Mutual Coupling in Subtransmission Systems—A Real-World Experience

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***Abstract*—This paper presents a case study in which a single-line-to-ground fault on a 34.5 kV subtransmission line caused a misoperation of the adjacent subtransmission line protection. Investigation of the event revealed mutual coupling as the root cause behind the misoperation, which is often overlooked during the modeling stage by protection engineers for subtransmission systems. Where mutual coupling is suspected in overhead lines, using zero-sequence directional elements is uncommon, as they may cause false trips. In this case, the relay on the adjacent line had the negative-sequence voltage-polarized impedance-based ground directional element (32QZ) but the relay still misoperated on directional supervised 51NT.**

The paper begins with a refresher on the concept of mutual coupling between overhead conductors, followed by a detailed event analysis that examines fault oscillography records, symmetrical components, and ground directional overcurrent elements in the relay. It also describes the subtransmission system modeling and mutual coupling studies that were performed to confirm the presence of mutual coupling.

By combining investigative efforts from both relay settings and system modeling standpoints, the paper offers valuable lessons learned and proposes a corrective action plan via relay settings changes to improve security against future misoperations.

I. Introduction to Mutual Coupling Phenomena

The deep-rooted principle of electromagnetic coupling is the very foundation that the whole power system is built on. From generators to transformers to motors, electromagnetic coupling is at play everywhere, which has allowed engineers to harness the power of natural resources to serve high demands of an ever-growing population and infrastructure.

The principle of electromagnetic coupling is directly responsible for the impedance that transmission and distribution lines offer to the flow of power. Although electromagnetic coupling is a well-documented, century-old principle, we wish to revisit the conceptual grassroots of this principle and summarize the fundamentals of self- and mutual impedances in electrical circuits before moving on to a case study of misoperation due to mutual coupling.

The following is a list of key points of electromagnetic coupling fundamentals:

- One property of a current-carrying conductor is that it produces a magnetic field around itself.
- The density of a magnetic field is strongest closer to the conductor, and it decreases farther away from the conductor.
- As alternating current (ac) in conductors oscillates sinusoidally at a 60 Hz frequency, the resultant magnetic flux due to ac is also time-varying in nature. For instance, when the current is at a positive peak in the sinusoidal waveform, the magnetic field intensity is the largest. When the current changes polarity from positive to negative, the magnetic field also changes direction spatially.
- When exposed to varying magnetic flux, a coil produces an electromagnetic field (EMF) that opposes the change of flux. The current flow due to the EMF, in turn, produces magnetic flux that tends to cancel or reduce the original varying magnetic field.
- The produced EMF is directly proportional to the rate-of-change of flux. A higher current magnitude produces a larger magnetic field density. A shorter distance between the coil and current-carrying conductor yields higher magnetic coupling. Both factors, in turn, increase the magnitude of the produced EMF.

A. Fundamentals of Self- and Mutual Impedances

The self-impedance, Zs, of a current-carrying conductor comprises resistive and inductive components. The inductive component is the manifestation of electromagnetic coupling. The conductor produces an EMF to oppose the rate-of-change of flux caused due to the current flowing through it.

The impedance caused by self-electromagnetic coupling is far larger than the resistive impedance in transmission lines; hence, the predominately inductive nature of transmission lines.

The mutual coupling between two conductors is again the electromagnetic coupling phenomenon in which one conductor produces an EMF to oppose the rate-of-change of flux introduced by the time-varying current (Iy) in the second conductor.

The EMF is represented as a voltage drop (Vx), which is a product of the current Iy and the mutual impedance (Zxy) between Conductors X and Y, as shown in Fig. 1.

In practical terms, for 1 A of current (Iy) flowing in Conductor Y, the voltage (Vx) produced in Conductor X is the mutual impedance Zxy [1].

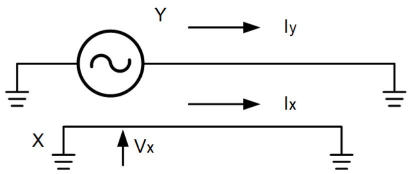

Fig. 1. Electromagnetic coupling between Conductors X and Y.

A single three-phase circuit comprising Phase Conductors a, b, and c will have self- and mutual impedances. The Kirchhoff's voltage law (KVL) equations shown in (1) describe the effect of voltage drops due to self-impedances Zaa, Zbb, and Zcc and voltage drops due to mutual impedances Zab, Zbc, and Zca.

$$\begin{aligned} Va - Ia.Zaa - Ib.Zab - Ic.Zac - Va' = 0 \\ Vb - Ib.Zbb - Ia.Zab - Ic.Zbc - Vb' = 0 \\ Vc - Ic.Zcc - Ia.Zac - Ib.Zbc - Vc' = 0 \end{aligned} \quad (1)$$

The term Ib.Zab in the first equation represents a voltage drop (due to electromagnetic coupling) in the A-phase due to current Ib flowing in the B-phase. The same analogy could be applied to other terms in the equations.

These equations could also be represented in matrix form [2], as shown in (2).

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \begin{bmatrix} Zaa & Zab & Zac \\ Zab & Zbb & Zbc \\ Zac & Zbc & Zcc \end{bmatrix} \bullet \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \quad (2)$$

The diagonal terms form the self-impedances. The off-diagonal terms form the mutual impedances.

There is a plethora of literature that describes and lists the formula for mutual impedance [3][4].

The self-impedances will be equal (Zs) if the distance of each phase conductor to ground is the same. This would be the case for a flat line geometry tower configuration.

The mutual impedances will be equal if the distance between phase conductors is equal. This would be the case for a triangular line geometry tower configuration.

Performing line transposition for a flat line geometry also brings the average distance between the phase conductors so they are the same, which, in turn, will make the mutual impedance between the phase conductors be the same (Zm).

For a case where there are equal Zs for all three phases and equal Zm between the three phases, (2) could be further reduced to obtain the sequence impedance matrix Zsym consisting of only diagonal terms of Z0, Z1, and Z2, as shown in (3).

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} Z0 & 0 & 0 \\ 0 & Z1 & 0 \\ 0 & 0 & Z2 \end{bmatrix} \bullet \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix} \quad (3)$$

Z0 = Zs + 2Zm
Z1 = Zs – Zm
Z2 = Zs – Zm

The empty off-diagonal terms represent the fact that the positive-, negative-, and zero-sequence networks are decoupled from each other. It means if there was a positive-sequence voltage applied to the three-phase line, only positive-sequence current would flow through it.

Practically, this is achieved due to equal electromagnetic coupling between the phase conductors as the distances between the three-phase conductors are equal. On the contrary, should the self-impedances or mutual impedances not be equal, the Zsym matrix will comprise off-diagonal terms too, as shown in (4). That means there is coupling between the sequence networks.

$$\begin{bmatrix} V0 \\ V1 \\ V2 \end{bmatrix} = \begin{bmatrix} Z00 & Z01 & Z02 \\ Z10 & Z11 & Z12 \\ Z20 & Z21 & Z22 \end{bmatrix} \bullet \begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix} \quad (4)$$

A practical example is the application of a three-phase fault on an untransposed line, which also yields negative- and zero-sequence currents besides the expected positive-sequence currents.

B. Mutual Coupling Between Two Three-Phase Circuits

In a case where a tower or pole carries two three-phase circuits, as shown in Fig. 2, there will be electromagnetic coupling between any pair of two conductors. From here on, we refer to electromagnetic coupling between two conductors as mutual coupling.

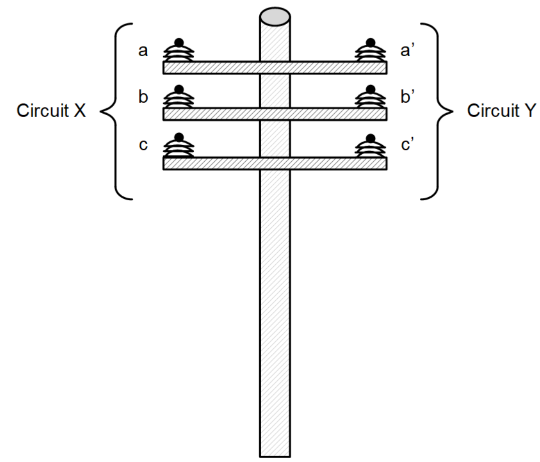

Fig. 2. Two parallel circuits shared on a pole.

