Detection and Isolation of Broken Conductors in Power Distribution Systems: A Key Wildfire Mitigation and Public Safety Strategy

Tanushri Doshi, Rohit Sharma, and Anthony Rahiminejad
Schweitzer Engineering Laboratories, Inc.

Charlie Cerezo
San Diego Gas & Electric

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DETECTION AND ISOLATION OF BROKEN CONDUCTORS IN POWER DISTRIBUTION SYSTEMS: A KEY WILDFIRE MITIGATION AND PUBLIC SAFETY STRATEGY

Tanushri Doshi, PE
Senior Member, IEEE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163 USA
tanushri_doshi@selinc.com

Rohit Sharma
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163 USA
rohit_sharma@selinc.com

Anthony Rahiminejad, PE
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court
Pullman, WA 99163 USA
anthony_rahiminejad@selinc.com

Charlie Cerezo, PE
San Diego Gas & Electric
8330 Century Park Court
San Diego, CA 92123 USA
ccerezo@sdge.com

Abstract – Successfully detecting high-impedance faults due to downed or broken power distribution conductors in a timely manner has been a big challenge for decades. When an energized broken conductor makes contact with the ground, it may result in a high-impedance fault that may be a challenge to detect using traditional protection methods. This paper provides a review of the existing solutions to detect downed conductors that have made contact with the ground. It is important to highlight that these solutions detect and isolate the affected circuit section only after the energized conductor has been on the ground for several seconds or minutes. This creates a critical "race-against-time" scenario, posing wildfire risks and public safety hazards.

This paper dives deeper into an innovative method that was developed and successfully implemented on 12 kV distribution circuits to detect and isolate broken conductors while they are in the air and before they touch the ground. The IEC 61850 Generic Object-Oriented Substation Event and IEEE Std. C37.118 synchrophasor-based falling conductor protection solution is designed to detect and isolate broken conductors well within 500 ms of the break. This protection-speed solution is applicable to three-phase circuits along with two-phase and single-phase laterals that may be in high fire risk areas. This paper further explores the implementation of the falling conductor protection solution using Ethernet radios, and direct fiber, as well as private long-term evolution communication networks, which form the backbone of the falling conductor protection solution.

Index Terms — Downed Conductor, Wildfire Mitigation, High-Impedance Fault, Broken Conductor, Synchrophasor, Generic Object-Oriented Substation Event, Real-Time Digital Simulator, Hardware-in-the-Loop.

I. INTRODUCTION

Several geographical areas have been increasingly threatened in recent years by wildfires due to climate change and drought. Not only are these wildfires more frequent, but they are also more catastrophic and ever expanding into wider geographical areas [1]. There are typically certain times of the year or seasons when there are elevated fire risks due to dry areas or high-speed winds. Recent trends have shown that these fire risks can be all year long. There are various causes of wildfires, whether natural or man-made (including resulting from human negligence). Between 2016 and 2020, 19 percent of the wildfires in California were caused by the electrical power network [1]. The area burned was approximately 643,000 acres [1]. Power conductors can ignite wildfires in various ways, most of which can be prevented by the appropriate mitigation technique. Some of the common ways power conductors can ignite wildfires are vegetation contact, conductor slap, repetitive faults, and downed power conductors [2].

This paper focuses on the downed or broken distribution conductors as a cause of wildfires and as a public safety hazard. There are various causes for broken conductors including lightning, vegetation, car collision with a distribution pole, strong winds, aging equipment, and vandalism. A broken and energized overhead power distribution conductor, on the ground, often creates a high-impedance fault (HIF), releasing energy in the form of an arc. These broken and energized conductors lying on the ground can pose a major safety hazard to the public or ignite a wildfire. The HIF caused by downed conductors generates very low fault currents, which may be a challenge to detect using traditional system protection. The ground fault current magnitudes can vary anywhere from milliamperes to less than 100 amperes, depending upon whether the system is ungrounded or multigrounded and the conductivity of the surface [3].

This paper includes a review of several methods developed to detect broken conductors or HIFs caused by downed conductors. However, it is noteworthy that the traditional HIF detection methods detect the broken conductor after the energized conductor has been in contact with the ground and may take several seconds to minutes in order to isolate the fault. This condition presents wildfire risks and public safety hazards, as shown by the dramatic arcing in Figure 1.

