfaulted Line B. Similar to Configuration 2b, the induced voltage (ILC0 • Z0MBC) on Line B will result in current flow ILB0, but now it will circulate through the ZTAP0, ZLB0, and ZR0 impedances. This results in a smaller value of ILB0 compared to Configuration 2b. At R4 the zero-sequence voltage measured is negative, and the current flow is positive. This equates to a forward fault. At R3, the zero-sequence voltage measured is positive because the voltage rise, due to mutual coupling, is larger than the voltage drop across ZLB0 and ZR0. Because the current flow is negative and the voltage is positive, R3 also declares this fault forward. In Configuration 2c, Line B will trip out of service for the external fault via a directional comparison scheme if 67G is set lower than the ILB0 current.

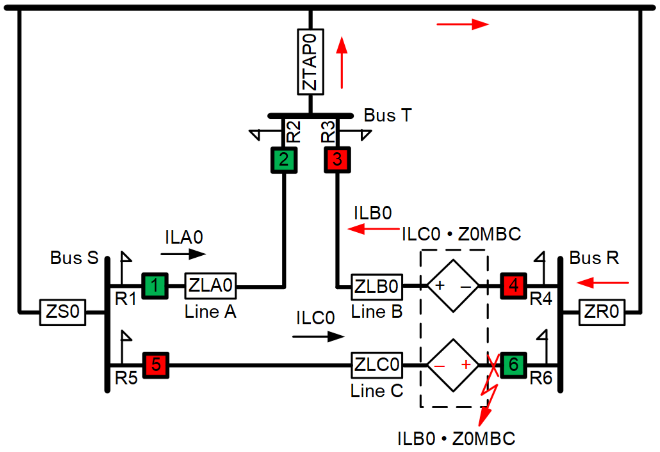

Fig. 11 Configuration 2c zero-sequence network.

C. 32I Security Analysis for Configuration 2c

In Configuration 2c, because there is no electrical connection between the faulted Line C and unfaulted Line B, the zero-sequence current flow from right to left in the unfaulted Line B is because of mutual coupling. The mutually coupled voltage on Line B becomes the only voltage source in the closed zero-sequence network, which is isolated from positive- and negative-sequence networks. The zero-sequence current flows from the line into the zero-sequence reference bus at Relay R3. At Relay R4, the current flows from the reference bus to the line. Effectively, zero-sequence current is circulating within the zero-sequence network. Compare this to a traditional phase-to-ground fault in which current flows out of the reference bus at each terminal in the zero-sequence network to the fault and returns to the positive-sequence voltage source.

When zero-sequence current flows into the reference bus, this is sometimes referred to as ground current flow "down the neutral," which is opposite to the expected ground current flow "up the neutral" [20]. Ground current flow up the neutral at one relay terminal (R4) and down the neutral at the other relay terminal (R3) leads to a 32I forward declaration at both terminals.

V. SECURITY IMPROVEMENTS FOR 32V

A positive measured voltage at a relay location in the zero-sequence network has historically been referred to as a zero-sequence voltage reversal [21] [22]. In the opinion of the authors, the term "reversal" is better suited to identify a change in current direction, while the term "inversion" is better suited to identify a change in the voltage sign. A zero-sequence voltage inversion occurs on a line when the voltage rise, due to mutual coupling, exceeds the voltage drop, due to the current flow, through the line impedance. When a voltage inversion occurs, both relays of a protected line will calculate a negative zero-sequence impedance value. One relay will measure a negative voltage and a positive current, while the other relay will measure a positive voltage and a negative current.

A voltage inversion severely compromises the security of zero-sequence directional elements. However, settable impedance-based directional thresholds that can be biased towards security may be a useful tool against voltage inversion. In this section, we discuss systems in which there is transfer impedance between the two mutually coupled lines in the zero-sequence network.

A. V_0 (R3) for Configuration 2d

In Configuration 2a, Breaker 6 is open to remove the electrical connection on the right side of Line B and Line C. Fig. 7 includes Line A and, up to this point, has either been in service (Configuration 1, 2a, 2b), or out of service to remove the electrical connection on the left slide of Line B and Line C (Configuration 2c). In [19], another mechanism that can lead to a voltage inversion is a weak electrical connection between Line B and Line C. This can practically occur when Line B and Line C are mutually coupled, but a transfer impedance exists between Bus S and Bus T when Line A is out of service (see Fig. 12). We can vary this transfer impedance, which we continue to refer to as ZLA0, from 0 (strong electrical connection, like Configuration 2a) to infinity (electrical isolation, like Configuration 2c) and see the effects on the zero-sequence voltage at R3 as the zero-sequence electrical connection between Line B and Line C becomes weaker.

To illustrate, we treat Fig. 7 as a circuit in which all impedances are equal to 1 pu except for ZLA0, which we will vary from zero to infinity. We refer to this as Configuration 2d.

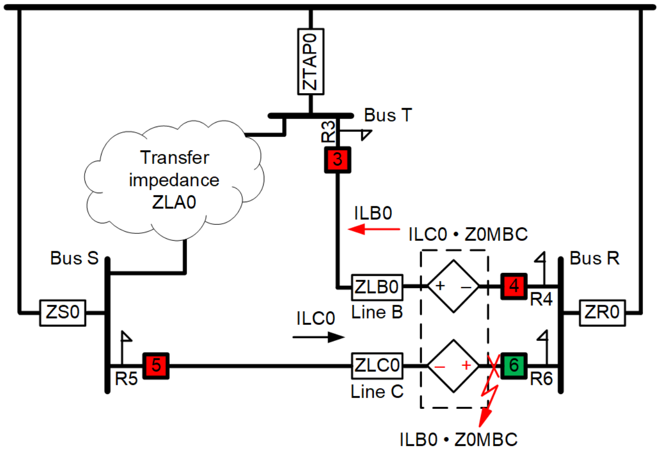

Fig. 12 Configuration 2d zero-sequence network.

Fig. 13 shows the zero-sequence voltage at Relay R3 as the transfer impedance increases. A baseline case where Z0MBC = 0, and the case of interest where Z0MBC = 0.5 pu (50 percent mutual coupling between Line B and Line C) is shown. Remember that the fault location does not change in this example, only the transfer impedance ZLA0.

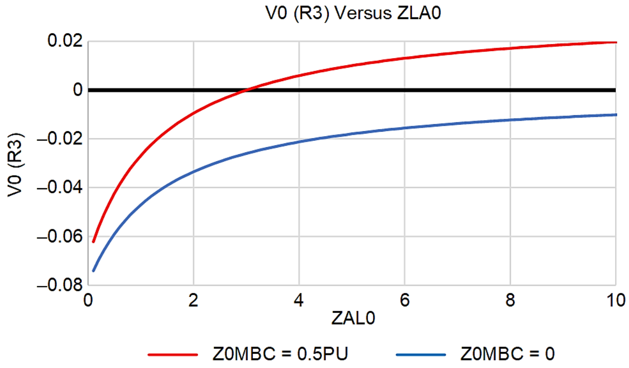

Fig. 13 Measured V0 (R3) for reverse fault as ZLA0 increases.

Fig. 13 shows that as the electrical connection weakens between ZLB0 and ZLC0 (ZLA0 increases) with mutual coupling present, the V_0 voltage at R3 transitions from a negative value to a positive value when ZLA0 =3 pu. This means that when ZLA0 > 3 pu, a voltage inversion occurs and we can no longer rely on the sign of the calculated scalar zero-sequence impedance to indicate the correct direction of the fault. When there is no mutual coupling between the two lines (Z0MBC = 0), V0 (R3) never becomes positive because there are no voltage rises in the zero-sequence circuit.

B. Z0 (R3) for a Forward and Reverse Fault (Configuration 2d)

The 32V directional element compares the calculated signed scalar impedance to settable thresholds to determine directionality. While a voltage inversion will produce a negative scalar impedance for a reverse fault at R3, it does not necessarily mean that the relay will misoperate with security-biased impedance thresholds.

To illustrate, we compare the calculated scalar impedance at R3 for a reverse fault ($Z0R_{APP}$) in Configuration 2d and the calculated scalar impedance for a forward fault ($Z0F_{APP}$) at the end of Line B with Breaker 4 open (see Fig. 14). Recall that for a forward fault, the relay will calculate the negative of the apparent source impedance ($Z0F_{APP}$) behind the relay. In this case, $Z0F_{APP}$ varies with ZLA0. When ZLA0 = 0, the impedances ZS0, ZTAP0, and ZR0 (via Line C) are in parallel, making $Z0F_{APP}$ low. However, when ZLA0 approaches infinity, $Z0F_{APP}$ equals ZTAP0.

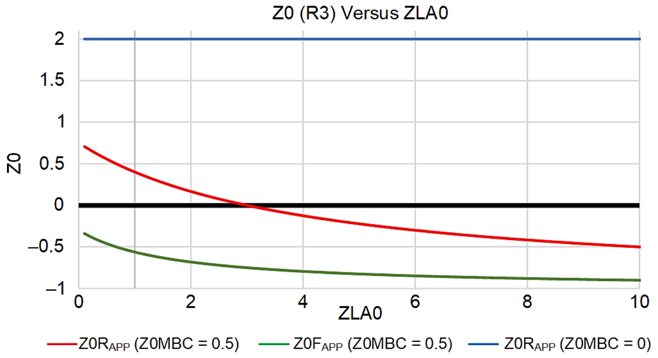

Fig. 14 Calculated Z0 (R3) for forward and reverse faults.