The KVL equations in matrix form for this twin-circuit configuration is described as shown in (5).

$$\begin{bmatrix} Va \\ Vb \\ Vc \\ Va' \\ Vb' \\ Vc' \end{bmatrix} = \begin{bmatrix} Zaa & Zab & Zac & Zaa' & Zab' & Zac' \\ Zba & Zbb & Zbc & Zba' & Zbb' & Zbc' \\ Zca & Zcb & Zcc & Zca' & Zcb' & Zcc' \\ Za'a & Za'b & Za'c & Za'a' & Za'b' & Za'c' \\ Zb'a & Zb'b & Zb'c & Zb'a' & Zb'b' & Zb'c' \\ Zc'a & Zc'b & Zc'c & Zc'a' & Zc'b' & Zc'c' \end{bmatrix} \bullet \begin{bmatrix} Ia \\ Ib \\ Ic \\ Ia' \\ Ib' \\ Ic' \end{bmatrix} \quad (5)$$

The set of equations shown in (5) could be further reduced to obtain a 6 x 6 matrix comprising sequence impedances [4] [5], as shown in (6).

$$\begin{bmatrix} V0 \\ V1 \\ V2 \\ V0' \\ V1' \\ V2' \end{bmatrix} = \begin{bmatrix} Z00 & Z01 & Z02 & Z00' & Z01' & Z02' \\ Z10 & Z11 & Z12 & Z10' & Z11' & Z12' \\ Z20 & Z21 & Z22 & Z20' & Z21' & Z22' \\ Z0'0 & Z0'1 & Z0'2 & Z0'0' & Z0'1' & Z0'2' \\ Z1'0 & Z1'1 & Z1'2 & Z1'0' & Z1'1' & Z1'2' \\ Z2'0 & Z2'1 & Z2'2 & Z2'0' & Z2'1' & Z2'2' \end{bmatrix} \bullet \begin{bmatrix} I0 \\ I1 \\ I2 \\ I0' \\ I1' \\ I2' \end{bmatrix} \quad (6)$$

In (6), Z01 represents the mutual impedance between the zero-sequence network and positive-sequence network for Circuit X. Practically, Z01 signifies the zero-sequence voltage produced in Circuit X when positive-sequence current flows through Circuit X. Z01' signifies the zero-sequence voltage produced in Circuit X when positive-sequence current flows through Circuit Y. Z1'1 signifies the positive-sequence voltage produced in Circuit X when positive-sequence current flows in Circuit Y. Z00' signifies the zero-sequence voltage produced in Circuit X due to the zero-sequence current flow in Circuit Y.

Similar analogies could be applied to understand other terms in (6).

The positive- and negative-sequence currents are balanced in nature—with equal current magnitudes, and they are 120 degrees apart with the only difference being the opposite phase rotation. The instantaneous magnetic flux produced per phase is proportional to the instantaneous value of the current. The spatial direction of magnetic flux also directly relates to the electrical polarity of the instantaneous current. This means that the net magnetic flux (at a point far away from the three-phase circuit) produced by balanced I1 or I2 phase currents is going to be spatially balanced too. Fig. 3 portrays this electromagnetic coupling.

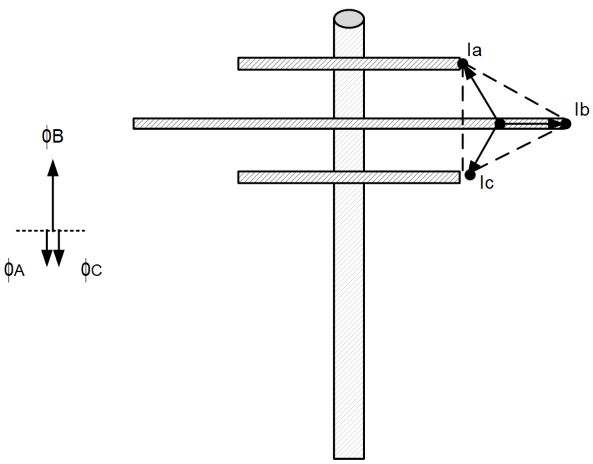

Fig. 3. Net magnetic flux due to balanced currents.

Now we will bring the second three-phase circuit into perspective as well. Since the distances between a conductor on the adjacent circuit (Y) and conductors of the X circuit carrying balanced current I1 or I2 are not the same, the net magnetic flux linking with Conductor Y will not be balanced. The net flux will not be high but will not be zero either.

Should the lines be transposed, the average distances between a conductor of the Y circuit and conductors of the X circuit will be the same; hence the net magnetic coupling over the whole length of the line will be zero. This is represented by all the zero terms in (7).

$$\begin{bmatrix} V0 \\ V1 \\ V2 \\ V0' \\ V1' \\ V2' \end{bmatrix} = \begin{bmatrix} Z0 & 0 & 0 & Z0m & 0 & 0 \\ 0 & Z1 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z2 & 0 & 0 & 0 \\ Z0m & 0 & 0 & Z0' & 0 & 0 \\ 0 & 0 & 0 & 0 & Z1' & 0 \\ 0 & 0 & 0 & 0 & 0 & Z2' \end{bmatrix} \bullet \begin{bmatrix} I0 \\ I1 \\ I2 \\ I0' \\ I1' \\ I2' \end{bmatrix} \quad (7)$$

The terms Z00' and Z0'0, simply referred to as Z0m, are not zero.

This is because, whether transposed or not, the net magnetic flux due to a zero-sequence current flow is spatially additive in nature. This signifies that whenever there is zero-sequence current flow on one circuit (such as faults involving ground), there will be zero-sequence voltage generated on the other circuit due to additive electromagnetic coupling of the I0 current.

The zero-sequence mutual coupling is represented by Z0m.I0m, where I0m is the zero-sequence current in the faulted line.

II. Modeling Mutually Coupled Lines and Simulation Results

To better understand the impacts of mutual coupling on distribution circuits, consider two examples: the first in which two distribution feeders are coupled with each other and the second in which a distribution feeder is coupled with a transmission circuit.

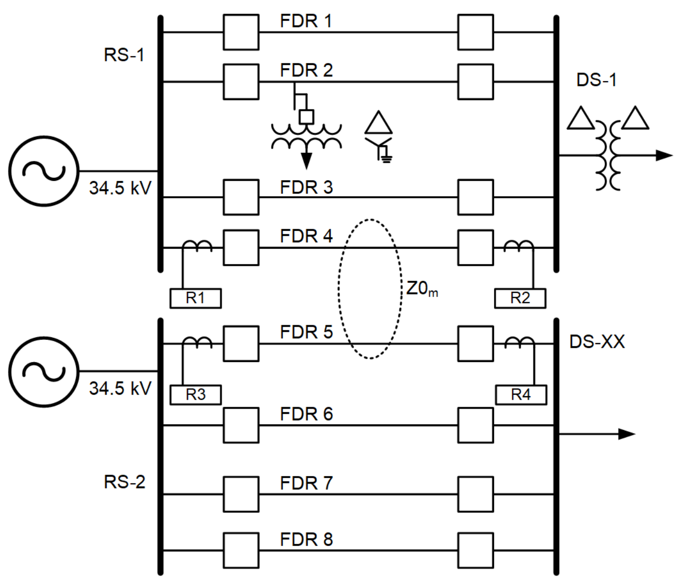

Fig. 4. Single-line diagram for Example 1.

Example 1 consists of two substations that feed eight 34.5 kV feeders, all 5 miles long, as shown in Fig. 4. The bus fault current at Receiving Station (RS) 1 and RS 2 buses is 4,200 A for a single-line-to-ground (SLG) fault at either bus. All feeders are modeled to be of the same conductor type (477 26/7 ACSR). The system under study does not use ground wires.

The ground fault current measured by Relay R1 at FDR 4 for faults at the end of the feeder is 1,030 A when the remote-end breaker is closed and 1,787 A when that breaker is open. The feeders are modeled such that FDR 4 and FDR 5 are mutually coupled as they share the same right of way. The spacing between these two is an average of 9 feet. To understand the impact of mutual coupling on this system, the length of mutual coupling between the feeders is varied while the same fault is simulated (at the end of FDR 5) to observe the induced ground current on FDR 4. The length of mutual coupling varies from 0 to 5 miles (the entire length of the feeders) in steps of 0.5 miles.

Fig. 5 shows the results from these simulations in a graphical format. Fig. 5a shows the absolute magnitude of the induced ground current on FDR 4 as the mutually coupled distance is varied from 0 to 5 miles. It is clear that as the mutually coupled length increases, the induced ground current also increases. Also, the magnitude of the induced current is higher when the remote end of FDR 5 is open. Fig. 5b shows the same information, but the induced ground current in FDR 4 is plotted as a ratio of the ground fault current at the end of the same feeder (FDR 4). Here, it is evident that the induced current can reach a value as high as 50 percent of the ground fault current on the same feeder.

Fig. 5a

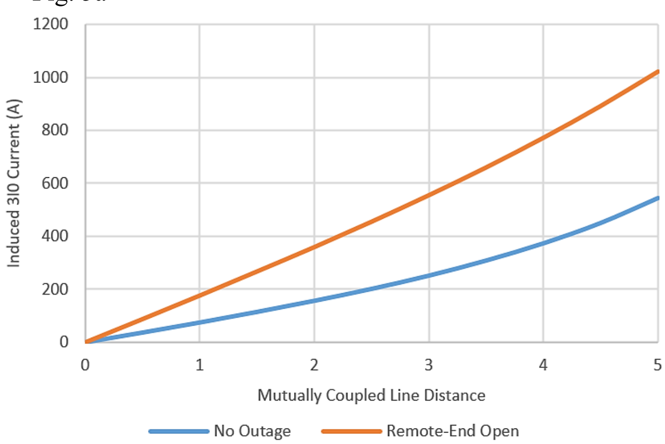

Fig. 5b

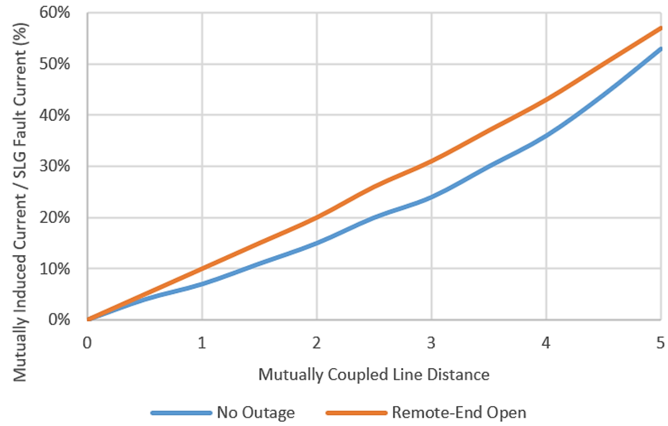

Fig. 5. Ground current is induced in FDR 5 due to mutual coupling with FDR 4.