Figure 1 HIF Caused Due to a Downed Conductor

This paper dives deeper into a novel solution developed using the IEEE C37.118 Synchrophasor and IEC 61850 Generic Object-Oriented Substation Event (GOOSE) protocols to detect and isolate falling conductors within milliseconds of the break, while they are still in the air and before they touch the ground, thereby mitigating wildfire risks as well as public safety hazards. Since 2021, a high-speed and low-latency communications-based falling conductor protection (FCP) solution has been successfully implemented on seven 12 kV three-phase radial distribution circuits. The solution has been implemented using Ethernet radios, as well as a private long-term evolution (pLTE) network [4]. Before large-scale field deployment, the FCP solution was validated using a real-time digital simulator with hardware-in-the-loop (HIL) capability in a controlled laboratory environment.

The term broken conductors is used in this paper to signify a physical break in one or more conductors, which may or may not result in one or both ends making contact with the ground. The term downed conductors is used to signify an energized conductor that has contacted the ground or object connected to the ground without a physical break [5]. The term falling conductor is used to define a break in the conductor before the conductor touches the ground. There are various causes of HIFs, including, downed or broken conductors, dirty insulators, and overgrown vegetation brushing overhead distribution conductors. Throughout this paper, the authors are referring to HIF events caused by either broken or downed conductors.

II. REVIEW OF EXISTING DOWNED AND BROKEN CONDUCTOR DETECTION METHODS

A. *Sensitive Ground Overcurrent Element*

A ground overcurrent element is typically set sensitive by utilities on distribution feeders to detect single-line-to-ground faults. The ground fault current can either be calculated using the summation of the three-phase currents or measured using core-balance CTs on the residual circuit. The ground current magnitude provides an indication of a ground fault, which can potentially be caused by a HIF event from a broken or downed conductor. As discussed previously, the fault currents during a HIF event caused by a downed or broken conductor may be very low in primary magnitude, ranging from a few milliamperes to several amperes, therefore making the detection of a HIF event by a sensitive ground overcurrent element unreliable.

Several single-phase-to-ground loads can cause a significant system unbalance in multigrounded distribution circuits. Dynamic changes to single-phase-to-ground loads may cause an unbalance large enough to inadvertently trip the sensitive ground overcurrent element in the feeder relay. Setting the sensitive ground overcurrent element to be sensitive and secure at the same time is an art. The pickup of the sensitive ground overcurrent element is limited by the system unbalance as it may create nuisance tripping when the system is highly unbalanced. Therefore, the pickup set point of the sensitive ground overcurrent element is set as a percentage of the feeder loading and with a margin to compensate for the maximum system unbalance. The dynamic and unpredictable nature of single-phase loading makes the sensitive ground overcurrent element unreliable for detection of HIF events [6], which may be caused by downed or broken conductors.

B. *Harmonics and Interharmonics Signature Detection Method*

It is a challenge to detect all HIFs using a substation relay because of the low fault current signature that is typical to these faults. The magnitude of the current that is produced by a HIF due to a broken or downed conductor will depend largely on the conductivity of the surface in contact with the conductor. This solution increases the probability of detecting these HIFs by using either harmonic or interharmonic signatures in the fault current due to the nonlinear nature of the arc [6] [7]. Depending on the ground surface with which the downed or the broken conductor is in contact, the content of these harmonic and interharmonic signatures vary in the fault current. However, harmonic content is also generated by any nonlinear loads on the system such as electric arc furnaces, rail trains, and motor variable frequency drives. Therefore, adaptive tuning features are included in this algorithm to make it secure.

The objective behind this detection method included in [6] and [7] is to detect and provide protection against HIFs as much as possible. This solution, shown in Figure 2, is an advanced algorithm that is divided into four building blocks, explained as follows:

- Sum of difference currents (SDIs): This is the informative quantity that represents the HIF signatures while staying immune to loads and other power system conditions. SDI is the operating quantity for this solution and monitors the interharmonic content in each of the measured phase currents.
- Infinite impulse response (IIR): An IIR limiting average uses the SDI to form a stable pre-fault reference.
- Adaptive tuning: Along with the IIR limiting average, the adaptive tuning stage monitors the background noise on the feeder and establishes the threshold for the trending and memory block in the decision logic.
- Decision logic: The decision logic consists of the trending and memory block, which compares the real-time SDI with a stable reference from the IIR and sets the time and ratio for the tuning stage. The decision logic uses the threshold set by the trending and memory stage to detect the HIF signature in the fault current.