When no mutual coupling is present, $Z0R_{APP}$ for a reverse fault is ZR0 + ZL0 (1 pu + 1 pu = 2 pu), as discussed in Section III.B. We can see that there is a large margin between $Z0F_{APP}$ (negative) for a forward fault and $Z0R_{APP}$ for a reverse fault (positive) when mutual coupling is not present.

When mutual coupling is present, $Z0R_{APP}$ becomes much smaller for a reverse fault, even with a strong electrical connection between Line B and Line C (ZLA0 = 0). When ZLA0 is greater than 3 pu, $Z0R_{APP}$ becomes negative because of a voltage inversion, and we are now at risk of declaring forward for this reverse fault. As ZLA0 increases towards infinity (not shown in Fig. 14), $Z0R_{APP}$ converges to the same impedance the relay sees for a forward fault ($Z0F_{APP}$), making a directional decision based on impedance impossible.

C. 32V Security-Biased Settings

However, there is still a glimmer of hope to maintain dependability and security of the 32V element using a manual method to set the impedance-based directional threshold. This is accomplished by setting both the forward (Z0F) and reverse (Z0R) directional thresholds negative, which biases the directional element towards security [18]. To maintain dependability, the apparent zero-sequence source impedance ($Z0F_{APP}$) of the line must be found. The forward threshold is set with a negative sign and with enough margin to ensure dependability for forward faults. The reverse threshold, Z0R, is set slightly larger than Z0F, but will still have a negative sign. This setting method maximizes security of the 32V element by correctly declaring the reverse direction, even under some voltage inversion cases while still providing dependability for forward faults (3).

$$\begin{aligned} Z0F &= -0.5 \bullet Z0F_{APP} \\ Z0R &= Z0F + 0.1 \end{aligned} \tag{3}$$

To illustrate, Fig. 15 is the same as Fig. 14, but now with the addition of impedance-based thresholds set per (3).

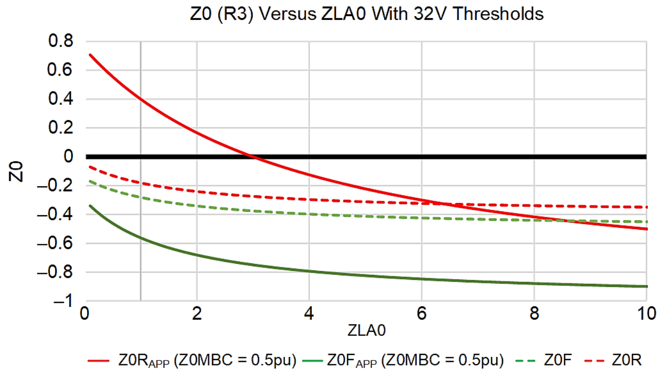

Fig. 15 Impedance-based thresholds biased towards security.

With these settings, the relay will dependably declare forward faults with an adequate margin ($Z0F_{APP}$ is lower than Z0F). The relay will also correctly declare reverse faults for ZLA0 values less than 6 pu ($Z0R_{APP}$ is higher than Z0R). However, for cases when ZLA0 is greater than 6 pu, alternative methods must be used to provide 67G security. This includes raising the 67G pickup above induced 3I0 current due to mutual coupling, using a time delay for the 67G element, or a combination of both (see Section VI.C and Section VIII).

Security-biased thresholds can be used at all times, but they can provide the most benefit if Z0R_{APP} is a small positive value (i.e., less than 0.5 ohms) or negative (voltage inversion). Find the apparent impedance for a reverse fault ($\text{Z0R}_{\text{APP(N–X)}}$) where X is the number of contingencies considered. Find the apparent impedance for a forward fault with all sources in service (Z0F_{APP}). If (4) evaluates to a positive number, then security-biased thresholds are feasible for the contingency considered. An example is given in Section VIII for more information.

$$\text{Z0R}_{\text{APP(N-X)}} - (0.5 \bullet \text{Z0F}_{\text{APP}} + 0.1) > 0 \qquad (4)$$

In this section, we have considered a system with one common bus between the mutually coupled lines (Bus R). In this bus arrangement, voltage inversions are possible for N-1 and likely for N-2 system contingencies.

If there is no common bus between the mutually coupled lines, voltage inversions can occur under normal conditions (N-0). If there are two common buses between the mutually coupled lines, a voltage inversion is unlikely for credible system contingencies.

D. Electrical Connection Strength in the Negative-Sequence and Zero-Sequence Network

Up to this point we have focused on electrical connection strength between Line B and Line C in the zero-sequence network. However, the strength of the electrical connection in the negative-sequence network can be used as an indicator of zero-sequence isolation.

When Line A is in service between Bus S and Bus T, there is an electrical connection in both the negative-sequence network and the zero-sequence network. When Line A is out of service (Configuration 2c), ILB2 (negative-sequence current for Line B) will not flow for the fault near Breaker 6 because there is no electrical connection in the negative-sequence network. However, we do know the zero-sequence current will flow because of mutual coupling, and our 32V directional elements cannot rely on impedance-based thresholds to maintain security. We can use the absence of negative-sequence current in Configuration 2c to our advantage. When ILB2 current is not present we restrain 32V forward directional decisions by supervising 67G with a low-set 50Q element. This solution has been discussed in the past [22] and works well for Configuration 2c.

If there are other transmission lines between Bus S and Bus T in addition to Line A, a transfer impedance will still exist in the negative-sequence network when Line A is out of service and the set point of 50Q must be carefully selected. However, if there are additional lines between Bus S and Bus T, security-biased 32V thresholds can again become viable because there is also a transfer impedance in the zero-sequence network between Bus S and Bus T.

1) Mutually Coupled Lines Operating at Different Transmission Voltage Levels

If Line B is a transmission line and Line C is at a lower transmission voltage, there is likely an autotransformer providing the electrical connection between the two voltages. The autotransformer will provide a strong electrical connection in the negative-sequence network between Line B and Line C, but a very weak electrical connection in the zero-sequence network. In this case, negative-sequence current supervision of 67G must be carefully set and may not provide additional security without sacrifices in 67G sensitivity. It may be possible to set 32V directional thresholds securely depending on the strength of the electrical connection in the zero-sequence network between the two mutually coupled lines. Typically, these line configurations are modeled in fault study programs, and adequate settings can be developed, which is discussed in Section VIII.

2) Mutually Coupled Lines Operating at Transmission and Distribution Voltage Levels

If Line B is a transmission line and Line C is a distribution or sub-transmission line, there is likely a delta/wye transformer providing the electrical connection between the two voltages. The delta/wye transformer will provide an electrical connection in the negative network between Line B and Line C, but full electrical isolation in the zero-sequence network. In this case, negative-sequence current supervision of 67G may provide some benefit to security if the negative-sequence electrical connection between Line B and Line C is weak. 32V impedance thresholds *cannot* be set securely for this case because full electrical isolation in the zero-sequence network between the two lines guarantees directional element misoperation. Unfortunately, distribution circuits sharing the right of way with a transmission line may not be modeled in your short circuit program as sometimes the location of nearby distribution circuits may be unknown to the engineers setting the transmission line relays.

Fig. 16 shows an example of a transmission line and distribution circuit being mutually coupled (ZM) but only sharing the same right of way for a portion of the transmission line.

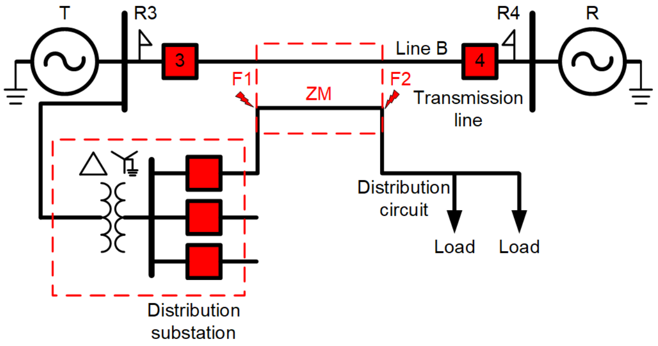

Fig. 16 Mutual coupling between transmission line and distribution circuit.

For a close-in fault (F1 in Fig. 16) on the distribution circuit, the fault current will be at the maximum value because the fault is near the source; however, for this fault there will be no induced voltage on Line B because no current is flowing through the mutually coupled portion of the line.

For fault F2 (Fig. 16) on the distribution circuit, the fault current will be less compared to Fault F1, but will induce a voltage on Line B. As the mutual coupling portion between the transmission line and distribution circuit is further away from the distribution substation, the impact of mutual coupling on the transmission circuit, due to faults on the distribution circuit, will reduce.