In Example 2 (shown in Fig. 6), the interaction between a transmission and distribution circuit is considered. Once again, there are two substations; however, one is 115 kV while the other is 34.5 kV. The three 34.5 kV feeders are identical to Example 1. Each of the three 115 kV lines is 25 miles long and modeled to be of the same conductor type (1,351.5 54/19 ACSR). FDR 1 is modeled to be mutually coupled with Line 3. The two are 25 feet apart.

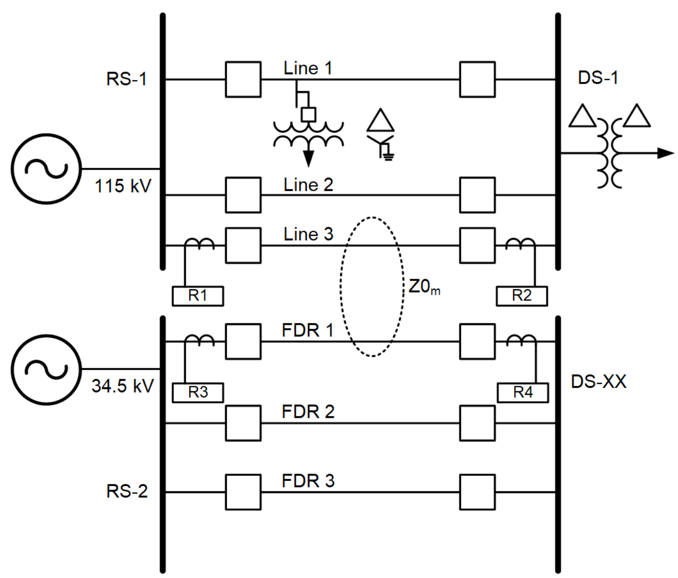

Fig. 6. Single-line diagram for Example 2.

The ground fault current contribution from the 34.5 kV bus is the same as Example 1 (4,200 A). For these simulations, the contribution from the 115 kV bus for a fault on Local Bus RS-1 is set at 2,000 A (based on a set source impedance). It is evident that the 115 kV source will have a higher fault duty (MVA value). As in the previous example, a remote-end fault is simulated at the end of Line 3 and the induced ground current on FDR 1 is plotted as a graph, shown in Fig. 7. Similar to the last example, the induced current increases with increasing mutual coupling.

Fig. 7a

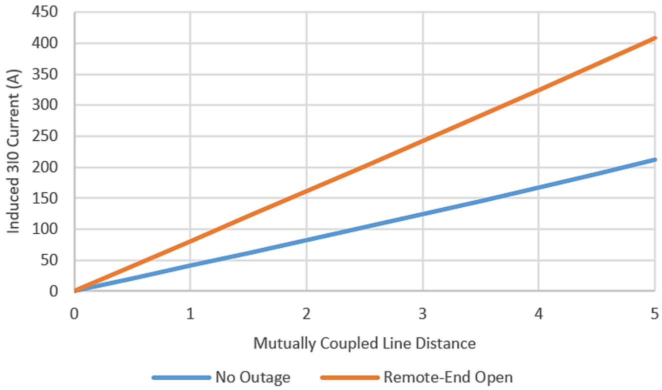

Fig. 7b

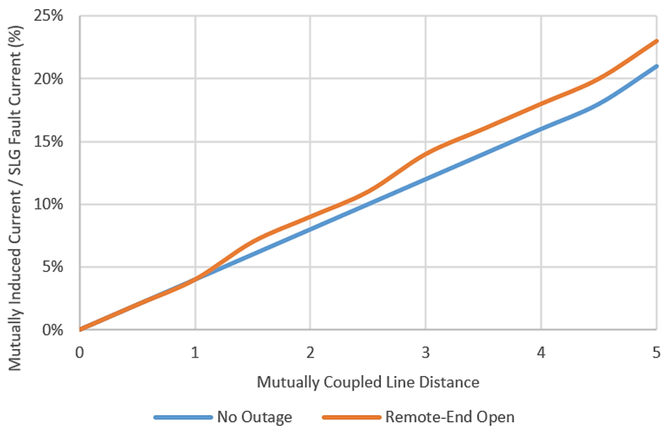

Fig. 7. Ground current is induced in Feeder 1 due to mutual coupling with Line 3.

Fig. 8a

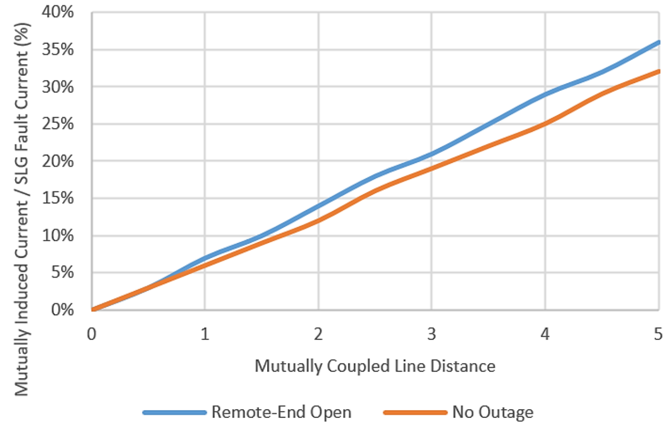

Fig. 8b

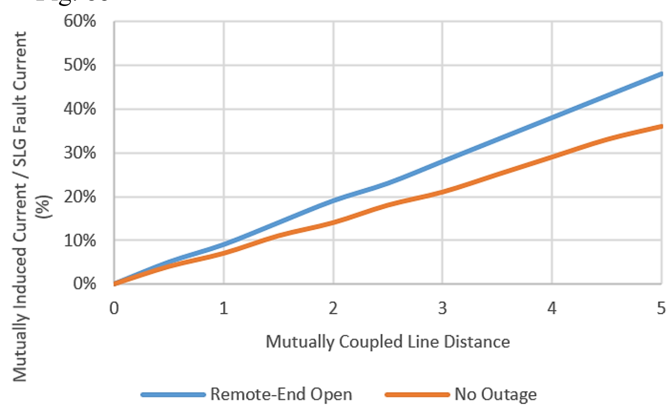

Fig. 8. Ground current is induced in Feeder 1 due to mutual coupling with Line 3 for a (a) 5000 A source and (b) 10,000 A source.

To study the impact of transmission system strength on the induced current on the distribution system, the simulations from Example 2 were repeated with stronger transmission sources. In Fig. 8a, the ratio between the induced current and the ground fault current for a remote bus fault is shown when the transmission source provides 5,000 A of ground fault current, while Fig. 8b shows the same simulation results repeated with a 10,000 A source. Both 5,000 A and 10,000 A were the fault currents obtained when simulated on the local bus (RS-1). Note that in both cases, there was no modification made to the strength of the distribution source. It is clear that the amount of induced current increases as the length of mutual coupling increases. It is evident that the stronger the source providing the fault current, the greater the current induced in the mutually coupled feeder. Vmutual is equal to Zmutual times Ifault. Vmutual is the source on the unfaulted circuit. Dividing Vmutual by Zcircuit equals Icircuit. Vmutual is greater if Zmutual is larger and/or the fault current is higher.

It is common to see transmission towers with underbuilt distribution wires. In these cases, depending on the length of the shared right of way, it may be essential to model the associated mutual coupling to ensure that protection settings are calculated appropriately. Failure to do so may result in an unnecessary operation of the ground fault protection elements on the mutually coupled distribution line for faults in the transmission system.

III. Protection Philosophy at the Utility

In subtransmission or distribution systems in general, it is common to encounter radial circuits where sources are not present on both ends of the line. In such cases, directional elements may not be utilized and protection often relies on nondirectional phase and ground instantaneous overcurrent (IOC) elements, as well as time-overcurrent elements. The implementation of distance protection or communications-assisted schemes, such as permissive overreaching transfer trip or permissive underreaching transfer trip, may not always be cost-effective for these circuits and, therefore, may not be deployed.

Most of the utility's subtransmission networks have relays with overcurrent and directional overcurrent protection. The philosophy is as follows:

- The subtransmission network is modeled such that the lines originate from the RS 34.5 kV bus (low side of the RS load transformer), which is modeled as the Thevenin equivalent generating source. The subtransmission line is then terminated at a distribution station (DS). The subtransmission relay at the RS terminal is set with overcurrent settings protection only since, during a line fault, the current leaves the RS 34.5 kV bus and DS lines do not feed back to the RS 34.5 kV bus.
- At the DS, the subtransmission lines are set with directional overcurrent relay settings since, during a line fault, the current can flow in either direction.
- At the RS, the subtransmission line phase overcurrent relay minimum trip setting is typically set at 2 times the emergency rating of the line. The time-overcurrent time dial index is selected based on a coordination time margin between 15 and 18 cycles. The neutral ground time overcurrent minimum trip is typically set at half the phase pickup or above the maximum expected unbalanced current.
- At the DS, the subtransmission line phase overcurrent relay minimum trip setting is typically set at 1.25 times the emergency rating of the line. The directional time-overcurrent time dial index is selected based on a coordination time margin between 15 and 18 cycles. The neutral ground time overcurrent minimum trip is typically set at half the phase pickup.