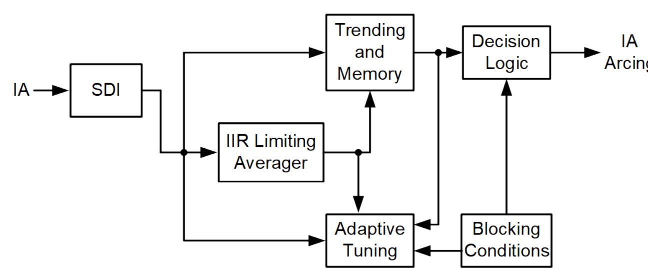

Figure 2 Block Diagram for HIF Detection Using Harmonics and Interharmonics Signature; IA is the Operating Current of A-Phase

The algorithm is blocked when the system experiences a large phase current and significant voltage swing as these are not HIF signatures but may represent short-circuit faults. The algorithm detects and monitors events in all three phases simultaneously, using these as a blocking condition based on the assumption that all three phases are highly unlikely to be involved in HIF events.

This HIF detection method has proven effective at detecting the arcing signature associated with HIFs in several of the staged downed conductor tests and in real-world applications. When the downed conductor makes contact with certain surface types, it results in little to no arcing and is challenging to detect. It is important to note that not all HIFs are the result of broken or downed conductors. This HIF detection method alone is not able to discriminate between HIFs that are caused by broken or downed conductors and those caused by other sources.

HIF detection using this method is improved by applying it in the recloser controllers throughout the distribution network because the attenuation of the high-frequency fault signatures can make them challenging to detect using devices that are located farther away from the fault. A distributed detection solution can also improve selectivity by allowing the closest HIF detection device to isolate the fault, instead of de-energizing the entire feeder and taking a large number of customers out of service. In cases where multiple devices can see the same HIF, a race condition may exist unless additional considerations are made to coordinate their response.

C. Supervisory Control and Data Acquisition (SCADA) Integration Along With Dedicated HIF Solutions

With communications networks becoming more robust in the distribution system, SCADA systems can be leveraged by integrating them along with dedicated HIF detection solutions to detect and isolate HIF events caused by broken or downed conductors [5]. This is especially helpful in applications with dynamic system conditions. The dedicated HIF solutions that are programmed within a recloser controller are used to detect HIF events and send that signal to a centralized controller or the SCADA system. Additional power system monitoring devices can be installed on laterals to detect changes in load current. The data from these additional monitoring devices as well as the recloser controller can be accumulated in a centralized controller or the SCADA system for decision making. Qualifying the HIF detection from the recloser controller using these additional load current monitoring devices provides additional security and helps with accurate location of the faulted section.

When the conductor breaks, there is a reduction in the load current depending on where the break has occurred. If the break is in one of the laterals, it may not significantly affect the loading at the feeder breaker. A sudden loss of load in one or more phases seen by a current measuring device located at a lateral along with an upstream recloser controller, provides a high degree of confidence that there is a downed or broken conductor in the lateral. SCADA operators can take quick action to isolate the affected circuit, or automatic actions can be programmed into the centralized controller. There may be challenges detecting HIF events on lightly loaded laterals.

D. Artificial Neural Network (ANN) and Decision Tree

ANN and decision tree methods are based on developing an ANN or decision tree model and training on the data set for cost-effective function. These models learn the patterns of the HIF signature in the fault current. Once trained on the data set, the models are then tested using the test data set to analyze the performance of the ANN model or the decision tree. These models are trained on various data sets including normal operating conditions of the power system, switching conditions, abnormal loading conditions, fault conditions, different loading, and combination of one or more of these conditions. This training enables the model to differentiate the signature of the HIF conditions from other power system events [8] [9].

Both of these methods not only require a large amount of data to accurately train the models for HIF detection but also may not prove cost-effective.

E. Current-Based Methods

The current-based method uses a complex ratio between the zero-sequence, positive-sequence and negative-sequence current quantities [10] and uses local measurements to detect broken conductors before they touch the ground. This method uses local current measurement by the relay for detection. However, system unbalance, loss of load, and load rejection may introduce security concerns. The dependability of this method relies on the feeder load characteristic and can be improved by applying it at multiple locations throughout the distribution system. However, the dependability of this method should be weighed against the potential security concerns for each location.

F. Impedance-Based Methods

The impedance-based methods are based on the concept that when a conductor breaks, the load impedance can change significantly as compared to the conductor prebreak condition [11]. The impedance change ratio (ICR) is the ratio of the difference in the calculated impedance and the conductor prebreak impedance. The ICR is compared against a user-settable threshold to declare a broken conductor using high-speed communications protocols. This method requires significant load flow studies to determine the impedance threshold for each circuit. Therefore, the universal set points cannot be implemented. Furthermore, adding coverage to lightly loaded circuits may present a challenge. A phasor measurement unit (PMU) placement study based on the load flow studies is required if additional PMUs are to be added to the laterals to increase coverage. The algorithm may not be able to differentiate between single-phase load trips and broken conductor conditions for heavily loaded circuits [11].