In cases where the zero-sequence induced current from the coupled distribution circuit is high, a time-delayed sensitively set 67G element (see Section VI.C) is a feasible solution for security only in cases where the distribution circuit can trip instantaneously for faults on the distribution circuits [23].

If distribution faults on the coupled line induce significant zero-sequence current on transmission line and it takes a long time to clear, then time delays to improve security are not feasible. If distribution faults are cleared slowly and negative-sequence current supervision provides no benefit, the only remaining option is to raise the 67G pickup above the induced current.

Equation (5) can be used to approximate the induced current on Line B (ILB0), due to a fault on Line C, when there is electrical isolation between the two lines in the zero-sequence network. For example, if we assume Z0MBC is 0.1 times the ZLB0 line impedance (weak coupling due to the lines running together for a short distance), and ZTAP and ZR0 are equal to ZLB0 (SIR = 1), then ILB0 = 0.03 • ILC0. The maximum fault current available at the distribution transformer terminals can be used as a conservative estimate for ILC0.

$$\mathrm{ILB0} = \mathrm{ILC0} \bullet \left(\frac{\mathrm{Z0MBC}}{\mathrm{ZTAP0} + \mathrm{ZLB0} + \mathrm{ZR0}} \right) \qquad (5)$$

VI. ADDITIONAL SECURITY IMPROVEMENTS

In this section we discuss additional security enhancements that can be made for lines that are mutually coupled.

A. Reclosing Solutions

It is possible to prevent zero-sequence voltage inversion from occurring in the first place with smart reclosing practices. Referring back to Fig. 11, we arrive in a challenging security configuration (Configuration 2c) during a reclose operation for a fault on Line C, with Line A out of service. If we reclose from Breaker 6, rather than Breaker 5, we will maintain a strong electrical connection between Line B and Line C, which helps maintain 32V security.

To expand on Fig. 7, which only considered mutual coupling between Line B and Line C, we now consider mutual coupling between all lines, as shown in Fig. 17. In Fig. 17, one line in a double-circuit tower is tapped to produce two new lines (Line A and Line B). The sum of Z0MAC and Z0MBC is equal to the mutual coupling value between the two original lines. Because the IBR generation source may be some distance from the tap point, a third mutual coupling impedance, Z0MAB, is included for new double-circuit line construction from the tap point to the tap point switching station.

Additionally, the location of the transfer impedance is shown between Bus S and Bus R, rather than Bus S and Bus T, which was shown for illustration purposes in the previous section. Regardless of the location of the transfer impedance, its effects are similar—there is no complete electrical isolation for N-2 contingencies between mutually coupled lines.

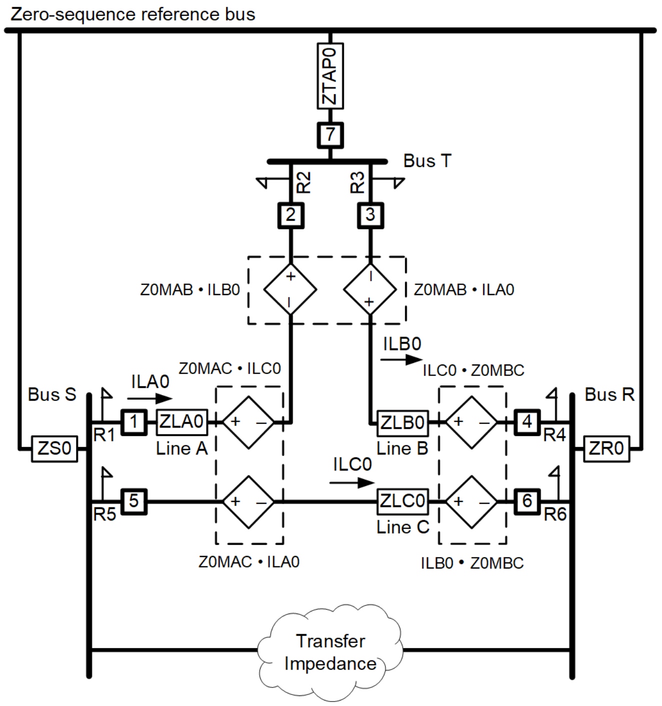

Fig. 17 Mutual coupling between three lines.

Table I provides the preferred reclosing breakers for each line out of service (OOS) for a credible N-2 contingency fault [19].

TABLE I
PREFERRED RECLOSING BREAKERS FOR SYSTEM IN FIG. 17

Coupling Present	Security Concern	Line OOS	Faulted Line	Preferred Reclosing Breaker
Z0MAB	Line A relays	Line C	Line B	3
Z0MAC		Line B	Line C	5
Z0MBC	Line B relays	Line A	Line C	6
Z0MAB		Line C	Line A	2
Z0MBC	Line C relays	Line A	Line B	4
Z0MAC		Line B	Line A	1

The conditions for which reclosing breakers at Bus T is preferable for relay security are highlighted in red, but these are unlikely to be implemented because reclosing from the IBR is uncommon. We can see that if Bus T is far from Line A and the Line B tap point (Z0MAB is large), some relays can have security concerns that likely cannot be addressed with reclosing. However, if Z0MAB is small, then reclosing from Breaker 2 and Breaker 3 is not needed for security.

It is unlikely that the Line C relays need special reclosing because those relays will not see IBR-only current under any contingency case. Therefore, Line C relays can continue to use 32Q instead of 32V.

This means that in many installations, the decision to reclose comes down to whether to reclose Breaker 5 to enhance Line A relay security, or reclose Breaker 6 to enhance Line B relay security. For example, consider that Z0MAC is greater than Z0MBC. In this case, Line A relays have a greater security concern than Line B relays. Therefore, reclosing from Breaker 5 is preferable.

B. Current Reversal Blocking in Pilot Schemes

While smart reclosing practices can help with relay security when an adjacent line is being re-energized, a pilot protection reverse extension timer (ZRBT) also provides security for a fault that is sequentially cleared on an adjacent line.

A ZRBT timer is intended to maintain communication scheme security during current reversals in double-circuit configurations due to sequential tripping of adjacent line breakers [11]. When a relay sees a reverse fault, it blocks local communications-assisted tripping elements for a settable amount of time (ZRBD). If a POTT scheme is enabled, sending permission is blocked via the ZRBT timer. If a DCB scheme is enabled, a block signal is held in for the duration of the ZRBT timer.

We identified in the previous section that when Line A is out of service and there is a fault on Line C, we prefer to reclose at Breaker 6. However, if Breaker 6 opens before Breaker 5 for a fault on Line C, we again have an electrical isolation case in which Line B relays are at risk of tripping.

While this is not a current reversal case in the traditional sense, Line B relays still benefit from the ZRBT timer. Before Breaker 6 opens, there is an electrical connection between Line B and Line C for the phase-to-ground fault, and R3 declares forward and R4 declares reverse. After Breaker 6 opens, but while Breaker 5 is still closed, R3 and R4 will both declare forward (Configuration 2c). However, communications-assisted tripping is blocked via ZRBT for ZRBD time.

In conventional current reversals, the ZRBT timer needs to be set long enough to secure the scheme after the first breaker trips. In general, a five-cycle ZRBD setting is more than enough to provide this security. In sequential clearing that creates zero-sequence isolation on the line, the ZRBD needs to be set longer than the slowest breaker-open time minus the fastest breaker-open time to maintain security. Because the latter implies a longer ZRBD time than the former, you can extend ZRBD time to aid in security for slow clearing breakers on adjacent lines.

Extending the ZRBD time will lead to delayed tripping for internal faults that occur shortly after nearby external faults. Because this occurrence is relatively rare, the side effect of extending ZRBD is minor. However, consider the upper limit for ZRBD time to be your typical breaker failure time plus margin.

C. Time-Delayed Sensitively Set 67G

In cases where none of the previously mentioned solutions provide the required security, implementing a time-delayed sensitively set 67G element in directional comparison schemes can provide security for unfaulted lines during zero-sequence voltage inversions. The time delay for this sensitively set 67G element should be set longer than maximum fault clearing time (including breaker failure timer in cases where it is applicable) plus margin to ensure that the faults on the coupled lines are given adequate time to be cleared. A second 67G element can be set above the mutually induced zero-sequence current with no intentional time delay to provide faster fault clearing for internal faults. A single reverse-looking 67G set below the remote terminal sensitively set 67G provides security for external faults with an electrical connection.

VII. CONCLUSION

IBRs create challenges in protection, and there are numerous papers available addressing these challenges [2] [3] [24] [25] [26]. In many of these papers, the solutions offered provide benefits for all systems, not just systems with IBRs. For example, [26] discusses line current differential protection setting recommendations to improve transmission line fault resistance coverage near IBRs, but the setting recommendations improve sensitivity for conventional systems as well. In many ways, the introduction of IBRs to the power system has forced protection engineers to optimize protection practices for better reliability. While these optimizations sometimes entail more work for the protection engineer, they can offer reliability benefits that justify the additional work.