IV. Event Analysis

The utility serves a densely populated metropolitan area. To provide reliable power, they run many double-circuit lines—both at the transmission and subtransmission level (34.5 kV). Some time ago, there was a misoperation on one of their 34.5 kV double-circuit lines on their subtransmission network. This section describes the sequence of operation and actions to address these types of challenges. The settings for all four relays used in the case study for this paper are shown in Table I, and the single-line diagram is shown in Fig. 9.

TABLE I
IN-SERVICE RELAY SETTINGS

Settings	R1	R2	R3	R4
51N	1.5 A, U3, 6.4 TD	2 A, U3, 3.2 TD	1.25 A, U3, 5.8 TD	4 A, U3, 2 TD
51NTC	1	32NF	1	32NF
E32	N	AUTO	N	AUTO
E79	1	1	1	1
79OI1	600 cyc	600 cyc	600 cyc	600 cyc
50N	OFF	OFF	OFF	OFF

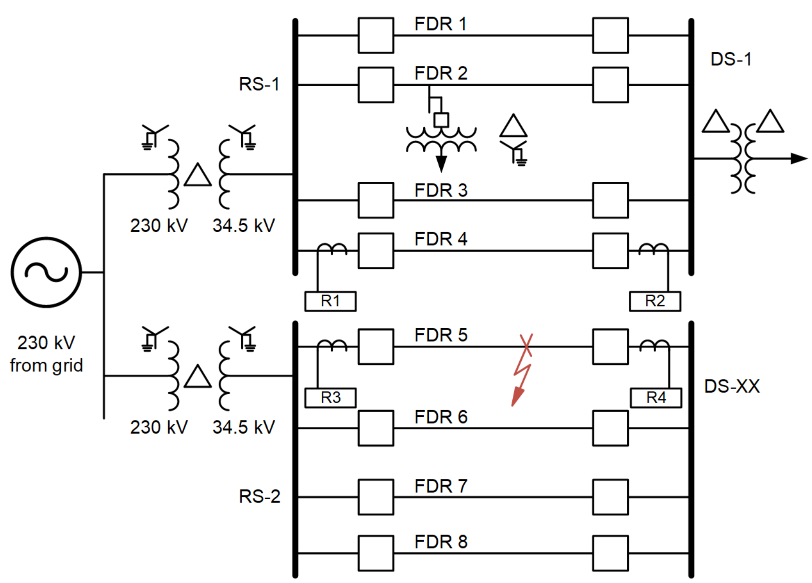

Fig. 9. Single-line diagram for the event analysis.

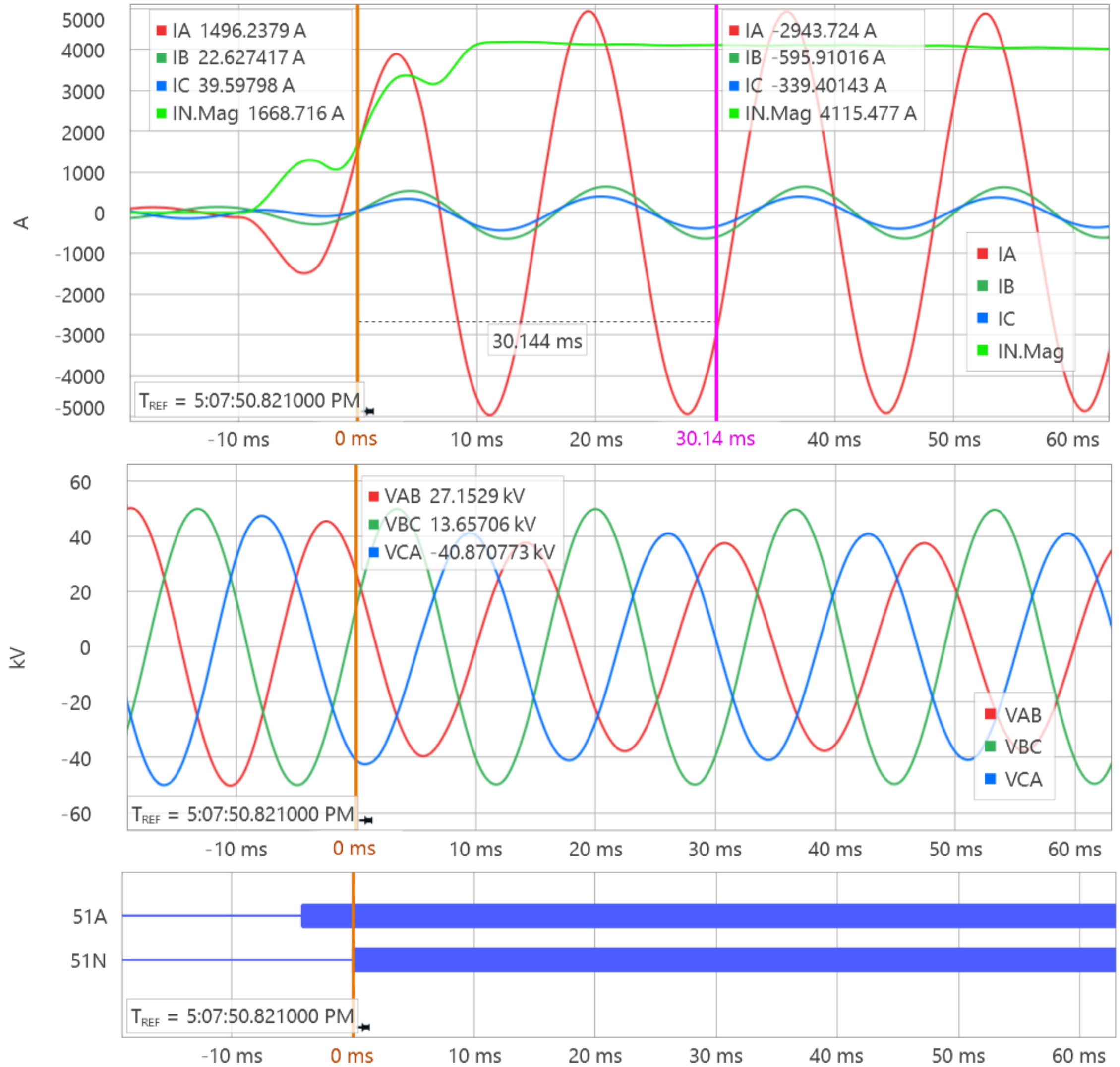

Fig. 10. Event recording at R3 at the start of the fault current.

The sequence of operation for the event is as follows.

1. At 5:07:50.815 p.m., an AG fault occurred on FDR 5. It was proven to be a fault because of a substantial increase in solely A-phase current and a drop in in VAB and VCA voltages. Potential transformers (PTs) were connected in an open-delta configuration. Fig. 10 shows the waveforms captured from Relay R3.

Neutral-time overcurrent (ANSI: 51N) and phase-time overcurrent (ANSI: 51P) were programmed under trip logic. Both 51P and 51N triggered for this fault and started to time toward trip. The relay R4 saw the same fault and started to time out on its 51N element. The fault current magnitude recorded by R3 was around 4,015 A primary, whereas it was about 2,950 A primary at R4.

Right after the fault, both relays R1 and R2 saw high ground current, but the voltages remained steady. This is because the voltage drop is pure zero sequence and an open-delta PT cannot measure 3V0. This change in current was due to the mutual coupling between FDR 5 and FDR 4. Fig. 11 shows that the relay R2 saw around 1,500 A primary of neutral current and its 51N picked up. The trip logic was set to (51AT + 51BT + 51CT + 51NT), which was basically set for phase or neutral time-overcurrent elements. The 51N element was supervised by the directional bit 32NF, which did assert, indicating a forward fault for R2. 32NF was driven by the negative-sequence voltage-polarized directional element (32Q). Further description of the directional element is explained in the next section. 51N on Relay R1 was nondirectional and it picked up as well.