III. FCP SOLUTION

A. FCP Design Overview

This section dives deeper into the novel voltage-based FCP scheme using GOOSE and synchrophasor protocols. For a typical distribution pole that is 30 ft tall, it takes about 1.37 s for a broken conductor to touch the ground after the break. The FCP algorithm is designed to operate well within 500 ms of the break, ensuring that the conductor is de-energized before it touches the ground. Figure 3 shows the communications architecture necessary to implement the high-speed and low-latency requirements for this solution. The existing system protection intelligent electronic devices (IEDs) are placed throughout the radial distribution circuit, including the feeder IEDs, which also function as PMUs to extend the coverage of FCP. These PMUs stream high-accuracy, time-stamped synchrophasor data, including phasors, analogs, and digitals to a central automation controller in the substation. This automation controller also functions as a phasor data concentrator and time-aligns the incoming synchrophasor data in a real-time environment. The automation controller is embedded with the FCP library, which analyzes the synchrophasor data and makes the decision to declare a broken conductor in a specific part of the circuit.

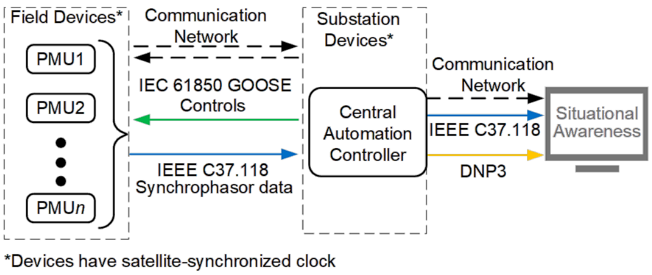

Figure 3 Communications Protocol Architecture for FCP

Once a broken conductor condition is declared by the automation controller, high-speed GOOSE trip commands are sent out to the PMUs or IEDs to open the associated breakers or reclosers. Automatic reclosing is blocked on receiving an FCP trip from the automation controller. The FCP algorithm offers selectivity by leveraging the existing IEDs or PMUs along the feeder laterals. This helps with coverage in the high-risk fire area laterals and, at the same time, only circuit sections that are affected by the broken conductor are taken out of service, whereas the rest of the circuit remains in service. This is achieved by defining different zones of FCP schemes determined by the PMU placement along the circuit.

B. *Detection Methods*

The voltage-based FCP solution uses five methods to detect the falling conductor event in the system. They are as follows:

- Rate-of-change of per-phase voltage (dV/dt)
- Negative-sequence voltage magnitude (V2Mag)
- Negative-sequence voltage angle (V2Ang)
- Zero-sequence voltage magnitude (V0Mag)
- Zero-sequence voltage angle (V0Ang)

1) Rate-of-change of per-phase voltage (dV/dt) method: The dV/dt calculated for all the PMUs participating in FCP in a distribution circuit is evaluated by the automation controller in real time. In a radial system, when a phase conductor breaks, the rate-of-change of phase voltage on either side of the break is opposite in polarity. The PMU upstream of the break experiences an increase in the phase voltage since it loses the downstream load, while the PMU downstream of the break experiences a sag in voltage after the conductor break. The voltage measured by the upstream PMU stabilizes close to nominal while the voltage measured by the downstream PMU eventually decays to zero after the conductor has broken. If the magnitude of the rate-of-change of phase voltage is greater than the user-defined threshold, a broken or falling conductor condition is declared by the automation controller for that phase. The dV/dT condition is supervised by a rate-of-change of zero-sequence voltage with respect to time (dV0/dt) to make the algorithm secure against power system voltage transients.

2) Negative-sequence voltage magnitude method and zero-sequence voltage magnitude method: The negative-sequence (V2) and zero-sequence (V0) voltage magnitudes calculated for all the PMUs participating in FCP in a distribution circuit are evaluated by the automation controller in real time. During a conductor break, the PMU downstream of the break observes a steep increase in V2 and V0 magnitudes, as compared to the PMU upstream of the break. Equation (1) is used to calculate the symmetrical components of voltages considering ABC phase rotation [12].

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_i = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix}_i \quad (1)$$

where:

V_0 is the zero-sequence component voltage vector of i^{th} PMU; i = 1 to n.
V_1 is the positive-sequence component voltage vector of i^{th} PMU; i = 1 to n.
V_2 is the negative-sequence component voltage vector of i^{th} PMU; i = 1 to n.
V_A is the A-phase voltage vector of i^{th} PMU; i = 1 to n.
V_B is the B-phase voltage vector of i^{th} PMU; i = 1 to n.
V_C is the C-phase voltage vector of i^{th} PMU; i = 1 to n.