In this paper we primarily discuss the use of zero-sequence directional elements (32V) to improve the sensitivity of 67G used in directional comparison schemes in systems in which negative-sequence directional elements (32Q) must be desensitized because of unreliable negative-sequence current from IBRs. If the protected line is not mutually coupled, then 67G supervised by 32V can be set sensitively, providing benefit with minimal additional effort.

However, in lines that are mutually coupled, the use of 67G supervised by 32V for maximum sensitivity without a loss of security does require additional effort. In this paper we discuss the following optimizations to improve reliability of 67G supervised by 32V used in directional comparison schemes:

- Supervise 67G with a low-set non-directional negative-sequence overcurrent element. This optimization has been used in the past [22], requires little additional work, and can be useful for relays at newly created IBR integration stations that tap an existing transmission line.
- Use a sensitively set 67G element with a time delay to ride through voltage inversions while still providing coverage for high-resistance internal faults. Use a second 67G with a pickup set above the maximum mutually induced zero-sequence current with no time delay to clear faults with high current levels quickly.
- Reclose from breakers that maintain a strong electrical connection between the mutually coupled lines. This can have a significant benefit with little additional work in some systems.
- Set the pilot reverse extension time (ZRBD) longer to ensure pilot scheme security for slow breakers on an adjacent mutually coupled line.
- Use security-biased zero-sequence directional thresholds. This optimization takes advantage of the ability to bias directional decisions towards security. Even if a voltage inversion occurs, it is possible to maintain 32V security in some systems. This does require additional work. While beneficial in mitigating

security risks due to voltage inversion, there are some systems where this will provide no benefit. Guidance has been provided for when security-biased thresholds can be used.

Section VIII provides a detailed procedure to determine the viability of these solutions for the sample system provided in Fig. 17.

While setting a sensitive 32V can improve ground fault resistance coverage via supervision of 67G, using 67Q supervised by 32Q in communications-assisted tripping schemes can also offer an improvement in ground fault resistance coverage with very little additional work. This is true even if the 67Q element is set above IBR full load current with margin. In a two-terminal line, because the IBR terminal has a large negative-sequence impedance relative to the traditional terminal, the current distribution for internal line faults can favor 67Q over 67G at the conventional terminal in regard to fault resistance coverage.

VIII. APPENDIX—RECOMMENDATIONS

In this section, we provide a procedure for setting directional overcurrent elements for 5A nominal current input relays in Fig. 17 that are used in directional comparison schemes.

We consider the Line B relays as the line we are calculating relay set points for, but Line A relays should be treated similarly. Line C relays, in many cases, will not see IBR-only current for N-1 conditions and likely can continue using sensitively set 32Q overcurrent supervision.

In the procedure below, you must find the apparent Z0 signed scalar impedance the relay will calculate for forward and reverse faults. For example, $Z0F_{APP(R3)}$ is the signed scalar impedance calculated by R3 for a forward fault. Find this value by finding the complex values of V_0 and I_0 at the relay location and convert to secondary values. Then, plug V_0 and I_0 into (6), where Z0ANG is angle of the zero-sequence impedance of the line you are protecting, and "*" is the complex conjugate operator.

$$Z0_{RELAY} = \frac{RE\left(V_0 \cdot [I_0 \cdot 1\angle Z0ANG]^*\right)}{|I_0|^2} \tag{6}$$

Consult your fault coordination program and follow the procedure in the following subsection. All the current values are assumed to be secondary amperes and all CT ratios match for the relays under consideration.

A. Gather the Required Data

Find $Z0F_{APP}$, which is the calculated signed scalar zero-sequence impedance for forward faults. The sign of $Z0F_{APP}$ will be negative.

- Find $Z0F_{APP(R3)}$ by placing a fault at the end of Line B with Breaker 4 open. This will allow zero-sequence mutual coupling between the lines in question to produce the lowest $Z0F_{APP}$ value.
- Find $Z0F_{APP(R4)}$ by placing a fault at the end of Line B with Breaker 3 open.

Find $Z0R_{APP}$, which is the calculated signed scalar zero-sequence impedance for reverse faults for an N-1 contingency.

- Find $Z0R_{APP(N-1)(R3)}$ by taking the smaller value out of the two cases:
  1. Open Breaker 6 and place a fault on Line C near Breaker 6.
  2. Open Breaker 1 and place a fault on Line A near Breaker 1.
- Find $Z0R_{APP(N-1)(R4)}$ by taking the lower value for two cases:
  1. Open Breaker 5 and place a fault on Line C near Breaker 5.
  2. Open Breaker 2 and place a fault on Line A near Breaker 2.

If applicable, find $Z0_{APP}$ for an N-2 contingency. Both relays may calculate a negative $Z0_{APP}$.

- Find $Z0_{APP(N-2A)(R3)}$, $Z0_{APP(N-2A)(R4)}$, $ILB0_{(N-2A)}$, and $ILB2_{(N-2A)}$ by opening Breaker 6 and placing a fault on Line C near Breaker 6 with Line A out of service.
- Find $Z0_{APP(N-2C)(R3)}$, $Z0_{APP(N-2C)(R4)}$, $ILB0_{(N-2C)}$, and $ILB2_{(N-2C)}$ by opening Breaker 2 and placing a fault on Line A near Breaker 2 with Line C out of service.

Based on the above obtained values, we provide setting recommendations below where:

- 50GF is the forward 32V overcurrent supervision.
- Z0F is the forward 32V directional impedance threshold.
- Z0R is the reverse 32V directional impedance threshold.
- 67GF is an instantaneous forward-looking directional overcurrent element used in the communications-assisted tripping scheme.
- 67GFT is an optional time-delayed forward-looking directional overcurrent element used in the communications-assisted tripping scheme.
- 67GFD is the time delay setting for 67GFT
- 67GF_EN is used to enable the 67GF element.
- 50Q is the negative-sequence overcurrent supervision (if needed).
- 67QF is the forward-looking directional overcurrent element used in the communications-assisted tripping scheme.
- ZRBD is the current reversal block timer used in the communications-assisted tripping scheme.
- FLOOR is the minimum allowable overcurrent setting for forward faults. Typically, 10 percent of the conductor rating to account for load unbalance.

The following settings are set as a function of the above settings, unless otherwise specified.

- 50GR is the reverse 32V overcurrent supervision: set at 0.5·50GF of the remote relay.
- 67GR is the reverse-looking directional overcurrent element used in the communications-assisted tripping scheme: set at 0.5·67GF of the remote relay.
- 67QR is the reverse-looking directional overcurrent element used in the communications-assisted tripping scheme: set at 0.5·67QF of the remote relay.

Follow guidance in [2] to set overcurrent supervision (50QF and 50QR) for 32Q and CFIDS logic.

B. Basic Settings

If $Z0R_{APP(N-1)(R3)}$ and $Z0R_{APP(N-1)(R4)}$ are greater than +0.5 ohms secondary, and $Z0F_{APP(R3)}$ and $Z0F_{APP(R4)}$ are less than –0.5 ohms secondary, then the following settings can be used. If this is not the case, see the advanced settings section.

If $ILB0_{(N-2A)}$ and $ILB0_{(N-2C)}$ are less than $0.5 \cdot 3I0_{PU}$, then the mutual coupling is weak and does not pose a problem. Use the following settings in R3 and R4. These are also the same settings to use if you know that no mutual coupling is present on the protected line.

- Z0F = –0.3 ohms
- Z0R = 0.3 ohms
- 50GF = FLOOR
- 67GF_EN = 1
- 67GF = max(FLOOR, $2 \cdot ILB0_{[N-2A]}$, $2 \cdot ILB0_{[N-2C]}$)
- 67QF = $3I2_{PU}$

If $ILB0_{(N-2A)}$ or $ILB0_{(N-2C)}$ is greater than $0.5 \cdot 3I0_{PU}$, then mutual coupling does potentially produce enough current to cause relay misoperation under N-2 contingencies, and you have some basic options to maintain security.

1) Negative-Sequence Supervision of 67GF

Supervise 67GF with negative-sequence current, and use the following additional settings in R3 and R4. Consider extending the pilot reverse block extension timer to provide additional security for sequential clearing on an adjacent mutually coupled line.

- 50Q = max(FLOOR, $2 \cdot ILB2_{[N-2A]}$, $2 \cdot ILB2_{[N-2C]}$)
- 67GF_EN = 50Q
- 67GF = FLOOR
- ZRBD = 10 cycles

This additional supervision will allow 67GF to operate only when negative-sequence current is present. This will provide additional security for 67GF when Line A or Line C is out of service (N-2). We expect 50Q to be set quite low, which will not hinder 67G sensitivity when all lines are in service. However, even low-set values of 50Q can reduce sensitivity at R3 for ground faults on the line fed only by the IBR (Line A out of service).

2) Use 67GF and 67GFT

If the amount of negative-sequence current present for N-2 contingencies still prevents adequate sensitivity levels for the 67GF element, then using two levels of ground directional overcurrent protection can be beneficial. Use the following settings in R3 and R4

- 67GF_EN = 1
- 67GF = max(FLOOR, $2 \cdot ILB0_{[N-2A]}$, $2 \cdot ILB0_{[N-2C]}$)
- 67GFT = FLOOR
- 67GFD = 10 cycles

These settings allow 67GF to quickly clear internal line faults with enough 3I0 to exclude security concerns with mutual coupling. 67GFT can clear resistance faults that produce low levels of 3I0, but does so with a time delay to provide security for out-of-zone faults in which mutual coupling can be problematic.