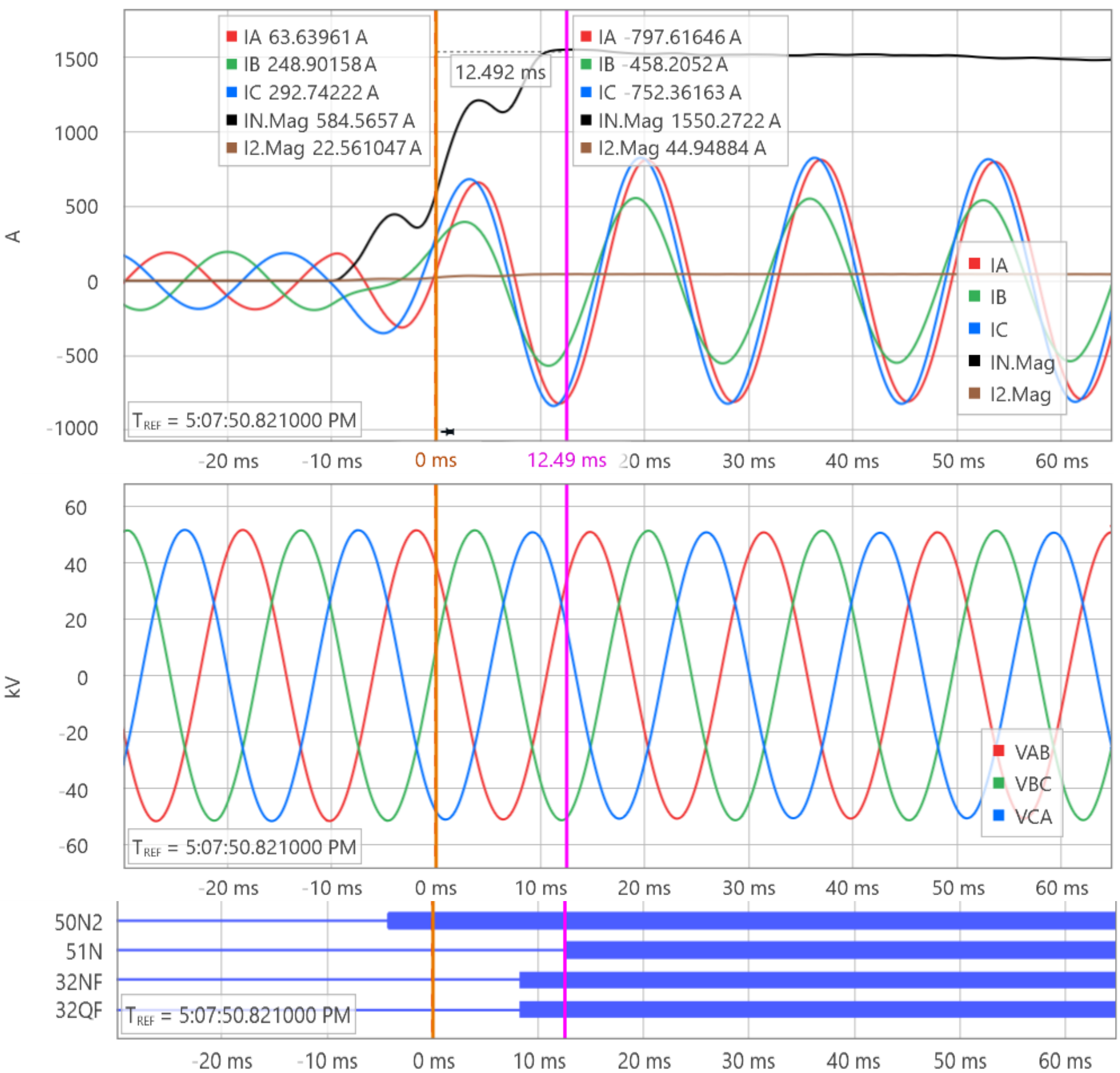

Fig. 11. Event recording at R2 at the start of the fault current.

Based on the time-overcurrent settings, R4 tripped open before R3 at 5:07:51.286 p.m. No communications-assisted trip schemes were enabled.

2. Right after R4 tripped open Breaker 4, the ground current seen by R3 increased to about 4,830 A primary. At the same time, R2 also observed an increased ground current of 1,969 A, as illustrated in Fig. 12. This is due to the fact that the effect of mutual coupling was highest when remote-end Breaker 4 opened and FDR 5 had an existing SLG fault. Soon after, R3 timed out on 51N and tripped. The time difference between the Breaker 4 open and Breaker 3 open was about 16 cycles. This time difference is shown between the red dashed line and magenta solid line in Fig. 12. This operation completely isolated FDR 5 and, therefore, the mutually coupled current disappeared. The mutually coupled line now sees only the load current.

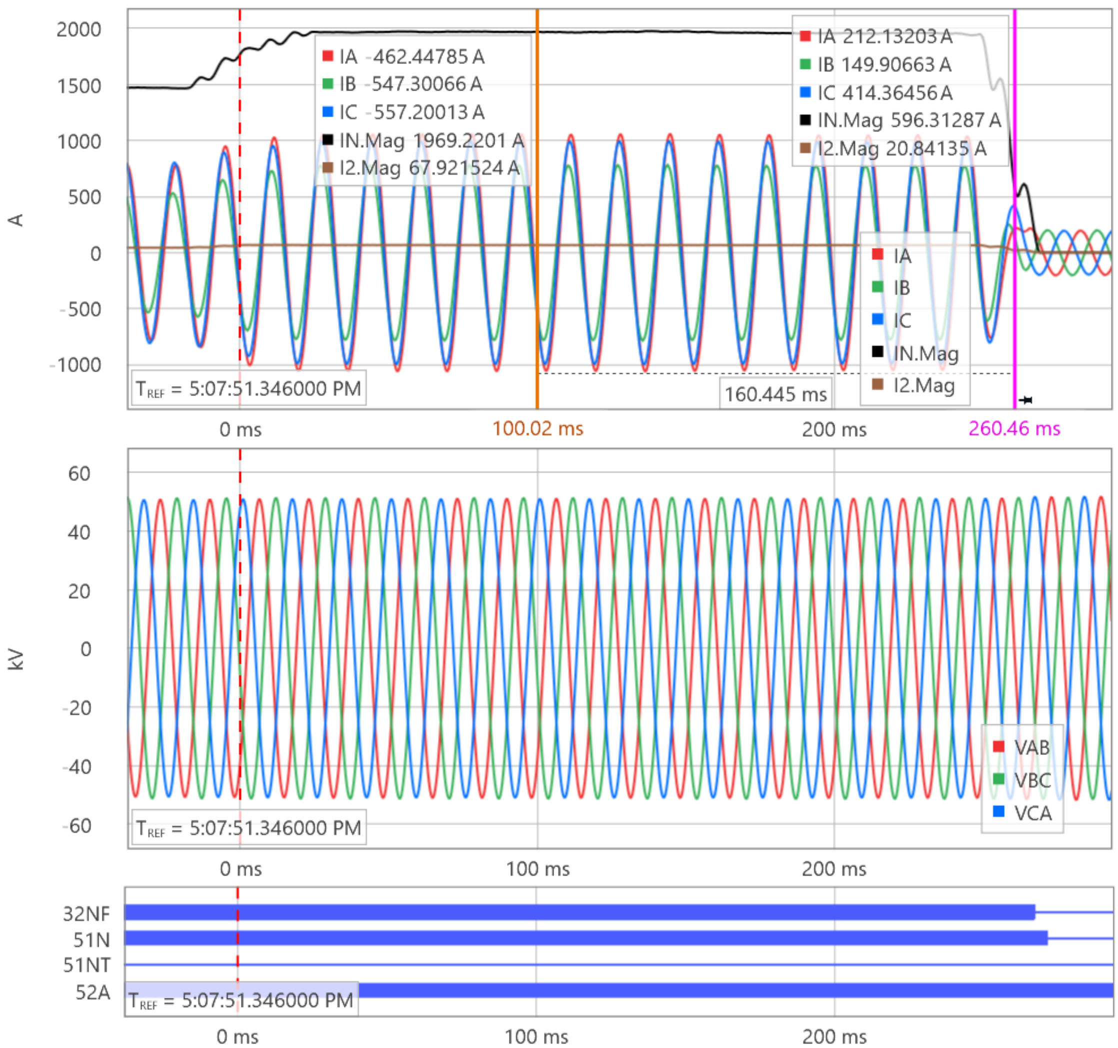

Fig. 12. Event recording at R2 when Breaker 4 opened.

3. Autoreclosing was enabled and programmed to one shot to lock out on all four relays. The open interval timer was set to 10 seconds. R3 sent the close command at 5:08:02.478 p.m. The close command initialization was not seen in the event report because the length of the event was not long enough. It was confirmed using the sequential event recorder data from R3. The ground current seen by R3 following the Breaker 3 close was around 4,825 A primary, as shown in Fig. 13. At the same time, R1 and R2 saw about 1,965 A primary, as illustrated in Fig. 14.

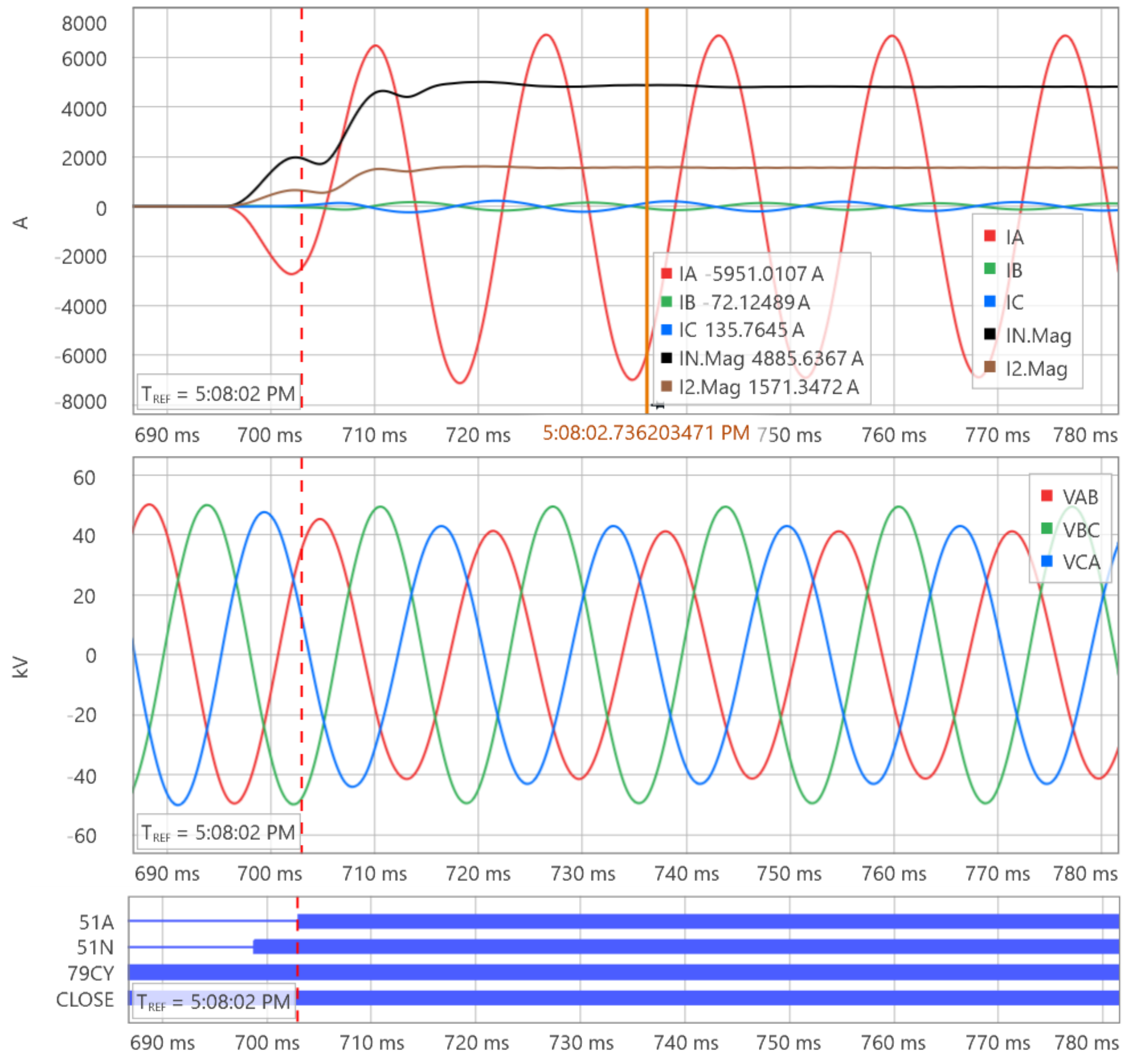

Fig. 13. Event recording at R3 when Breaker 3 reclosed.

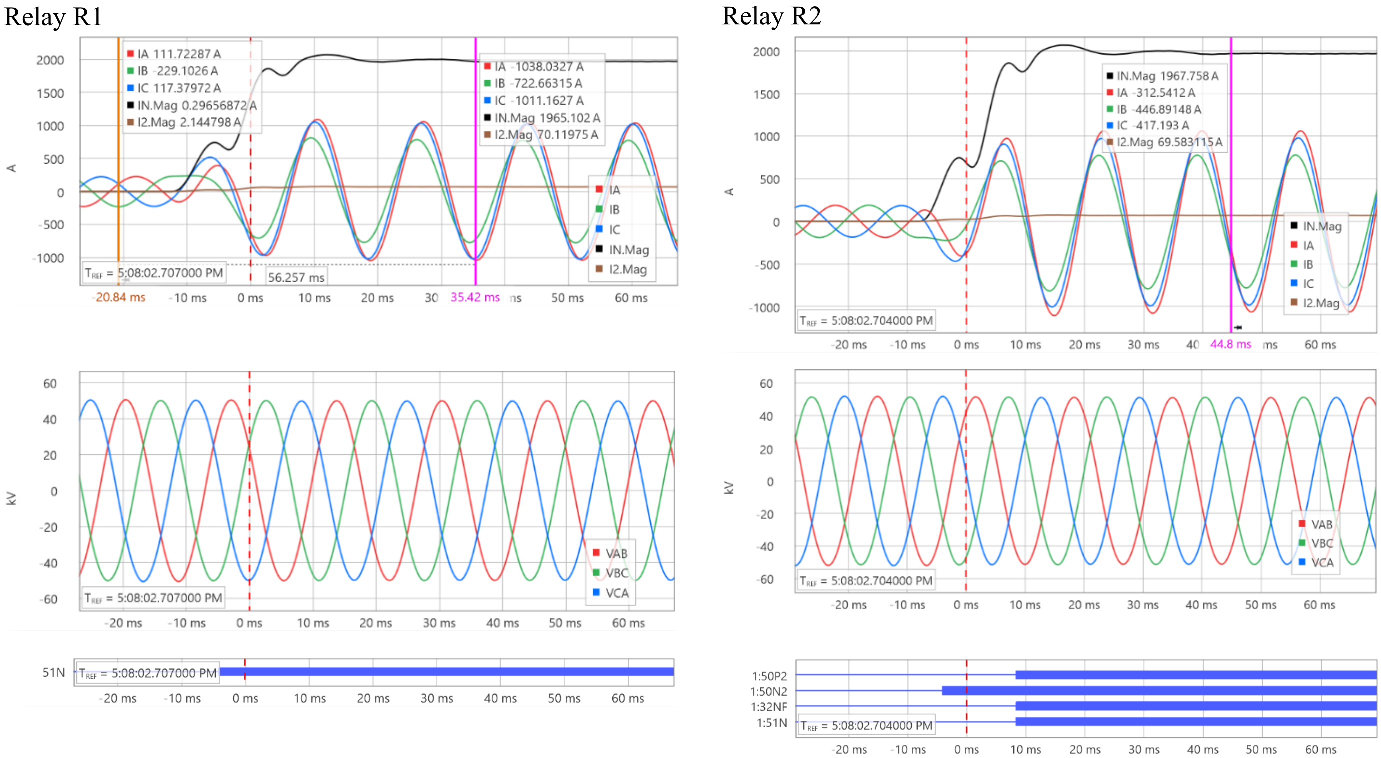

Fig. 14. Event recording at R1 and R2 when Breaker 3 reclosed.

4. At 5:08:03.33 p.m., R3 tripped again because it was a permanent fault. Based on the 51N settings, R3 was supposed to trip in around 0.64 s, and it operated correctly on 51NT. R2 also timed out on 51N and tripped on 51NT for the first time at 5:08:03.354 p.m., as shown in Fig. 15. R1 did not trip because R2 won in the race condition and cleared the currents by operating first.

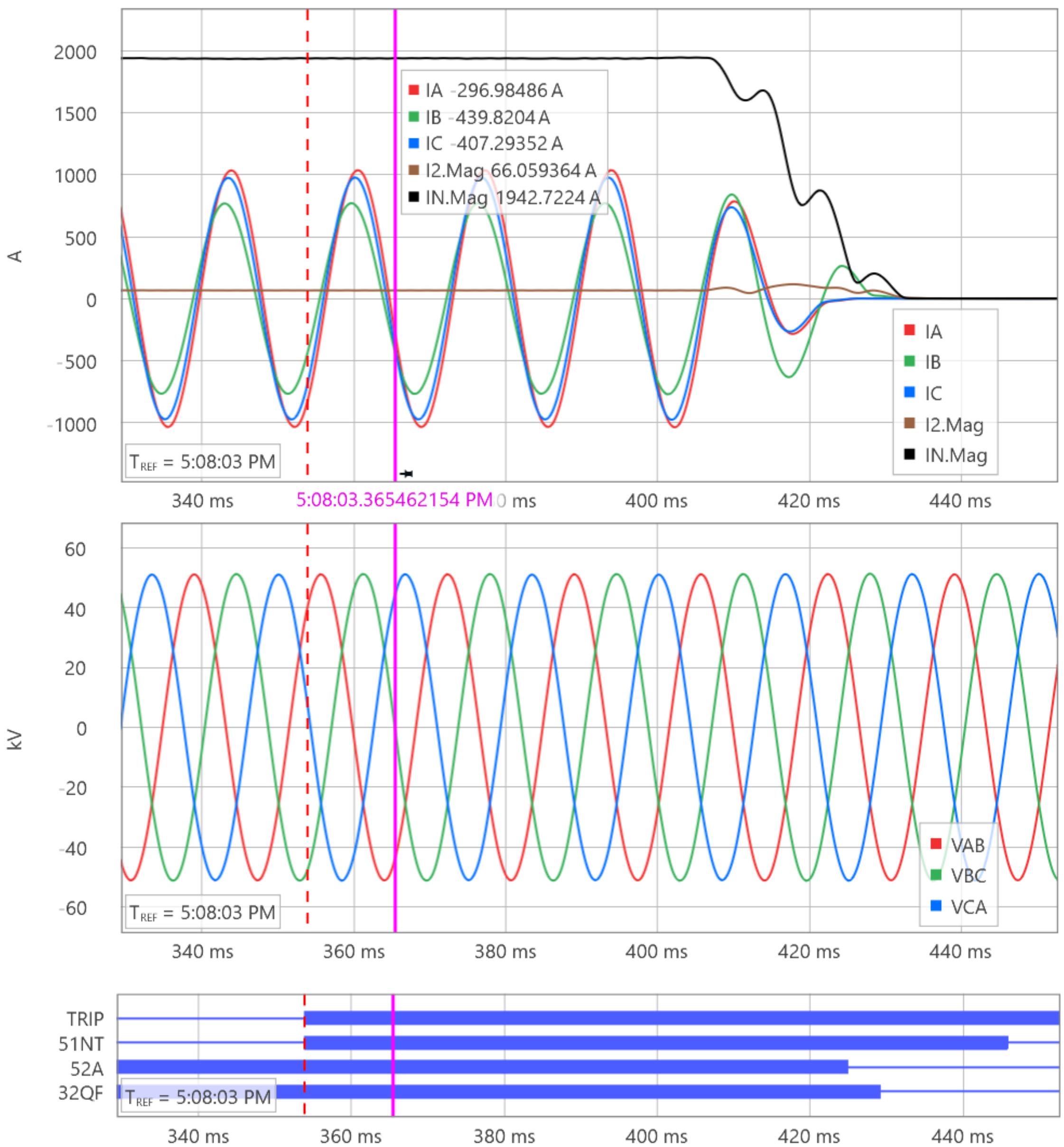

Fig. 15. Event recording at R2 when it tripped.