C. Advanced Settings

In this section we discuss further enhancements to relay settings that can be implemented using impedance-based directional threshold settings.

1) N-1 Setting Considerations

If $Z0R_{APP(N-1)(R1)}$ or $Z0R_{APP(N-1)(R2)}$ are less than +0.5 ohms secondary, then the thresholds selected in Section VIII.B cannot dependably detect reverse faults under an N-1 contingency, and security issues are possible in communications-assisted tripping schemes [18].

We can determine if biasing the 32V thresholds towards security (3) can provide reasonable sensitivity using (7). This equation assumes a 1V 3V0 error in the secondary voltage signal and determines forward directional overcurrent settings that ensure R4 is permitted to declare forward only when R3 can dependably declare reverse for faults behind R3 [18]. Equation (8) is similar but provides guidance for overcurrent supervision at R3. If (7) or (8) evaluate negative, do not use 32V for directionality because even securely set thresholds cannot provide security for an N-1 contingency. This should be an unlikely occurrence.

$$\frac{1\text{V}}{Z0R_{APP(N-X)[R3]} - (0.5 \cdot Z0F_{APP[R3]} + 0.1)} = 50GF_{(N-X)[R4]} \quad (7)$$

$$\frac{1\text{V}}{Z0R_{APP(N-X)[R4]} - (0.5 \cdot Z0F_{APP[R4]} + 0.1)} = 50GF_{(N-X)[R3]} \quad (8)$$

where:

x = 1 for N-1 contingency and x = 2 for N-2 contingency.

If (7) and (8) evaluate positive, then consider using 32V security-biased thresholds.

Set the R3 relay as follows:

- Z0F = $0.5 \cdot Z0F_{APP(R3)}$
- Z0R = $0.5 \cdot Z0F_{APP(R3)} + 0.1$
- $50GF_{(N-1)}$=result from (8) where x = 1
- $50GR_{(N-1)}$=result from (7) where x = 1, multiplied by 0.5

Set the R4 relay as follows:

- Z0F = $0.5 \cdot Z0F_{APP(R4)}$
- Z0R = $0.5 \cdot Z0F_{APP(R4)} + 0.1$
- $50GF_{(N-1)}$=result from (7) where x = 1
- $50GR_{(N-1)}$=result from (8) where x = 1, multiplied by 0.5

This method can be used to provide a stronger security bias in 32V directional elements in any system. Note that if (7) or (8) evaluates higher than $3I0_{PU}$, then 67G will not have the desired sensitivity. This will happen in cases where there is very little difference in the measured impedance for a forward fault compared to a reverse fault. Under N-1 contingencies, this is unlikely. Using (7) and (8) provides a security bias to 32V, and in many systems, will not hinder sensitivity.

To provide security for N-2 contingencies, 50Q supervision and reverse block extension timers can be used. These are discussed in Section VIII.B. An alternative is to consider if biasing the directional thresholds even further towards security for N-2 cases can help, which is discussed below.

2) *N-2 Settings Considerations (If Applicable)*

If the transfer impedance between Bus S and Bus R is low enough, it may be possible to make 32V secure for N-2 contingencies.

Find the following values:

- $Z0R_{APP(N\text{-}2)(R3)} = \min(Z0_{APP[N\text{-}2A][R3]}, Z0_{APP[N\text{-}2C][R3]})$
- $Z0R_{APP(N\text{-}2)(R4)} = \min(Z0_{APP[N\text{-}2A][R4]}, Z0_{APP[N\text{-}2C][R4]})$

Plug $Z0R_{APP(N\text{-}2)(R3)}$ into (7) and $Z0R_{APP(N\text{-}2)(R4)}$ into (8) and evaluate.

Based on the location of the transfer impedance in Fig. 17, it is likely that (7) will evaluate negative and (8) will evaluate positive. If (8) provides an acceptable level of sensitivity for 50GF at R3, then the relays can be set as follows.

Set the R3 relay as follows:

- $Z0F = 0.5 \cdot Z0F_{APP(R3)}$
- $Z0R = 0.5 \cdot Z0F_{APP(R3)} + 0.1$
- $50GF_{(N\text{-}2)}$ = result from (8) where x = 2
- $50GR_{(N\text{-}1)}$ = result from (7), where x = 1, multiplied by 0.5

Set the R4 relay as follows:

- $Z0F = 0.5 \cdot Z0F_{APP(R4)}$
- $Z0R = 0.5 \cdot Z0F_{APP(R4)} + 0.1$
- $50GF_{(N\text{-}1)}$ = result from (7) where x = 1
- $50GR_{(N\text{-}2)}$ = result from (8) where x = 2, multiplied by 0.5

For both credible N-2 contingencies that Line B relays can see, R4 can reliably declare reverse and prevent R3 operation with these settings. Additionally, 50Q supervision is not needed and ZRBD can be set at its default value.

3) *Custom Logic for Relays With Common Overcurrent Supervision for 32V and 32Q*

In relays that have common overcurrent supervision for 32V and 32Q, you cannot set 50GF differently than 50QF. This means that 32V and 32Q will have reduced sensitivity because you must maintain security of 32Q near IBRs. In [23], logic is provided to create a 32V element that can have more sensitive overcurrent supervision set. You can use this custom 32V element to supervise 67G and turn off the built-in 32V logic to gain ground fault sensitivity.

4) *Reclosing*

While adaptive reclosing is a possible consideration, it is challenging to implement and requires communications available between all terminals. For instance, for Relay R2 security, if Line B is out of service (between Bus T and Bus R), it is preferred to reclose with Breaker 5 at Bus S. This requires sending information from either Bus R or Bus T to Bus S.

However, as discussed earlier, you can use Table I to choose security-biased breaker reclosing on a per-line basis. For example, if, after going through the settings recommendations above, R2 lacks the desired sensitivity but R3 does not, then choose to reclose Breaker 5 on Line C before Breaker 6.

IX. APPENDIX—CIRCUIT ANALYSIS

We start with a two-terminal line representation to build the fundamentals of zero-sequence mutual coupling, as shown in Fig. 18.

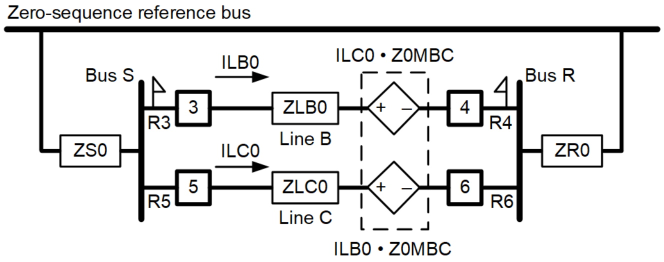

Fig. 18 Two sources and two lines with mutual coupling.

A. *Configuration 1: ILB0 and ILC0 Flow in Same Direction*

We will first consider a fault at Bus R. In this case, the currents ILB0 and ILC0 will have the same direction, as shown in Fig. 19.

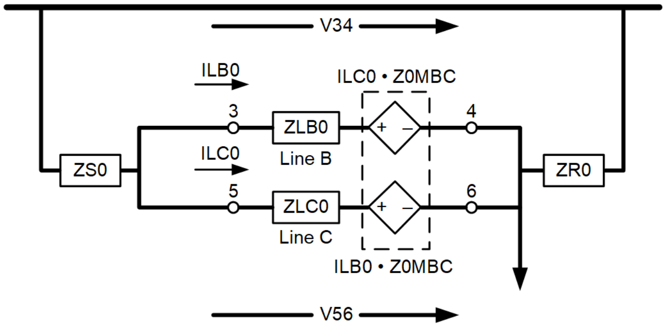

Fig. 19 Two sources with fault at Bus R.

The voltage across Line B and Line C, respectively, is shown below in (9).

$$\begin{aligned} V34 &= ILB0 \cdot ZLB0 + ILC0 \cdot Z0MBC \\ V56 &= ILC0 \cdot ZLC0 + ILB0 \cdot Z0MBC \end{aligned} \tag{9}$$

To find the apparent impedance across the line sections, we can take (9) and divide by the appropriate line current. The result is shown in (10).

$$\begin{aligned} Z34 &= ZLB0 + \frac{ILC0}{ILB0} \cdot Z0MBC \\ Z56 &= ZLC0 + \frac{ILB0}{ILC0} \cdot Z0MBC \end{aligned} \tag{10}$$

To solve for the apparent line impedance, we need to determine the ratio of ILB0 to ILC0 current. If we eliminate the dependent voltage sources, we will be able to use a current divider to define this ratio.

To eliminate the dependent voltage source, we can manipulate (9) using (11).

$$\begin{aligned}V34 &= ILB0 \cdot ZLB0 + ILC0 \cdot Z0MBC \\ &\quad + (ILB0 \cdot Z0MBC - ILB0 \cdot Z0MBC) \\ V34 &= ILB0 \cdot (ZLB0 - Z0MBC) + (ILB0 + ILC0) \\ &\quad \cdot (Z0MBC)\end{aligned} \tag{11}$$

$$\begin{aligned}V56 &= ILC0 \cdot ZLC0 + ILB0 \cdot Z0MBC \\ &\quad + (ILC0 \cdot Z0MBC - ILC0 \cdot Z0MBC) \\ V56 &= ILC0 \cdot (ZLC0 - Z0MBC) + (ILB0 + ILC0) \\ &\quad \cdot (Z0MBC)\end{aligned}$$

This manipulation allows us to redraw Fig. 19, as shown below in Fig. 20. Note that V34 and V56 now include the voltage drop across Z0MBC.

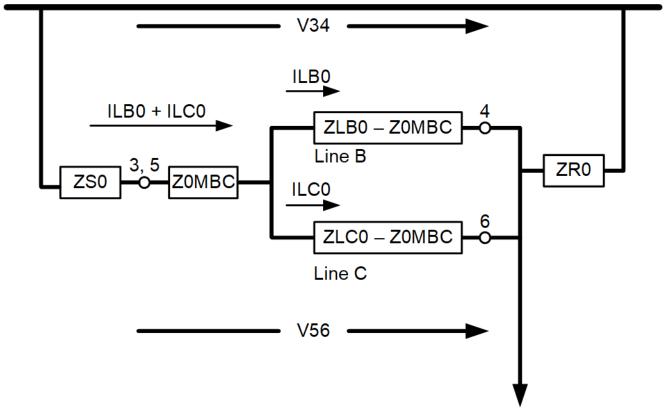

Fig. 20 Dependent sources removed from Fig. 19 for fault at Bus R.

We can define the ILC0 over ILB0, as shown in (12).

$$\begin{aligned}ILB0 &= (ILB0 + ILC0) \cdot \left(\frac{ZLC0 - Z0MBC}{ZLB0 + ZLC0}\right) \\ ILC0 &= (ILB0 + ILC0) \cdot \left(\frac{ZLB0 - Z0MBC}{ZLB0 + ZLC0}\right) \\ \frac{ILC0}{ILB0} &= \left(\frac{ZLB0 - Z0MBC}{ZLB0 + ZLC0}\right) \cdot \left(\frac{ZLB0 + ZLC0}{ZLC0 - Z0MBC}\right)\end{aligned} \tag{12}$$

If we assume that ZLB0 = ZLC0, then ILC0 = ILB0, and the apparent impedance of each line is shown in (13).

$$\begin{aligned}Z34 &= ZLB0 + Z0MBC \\ Z56 &= ZLC0 + Z0MBC\end{aligned} \tag{13}$$

This shows that current flowing in the same direction on each line leads to a larger apparent impedance than if no mutual coupling is present.

Because we are interested in the impedance-based directional element performance, we solve for VR3 and VR4 to see how Relay 3 and Relay 4 will respond (14).

$$\begin{aligned}VR3 &= -(ILB0 + ILC0) \cdot ZS0 \\ IR3 &= ILB0 \\ ZR3 &= -2 \cdot ZS0 \\ VR4 &= -(ILB0 + ILC0) \cdot (ZS0 + Z0MBC) \\ &\quad - ILB0 \cdot (ZLB0 - Z0MBC) \\ IR4 &= -ILB0 \\ ZR4 &= 2 \cdot ZS0 + ZLB0 + Z0MBC\end{aligned} \tag{14}$$

Relay 3 will see this fault in the forward direction (ZR3 is negative), and Relay 4 will see this fault in the reverse direction (ZR4 is positive). This is the expected behavior.

B. *Configuration 2a: ILB0 and ILC0 Opposite Direction*

Referring to Fig. 18, the next case we consider is a close-in fault at Breaker 6 with Breaker 6 open. The resultant zero-sequence diagram after eliminating the dependent current sources is shown in Fig. 21.

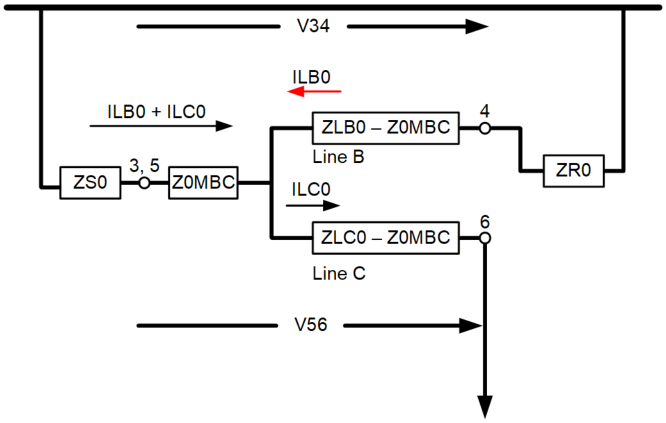

Fig. 21 Dependent sources removed for close-in fault at Breaker 6 with Breaker 6 open.

We can directly obtain ILB0 over ILC0 using a current divider, as shown in (15).

$$\begin{aligned}ILB0 &= -ILC0 \cdot \left(\frac{ZS0 + Z0MBC}{ZS0 + ZLB0 + ZR0}\right) \\ \frac{ILB0}{ILC0} &= -\left(\frac{ZS0 + Z0MBC}{ZS0 + ZLB0 + ZR0}\right)\end{aligned} \tag{15}$$

We can then plug (15) into (10) and obtain the apparent impedance Z34 and Z56, as shown in (16).

$$\begin{aligned}Z34 &= ZLB0 - \left(\frac{ZS0 + ZLB0 + ZR0}{ZS0 + Z0MBC}\right) \cdot Z0MBC \\ Z56 &= ZLC0 - \left(\frac{ZS0 + Z0MBC}{ZS0 + ZLB0 + ZR0}\right) \cdot Z0MBC\end{aligned} \tag{16}$$

If we assume ZS0 = ∞, then ILB0 = –ILC0 and the following simplification from (16) is shown in (17).

$$\begin{aligned}Z34 &= ZLB0 - Z0MBC \\ Z56 &= ZLC0 - Z0MBC\end{aligned} \tag{17}$$

We can then solve for the voltage and currents seen at Relay 3 (18).

$$\begin{aligned} VR3 &= -ILB0 \bullet (ZR0 + ZLB0 - Z0MBC) \\ IR3 &= -ILB0 \\ ZR3 &= (ZR0 + ZLB0 - Z0MBC) \end{aligned} \tag{18}$$

We can also solve for the voltages and currents seen at Relay 4 (19).

$$\begin{aligned} VR4 &= -ILB0 \bullet (ZR0) \\ IR4 &= ILB0 \\ ZR4 &= -ZR0 \end{aligned} \tag{19}$$

Relay 3 will see this fault in the reverse direction (ZR3 is positive), and Relay 4 will see this fault in the forward direction (ZR4 is negative). This is the expected behavior.

C. Configuration 2b: Line B Out of Service and Grounded

Fig. 22 shows Line B out of service and grounded with a close-in fault to Breaker 6 with Breaker 6 open.

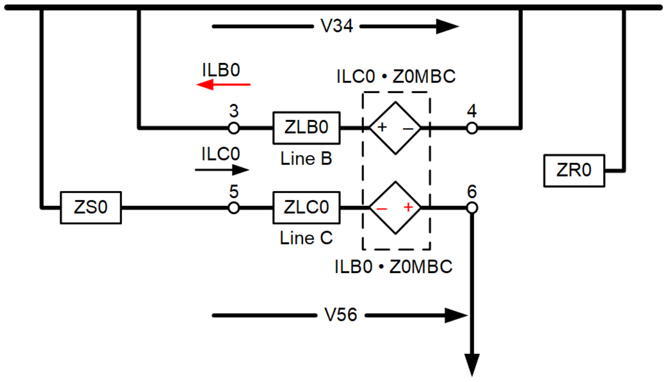

Fig. 22 Line B out and grounded with close-in fault to Breaker 6 with Breaker 6 open.

We can identify the current ILB0 using the voltage source of ILC0 • Z0MBC over the impedance in the closed circuit of ZLB0. From this we can define the ratio of ILB0 over ILC0 (20).

$$\begin{aligned} ILB0 &= -ILC0 \bullet \frac{Z0MBC}{ZLB0} \\ \frac{ILB0}{ILC0} &= -\frac{Z0MBC}{ZLB0} \end{aligned} \tag{20}$$

Plugging (20) into (10), we get the following impedance values (21).

$$\begin{aligned} Z34 &= 0 \\ Z56 &= ZLC0 - \frac{Z0MBC^2}{ZLB0} \end{aligned} \tag{21}$$

Because Line B is out and grounded, R3 and R4 will not have access to voltage and current signals. However, it is important to note that the apparent line impedance on Line C is reduced when Line B is out and grounded.

For completion, Fig. 23 shows the dependent sources removed for Configuration 2b.