V. Effect of Directionality

Mutual coupling between power systems compromises the reliability of zero-sequence voltage-polarized directional elements. A ground fault on one system induces zero-sequence currents and voltages in the other, potentially triggering relays on the healthy system. This issue affects both traditional torque-based zero-sequence voltage-polarized (T32V) and zero-sequence impedance-based directional relays (32Z). This paper focuses exclusively on 32Z.

In the conditions that have an electrical connection between the mutually coupled lines, the apparent zero-sequence impedance calculated by relays on the unfaulted line decreases as the fault approaches the remote end due to the zero-sequence mutual impedance [6]. Typically, forward and reverse thresholds for zero-sequence impedance-based elements are set based on the line impedance. Normally, if there is a strong source behind, the forward and reverse thresholds (Z0F and Z0R) for zero-sequence impedance-based elements are set to positive and to about half the zero-sequence line impedance magnitude. With mutual coupling, the zero-sequence apparent impedance changes and can lead to lower positive values. This can lead to forward declaration by the directional element and can operate supervised ground overcurrent elements if the zero-sequence current is high enough.

Depending on the system configuration and switching scenarios, it can be challenging to choose suitable forward (Z0F) and reverse (Z0R) thresholds. In contrast, negative-sequence directional elements are immune to mutual coupling effects, making them a preferred choice for ground fault detection.

Negative-sequence impedance-based directional elements (32QZ) provide distinct advantages over conventional negative-sequence voltage-polarized elements (T32Q) [7] and therefore are popularly applied in various systems across the world.

By utilizing calculated negative-sequence voltage and current, impedance-based elements determine the magnitude of negative-sequence impedance. For forward faults, the relay calculates an impedance equal to –ZS2 (the negative-sequence source impedance behind the relay), independent of fault location. For reverse faults, the calculated impedance equals ZL2 + ZR2 (the sum of the negative-sequence line impedance and remote source impedance), also independent of fault location. By comparing these calculated impedances to predefined thresholds Z2F (forward) and Z2R (reverse), the impedance-based directional element reliably determines fault direction with enhanced sensitivity and accuracy. This works for all fault types except three-phase faults. Modern relays have different ways to manage that, and it is outside the scope of this paper.

Unlike traditional T32Q elements, the impedance elements do require a few settings. For ease of use, automatic settings, as an option, had been developed in the past by the relay manufacturer. There are two different Z2F and Z2R set points automatically set if E32 is equal to AUTO or AUTO2. Considerations for which one to prefer over the other for specific use cases are explained well in [7]. For ground directional elements, the user also has the flexibility to choose available polarizing quantities with a priority order. It enhances the functionality of the directional element when certain polarizing quantities are measured at low levels. The selection is based on the priority of available and reliable polarizing quantities. The setting that governs this is called ORDER.

Some other settings that are set automatically when E32 is equal to AUTO or AUTO2:

- 50QFP (3I2 value): This is the pickup for the forward fault detector and is ideally set above normal load unbalance and below the expected negative-sequence current magnitude for unbalanced forward faults.
- 50QRP: Similar to the forward fault detector threshold, this is the pickup for the reverse fault detector and is set above normal unbalance and below the expected negative-sequence current magnitude for unbalanced reverse faults.
- A2 (positive-sequence current restraint factor): This I2/I1 factor increases the security of the directional element. It restrains the element from operating for negative-sequence currents that may occur because of line asymmetries and for cases like CT saturation during three-phase faults. The default for the automatic setting is set at 0.1. As per this set point, directional elements are enabled only if the negative-sequence current (I2) magnitude is greater than 1/10th of the positive-sequence current (I1) magnitude.
- K2 (zero-sequence restraint factor): This I2/I0 factor is applied to internally enable the negative-sequence ground directional impedance element. This negative-sequence current (I2) magnitude must be greater than the zero-sequence current (I0) magnitude multiplied by this factor to internally enable this element. This check ensures that the relay uses the most robust analog quantities to make directional decisions. This factor comes into play only when zero-sequence-based and neutral-current-based directional elements are internally enabled.

VI. Mitigation Strategies Via Protection Settings for Mutually Coupled Lines in Subtransmission Systems

A. Ground Directional Priority and Preference

As previously discussed, the impedance-based 32Q (32QZ) method is generally preferred for determining fault directionality in mutually coupled lines. In the relay used for our case study, the ORDER setting is set to Q. There are scenarios where negative-sequence directional elements may lack sufficient polarizing quantities to operate correctly for faults within their own line section.

To address such dependability challenges, ORDER = QV can be explored. However, zero-sequence-based directional elements (“V” in the ORDER setting) need to be examined carefully by studying the impact on mutually coupled lines [6].

B. Positive-Sequence Current Restraint Factor A2

The utility example described in the paper used the E32 = AUTO setting, which is biased toward dependability. Based on this setting, Z2F and Z2R are automatically set per the entered negative-sequence line impedance magnitude (same as positive-sequence line impedance for lines). Z2F is set to one-half of the protected line impedance and Z2R is set a bit higher, typically by 0.1 or 0.2 ohms secondary. The idea with this concept is that the relay does not know anything about source impedances at the local and remote ends. These guidelines consider the boundary condition of having an infinite bus (source impedance equals 0). They cannot be smaller than that. Even in the absence of $3V_2$, the scheme does get enabled and operate if enough $3I_2$ is available. In our example, Z2F is +0.46 ohms and Z2R is +0.66 ohms. To understand the event further, the Z2 characteristic from R2 was plotted for the duration of the fault, as shown in Fig. 16. Z2RTLIM and Z2FTLIM are scaled limits to Z2F and Z2R. Z2LIM shows the scaled limit of actual Z2 calculated by the relay R2. Z2 seen by the relay is –0.65 ohms and, therefore, the relay declared forward and operated the 51NT element.