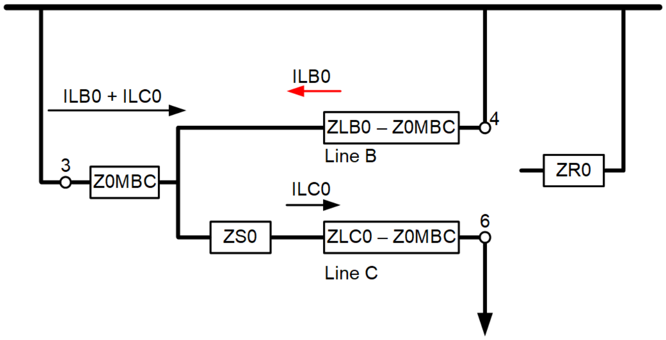

Fig. 23 Dependent sources removed for fault in Fig. 22.

Note that the relay location R5 has been removed. This is because V56, which does not include the voltage drop across ZS0, cannot be properly shown in this circuit. Fig. 23 can be used to solve for ILB0 and ILC0 currents, then return to Fig. 22 to solve for voltages in the circuit.

D. Configuration 2d: Vary the Electrical Connection Strength Between ZLB0 and ZLC0

In Configuration 2d, we convert the two-source system to a three-source system and break Line B into two segments, as shown in Fig. 24. This will allow us to better understand the mechanism for directionality issues associated with mutual coupling.

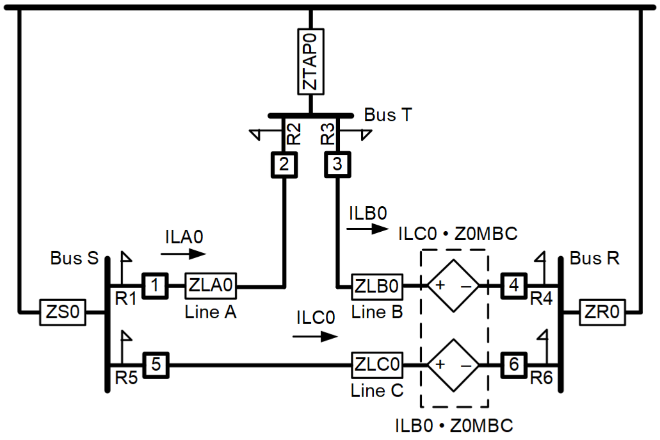

Fig. 24 Three sources and three lines.

We assume Breaker 6 is open and a fault occurs close-in to Breaker 6, just as we have done in Configuration 2a and Configuration 2b. Fig. 25 shows the zero-sequence network for this fault.

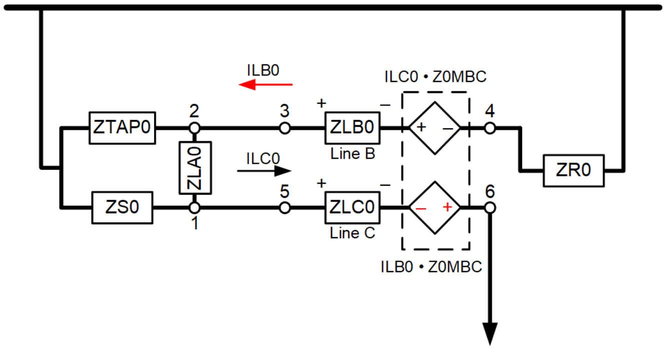

Fig. 25 Close-in fault to Breaker 6 with Breaker 6 open.

To be able to remove the dependent voltage source from the circuit, we need to first convert the ZTAP0, ZS0, and ZLA0 impedances from a delta connection to a wye connection. The newly defined ZA, ZB, and ZC impedances are defined in (22).

$$\begin{aligned} ZA &= \frac{ZTAP0 \cdot ZS0}{ZS0 + ZTAP0 + ZLA0} \\ ZB &= \frac{ZTAP0 \cdot ZLA0}{ZS0 + ZTAP0 + ZLA0} \\ ZC &= \frac{ZS0 \cdot ZLA0}{ZS0 + ZTAP0 + ZLA0} \end{aligned} \tag{22}$$

Fig. 26 shows the ZA, ZB, and ZC impedances as well as the removal of the dependent voltage source.

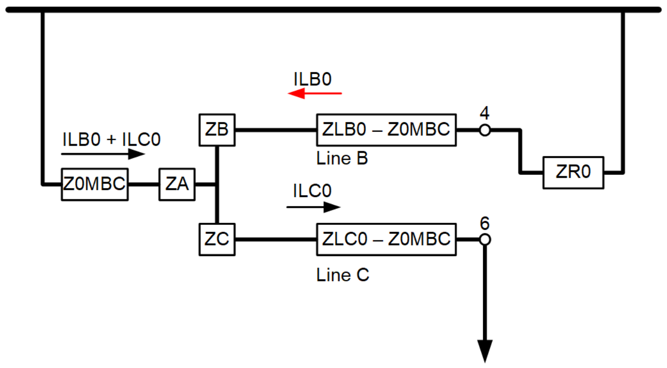

Fig. 26 Dependent voltage sources removed from Fig. 25.

With this manipulation of the circuit, we can no longer define V34 and V56 in the circuit. However, we can solve for currents and define ILB0 over ILC0 (23).

$$\begin{aligned} ILB0 &= -ILC0 \cdot \left(\frac{Z0MBC + ZA}{ZLB0 + ZB + ZA + ZR0} \right) \\ \frac{ILB0}{ILC0} &= -\frac{Z0MBC + ZA}{ZLB0 + ZB + ZA + ZR0} \end{aligned} \tag{23}$$

Plugging this back into (10), we get (24).

$$\begin{aligned} Z34 &= ZLB0 - \frac{ZLB0 + ZB + ZA + ZR0}{Z0MBC + ZA} \cdot Z0MBC \\ Z56 &= ZLC0 - \frac{Z0MBC + ZA}{ZLB0 + ZB + ZA + ZR0} \cdot Z0MBC \end{aligned} \tag{24}$$

If we assume that ZLA0 = 0, and ZS0 = ZTAP0 = ∞, then ZA = ∞ and this will closely resemble Configuration 2a. The apparent impedance from Z34 and Z56 is shown in (25).

$$\begin{aligned} Z34 &= ZLB0 - Z0MBC \\ Z56 &= ZLC0 - ZM0BC \end{aligned} \tag{25}$$

E. *Configuration 2c: Line B Full Electrical Isolation From Line C*

If we assume that ZLA0 = ∞, then ZA = 0, ZB = ZTAP0, and ZC = ZS0, and this will closely resemble Configuration 2b (electrical isolation), but with the addition of ZR0 and ZTAP0. The apparent impedance from Z34 and Z56 is shown in (26).

$$\begin{aligned} Z34 &= -ZTAP0 - ZR0 \\ Z56 &= ZLC0 - \frac{Z0MBC^2}{ZTAP0 + ZLB0 + ZR0} \end{aligned} \tag{26}$$

When Line B and Line C are electrically isolated, the apparent impedance at Relay 4 can be calculated as shown in (27).

$$\begin{aligned} VR4 &= -ILB0 \cdot (ZR0) \\ IR4 &= ILB0 \\ Z4 &= -ZR0 \end{aligned} \tag{27}$$

The apparent impedance at Relay 3 can be calculated as shown in (28) using the apparent impedance for Z34 obtained from (26).

$$\begin{aligned} VR3 &= -ILB0 \cdot (ZR0 - ZTAP0 - ZR0) \\ IR3 &= -ILB0 \\ Z3 &= -ZTAP0 \end{aligned} \tag{28}$$

Relay 3 and Relay 4 will both declare forward for this external line fault and see an apparent impedance consistent with expected values for an internal fault.

If we vary only ZLA0, we can view the effects of Line B and Line C with a strong electrical connection (ZLA0 = 0) to complete isolation (ZLA0 = ∞). This is beneficial in understanding the term "voltage inversion."

Because the magnitude values of I_0 and V_0 are of importance when varying ZLA0, some additional equations are provided below.

Equation (29) is the apparent total zero-sequence impedance of Fig. 26.

$$\begin{aligned} ZT0 = {} & \frac{(Z0MBC + ZA) \cdot (ZR0 + [ZLB0 - Z0MBC] + ZB)}{(Z0MBC + ZA) + (ZR0 + [ZLB0 - Z0MBC] + ZB)} \\ & + ZLC0 - Z0MBC + ZC \end{aligned} \tag{29}$$

Equation (30) shows the voltage calculation for Relay 4 and Relay 3, which can be observed from Fig. 25.

$$\begin{aligned} VR4 &= ILB0 \cdot ZR0 \\ VR3 &= VR4 + ILB0 \cdot ZLB0 + ILC0 \cdot Z0MBC \end{aligned} \tag{30}$$

F. *Configuration 2c: Forward Fault*

This configuration is provided to see the effects of mutual coupling for forward fault declarations. Fig. 27 shows the zero-sequence network. ZA, ZB, and ZC calculations are unchanged from (22).

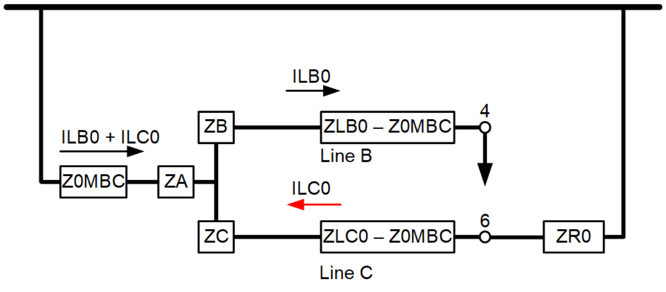

Fig. 27 Close-in fault to Breaker 4 with Breaker 4 open.

Equation (31) defines ILC0 over ILB0.

$$\frac{ILC0}{ILB0} = -\frac{Z0MBC + ZA}{ZLC0 + ZC + ZA + ZR0} \tag{31}$$

The total impedance of the circuit is defined in (32).

$$ZT0 = \frac{(Z0MBC + ZA) \bullet (ZR0 + [ZLC0 - Z0MBC] + ZC)}{(Z0MBC + ZA) + (ZR0 + [ZLC0 - Z0MBC] + ZC)} + ZLB0 - Z0MBC + ZB \tag{32}$$

The voltage at V3 can be solved by reinserting the current-dependent voltage sources and removing Z0MBC impedances, as shown in Fig. 28.

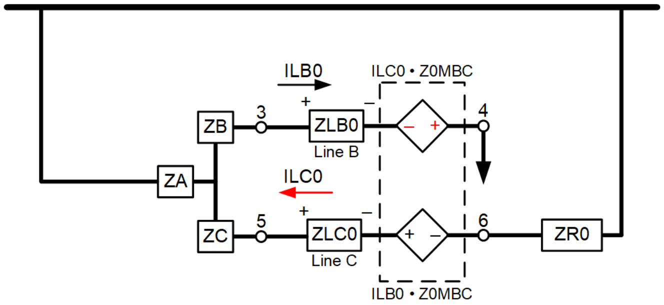

Fig. 28 Circuit to solve for circuit voltages.

The voltage at R3 is defined in (33).

$$VR3 = (ILB0 - ILC0) \bullet ZA - ZB \bullet ILB0 \tag{33}$$

G. *A Note on Current and Voltage Calculations*

In the examples above, ILB0 and ILC0 currents are solved by removing the current-dependent voltage sources and using Z0MBC in an impedance-only circuit. However, relay voltages are obtained in various ways. We summarize them here:

- If the relay voltage can still be represented as a physical location with the current-dependent voltage sources removed, then you can solve for relay voltages in an impedance-only circuit (Configurations 1 and 2a).
- If the relay voltages can no longer be represented as a physical location with the current-dependent voltage sources removed, then you must treat solving for voltages as a two-step process. Step 1 is to solve for currents in the impedance-only circuit. Step 2 is to solve for voltages. This can be accomplished in two ways:
  - Return to the circuit with current-dependent voltage sources and solve for the relay voltage (Configurations 2b and 2c—Forward). This method will always work regardless of the configuration.
  - Solve for the apparent line impedance, due to mutual coupling, in the impedance-only circuit (Z34 and Z56). Use Z34 and Z56 to calculate voltage drops across the line (Configuration 2c).

X. REFERENCES

[1] R. Chowdhury and N. Fischer, “Transmission Line Protection for System With Inverter-Based Resources – Part I: Problems,” IEEE Transactions on Power Delivery, Vol. 36, Issue 4, pp. 2416–2425, August 2021.

[2] R. Chowdhury and N. Fischer, “Transmission Line Protection for System With Inverter-Based Resources – Part II: Solutions,” IEEE Transactions on Power Delivery, Vol. 36, Issue 4, pp. 2426–2433, August 2021.

[3] B. Kasztenny, “Distance Elements for Line Protection Applications Near Unconventional Sources,” proceedings of the 75th Annual Conference for Protective Relay Engineers, College Station, TX, March 2021.

[4] M. Bini, R. Abboud, P. Lima, and F. Lollo, “Challenges and Solutions in the Protection of Transmission Lines Connecting Nonconventional Power Sources,” proceedings of the 48th Annual Western Protective Relay Conference, Spokane, WA, October 2021.

[5] M. J. Thompson, D. Heidfeld, and D. Oaks, “Transmission Line Settings Calculation – Beyond the Cookbook Part II,” proceedings of the 48th Annual Western Protective Relay Conference, Spokane, WA, October 2021.

[6] PJM Manual 07: PJM Protection Standards Rev. 4. Available: https://www.pjm.com/-/media/documents/manuals/m07.ashx.

[7] M. J. Thompson and D. Heidfeld, “Transmission Line Settings Calculation – Beyond the Cookbook,” proceedings of the 68th Annual Conference for Protective Relay Engineers, College Station, TX, March 2015.

[8] J. Roberts, E. O. Schweitzer, III, R. Arora, and E. Poggi, “Limits to the Sensitivity of Ground Directional and Distance Protection,” proceedings of the 22nd Annual Western Protective Relay Conference, Spokane, WA, October 1995.

[9] “Fault current contributions from wind plants,” 2015 68th Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2015, pp. 137-227, doi: 10.1109/CPRE.2015.7102165.

[10] M. Nagpal, et al., “Protection Challenges and Practices for Interconnecting Inverter Based Resources to Utility Transmission Systems,” in IEEE Power & Energy Society, PES-TR81, July 2020.

[11] W. Tucker, A. Burich, M. Thompson, R. Anne, and S. Vasudevan, “Coordinating Dissimilar Line Relays in a Communications-Assisted Scheme,” proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, March 2014.

[12] F. Plumptre, M. Nagpal, X. Chen, and M. Thompson, “Protection of EHV Transmission Lines With Series Compensation: BC Hydro’s Lessons Learned,” 62nd Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2009, pp. 288-303.

[13] E. O. Schweitzer, III, and J. Roberts, “Distance Element Relay Design,” proceedings of the 19th Annual Western Protective Relay Conference, Spokane, WA, October 1992.

[14] D. Costello and K. Zimmerman, “Determining the Faulted Phase,” proceedings of the 36th Annual Western Protective Relay Conference, Spokane, WA, October 2009.

[15] B. Kasztenny, R. Chowdhury, “Security Criterion for Distance Zone 1 Applications in High SIR Systems with CCVTs,” proceedings of the 76th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2023.

[16] J. Roberts and A. Guzmán, “Directional Element Design and Evaluation,” proceedings of the 21st Annual Western Protective Relay Conference, Spokane, WA, October 1994.

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

[18] R. McDaniel and M. J. Thompson, “Impedance-Based Directional Elements – Why Have a Threshold Setting?” proceedings of the 48th Annual Western Protective Relay Conference, Spokane, WA, October 2021.

[19] C. Holt and M. J. Thompson, “Practical Considerations When Protecting Mutually Coupled Lines,” 69th Annual Conference for Protective Relay Engineers (CPRE), College Station, TX, April 2016, pp. 1-16.

[20] D. A. Tziouvaras, H. J. Altuve, and F. Calero, “Protecting Mutually Coupled Transmission Lines: Challenges and Solutions,” proceedings of the 67th Annual Conference for Protective Relay Engineers, College Station, TX, March 2014.

[21] K. H. Engelhardt, “V0-Reversal on Mutually Coupled Lines – Relaying Analysis, Experience, and Remedies,” proceedings of the 1st Annual Western Protective Relay Conference, Spokane, WA, October 1974.

[22] E. H. Gove and E. A. Taylor, “A Practical Remedy for Zero Sequence Reversal,” proceedings of the 16th Annual Western Protective Relay Conference, Spokane, WA, October 1989.

[23] J. Roberts and K. Zimmerman, “Trip and Restore Distribution Circuits at Transmission Speeds,” proceedings of the 25th Annual Western Protective Relay Conference, Spokane, WA, October 1998.

[24] R. McDaniel and R. Chowdhury, “Ground Fault Protection for Resistance-Grounded Collector Feeders With Inverter-Based Resources,” proceedings of the 49th Annual Western Protective Relay Conference, Spokane, WA, October 2022.

[25] R. Chowdhury, M. Alla, N. Fischer and S. Samineni, “Restricted Earth Fault Protection in Low-Impedance Grounded Systems With Inverter-Based Resources,” in IEEE Transactions on Power Delivery, Vol. 38, Issue 1, pp. 505-512, Feb. 2023.

[26] R. Chowdhury, R. McDaniel, and N. Fischer, “Line Current Differential Protection in Systems with Inverter-Based Resources—Challenges and Solutions,” proceedings of the 49th Annual Western Protective Relay Conference, Spokane, WA, October 2022.

XI. BIOGRAPHIES

Ryan McDaniel earned his BS in computer engineering from Ohio Northern University in 2002. In 1999, he was hired by American Electric Power (AEP) where he worked as a relay technician and a protection and control engineer. In 2005, he joined Schweitzer Engineering Laboratories, Inc. (SEL) and is currently a principal engineer. His responsibilities include providing application support and technical training for protective relay users. Ryan is a registered professional engineer in the state of Illinois and a Senior member of IEEE.

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