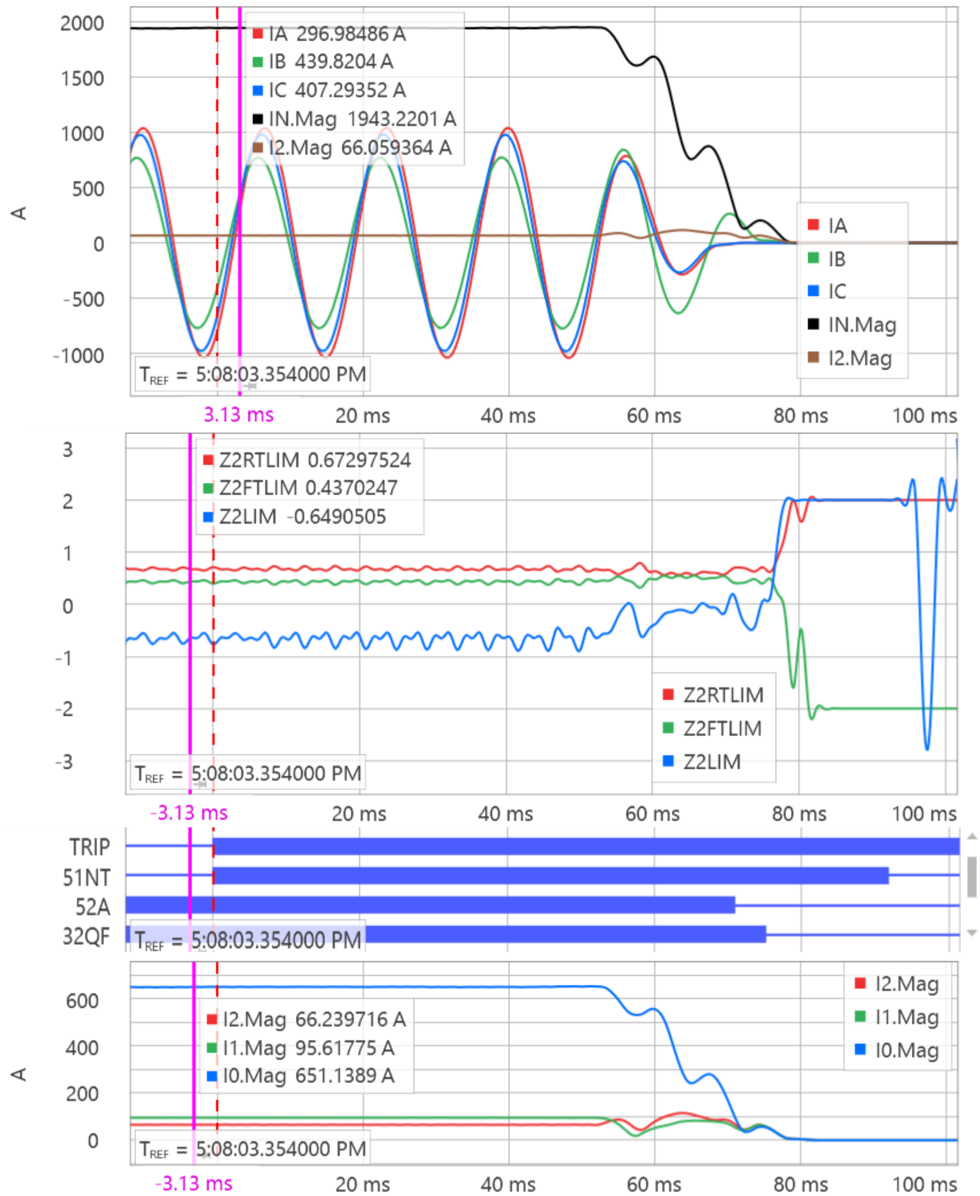

Fig. 16. Z2 impedance plot seen by Relay R2.

That is where the A2 factor comes in. As per the logic shown in Fig. 17, if A2 > I2_magnitude / I1_magnitude seen by the relay during the fault, then 32QGE will not assert and directionality will be defeated for neutral and residual-ground overcurrent elements. Fig. 16 shows that I2.Mag is 66 A and I1.Mag is 95 A. The ratio comes out to be 0.69. A2 in the case study shown in this paper was set at a default value of 0.1, and therefore it qualified the enable logic. One might think that with some margin, setting A2 to 0.75 could be a solution. This will not compromise dependability for LL and SLG faults. Ignoring the effect of load current for simplicity in this explanation, I2 is –I1 for LL faults, meaning the magnitude ratio will be 1. For SLG faults on a radial system, I2 is equal to I1 and that results in a ratio of 1. However, for LLG faults, a high A2 value could sacrifice dependability. If Z1 equals Z2 equals Z0, then I2 equals 0.5 times I1, which results in A2 equaling 0.5. So, A2 equals 0.5 is the highest value that can be set to have dependability for all fault types.

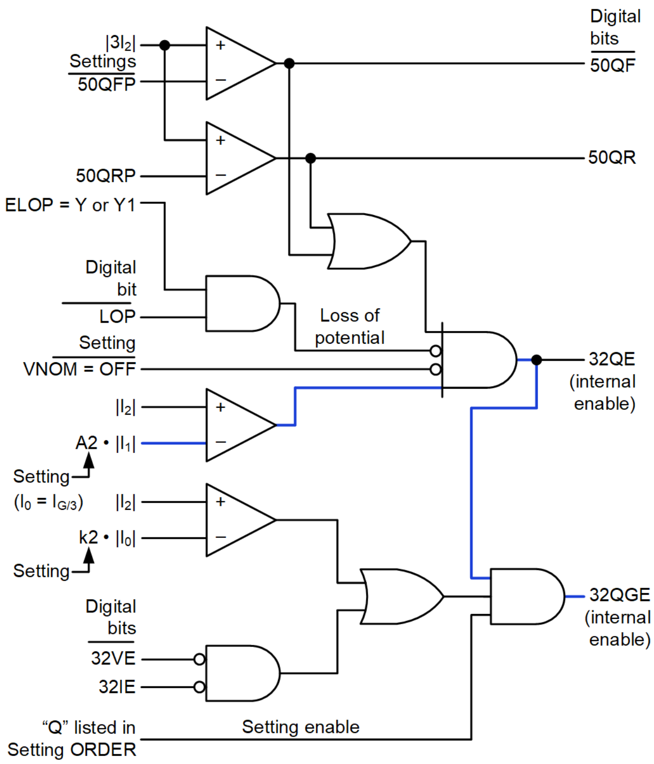

Fig. 17. Directional enable logic for negative-sequence voltage-polarized element.

C. Ground Overcurrent Pickups

The utility in this paper did not employ ground IOC elements (50N) but it is not uncommon to see this element applied on long lines. This element is used to provide protection for most of the line length without risking tripping on external ground faults. However, for mutually coupled lines, it is crucial for the settings engineer to simulate remote-end faults—specifically those occurring just before the remote breaker when it is open on an adjacent line. Due to mutual coupling, the resulting ground current on the unfaulted line section may vary significantly based on the system configuration or worst-case conditions triggered by switching sequences. While increasing the pickup setting enhances security by reducing the likelihood of misoperation, it also decreases the fault coverage of the ground IOC element. This tradeoff is often acceptable since time-delayed ground overcurrent elements can provide the necessary backup protection. The utility in this paper does not use 50N elements.

In isolated bus systems on both ends of the line, where there is no electrical connection between mutually coupled lines, a practical approach involves logically supervising 50N1T with 50Q1T in the trip logic. Since 50Q1 (negative-sequence overcurrent) will not pick up due to low negative-sequence currents in such scenarios, this logic prevents assertion while maintaining the original sensitivity of 50N1. This method avoids sacrificing sensitivity while ensuring security [8].

In areas requiring higher service reliability, looped systems are often employed at subtransmission levels. For example, in the utility case described in the Event Analysis section of this paper, the 50N element was disabled and 51N was supervised with a forward negative-sequence directional element (32QF). Adjusting the pickup setting of 51N is one potential solution; however, it requires careful consideration to balance sensitivity for ground faults on its own line while maintaining coordination. The appropriate pickup value should be determined based on the system configuration—whether it involves a common bus at both ends of the line, an isolated bus, or a common bus only at one end—and any worst-case conditions due to operational switching. The magnitude of induced zero-sequence current due to mutual coupling can vary significantly across these scenarios. Relevant discussions can be found in [5] and [6]. Additionally, these settings should be revisited whenever source impedances change due to new source additions. For mutually coupled lines, simulating worst-case mutual coupling conditions is critical.

Similar to the earlier discussion on 50N elements, supervising 51N with 50Q could also be considered in isolated bus systems. With low negative-sequence current on mutually coupled lines during faults in such configurations, this approach enhances security without compromising sensitivity.

D. Fault Detector Pickups (50QFP and 50QRP)

As seen in Fig. 17, both 50QFP and 50QRP are also inputs to the directional enable logic. If these fault detectors are set a bit higher, they can also block the directional element. I2.Mag seen by the relay as per Fig. 16 is 66 A primary and CTR = 160 results in 3 • 66 / 160 = 1.2375 A secondary. With some margin, if 50QFP was set at 1.3 A, the problem could have been solved. The short-circuit study from the utility showed that this set point was dependable for unbalanced forward faults.

VII. Conclusion

The impact of mutual coupling on protection is well known in high-voltage transmission systems. Most utilities model the system and design relay settings, taking the impact into consideration. Considering the effect in subtransmission systems is often ignored. This case study corroborated the need to model mutual coupling even for those systems. The general observation is that one should not ignore mutual coupling if lines or overhead feeders share the same right of way and are in proximity for more than 10 percent of the line length.

It is also well known that 32Q is a superior ground directional element to choose to avoid misoperations due to mutual coupling effects. However, we learned through our case study that the element has some limitations. Altering the directional enable logic of 32Q can help with security improvements.

The utility plans to apply higher 50QFP and increased 51N pickup on their system to be more secure in the future. Additionally, their corrective action plan involves the usage of geographic information system maps to identify the affected lines or overhead feeders that might be at risk due to mutual coupling.

VIII. Acknowledgments

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X. Biographies

Cleofas Rojas, PE, received a Bachelor of Science in Electrical Engineering from California State University, Los Angeles, in 1992. Cleofas is a registered professional engineer in the state of California and is a member of IEEE. Cleofas joined Los Angeles Department of Water and Power in 2001. From 2001 to 2007, he was a commissioning engineer for subtransmission and distribution protection systems. From 2008 to 2023, he was a relay protection engineer in the System Protection and Controls group, where he performed short-circuit studies, relay settings calculations, and fault analysis for transmission, generation, subtransmission, and distribution protection systems, as well as evaluated and oversaw NERC/FERC/Western Electricity Coordination Council (WECC) Protection & Controls (PRC) standards for regulatory compliance. From 2019 to 2023, he was a member of the WECC Relay Work Group. From April 2023 to August 2024, he served as a project manager in the Power Capital Projects and Facilities Engineering Division. Currently, he serves as the supervisor for the System Protection and Controls group.

Aadityaa Padmanabhan got his Bachelor of Engineering in Electrical and Electronics Engineering from Anna University, Chennai, India, in 2010 and his Master of Science in Electrical Engineering from North Carolina State University in 2012. Upon graduating in 2012, he worked for over nine years at Schweitzer Engineering Laboratories, Inc. (SEL) in their Engineering Services division as a project engineer involved in the design, development, and commissioning of protection systems. He is presently a technical leader at Electric Power Research Institute (EPRI) within their Distribution Operation and Planning research area focusing on distribution protection.

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