Figure 4 represents a simplified radial distribution system where power is fed from the source on the left-hand side as shown. The feeder breaker, controlled by the feeder IED, which also acts as a PMU (shown as PMU1), the recloser controller (shown as PMU2), and the line monitor (shown as PMU3) are all located along the lateral.

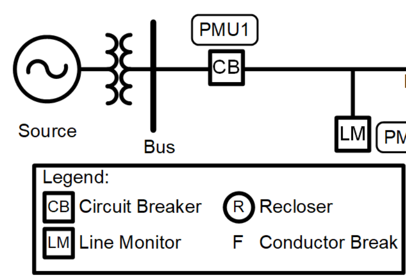

Figure 4 Example Three-Phase Distribution System

Consider an A-phase conductor break at Location F; using (1), the voltage symmetrical component for Recloser R can be calculated as follows:

$$V_{0_{(R)}} = \frac{1}{3}\left(V_{B_{(R)}} + V_{C_{(R)}}\right) \quad (2)$$

$$V_{1_{(R)}} = \frac{1}{3}\left(\alpha V_{B_{(R)}} + \alpha^2 V_{C_{(R)}}\right) \quad (3)$$

$$V_{2_{(R)}} = \frac{1}{3}\left(\alpha^2 V_{B_{(R)}} + \alpha V_{C_{(R)}}\right) \quad (4)$$

If the calculated V2 and V0 magnitudes are greater than the user-settable threshold and they qualify the timing to override any voltage transients, the automation controller declares a falling or broken conductor and the GOOSE trip commands are issued to isolate the affected section of the circuit.

3) Negative-sequence voltage angle method and zero-sequence voltage angle method: V2 angle and V0 angle methods use the principle that during a conductor break, the V2 angles and V0 angles seen by the PMUs on the opposite sides of the break align with each other. The PMUs upstream of the break aligns their V2 angle and V0 angle with a margin of error, and the PMUs downstream of the break follow the same pattern. A phase angle difference can be calculated between these two groups of PMUs; if this phase difference is greater than a user-settable threshold, then a falling or broken conductor condition is declared. For the reliability of the calculated sequence angles, a minimum sequence-voltage magnitude is necessary for the supervision.

These five voltage-based methods can be used in a voting scheme to determine the falling conductor condition in a distribution system. The voting scheme may be set to 5/5, which implies that all five methods need to be asserted to issue the GOOSE trip command. The voting scheme setting is user-settable and can be adjusted to provide a high degree of dependability and security.

C. FCP Detection in Single- or Two-Phase Lateral

Equation (1) shows that all three-phase voltages are required to calculate the symmetrical components of the voltage. So, for the single-phase or two-phase laterals, there will be a high-standing zero-sequence and negative-sequence voltage, which make it impossible to use symmetrical components to detect a falling conductor. But with enhancement to the algorithm based on the system configuration, these five methods can be used to detect a falling conductor for the single-phase and two-phase systems [13].

The utilities take various measures to regulate the system voltage along a distribution feeder. Therefore, the voltage drop between subsequent measuring points does not typically differ by a large percentage under normal system conditions. This understanding can be used to enhance the FCP algorithm to calculate the symmetrical components of the voltage for the missing phase on the system.

Figure 5 represents a three-phase feeder circuit that branches into a two-phase lateral with A-phase and B-phase. C-phase is missing on the lateral between the recloser (R) and the line monitor (LM). The algorithm is adapted such that it calculates the symmetrical components of voltage for the source side of the recloser, as all three phases are available. For the load side of the recloser and the LM, the algorithm references to the C-phase voltage of the source side of the recloser and then calculates the symmetrical component of voltage for the load side of the recloser and the LM. This is shown in Equation (5) using the LM as an example. For a falling conductor in the circuit section between the recloser and the LM, like in Figure 5, calculated sequence components are used along with the dV/dt method to declare a falling conductor. The recloser trips and de-energizes the affected section, whereas the circuit section above the recloser remains in service, thereby providing selectivity.

The concept of extending the sequence-based methods to two-phase laterals can be applied to single-phase laterals as well. The two missing phase voltages can be referenced to the voltages of the upstream device, as shown in Figure 6. The load side of the recloser and LM2 is missing the B-phase and C-phase voltages. Symmetrical components for these two can be calculated using the source side B-phase and C-phase voltage values of the recloser control. Therefore, a falling conductor in the zone between the recloser and LM2 can be accurately detected by the algorithm.

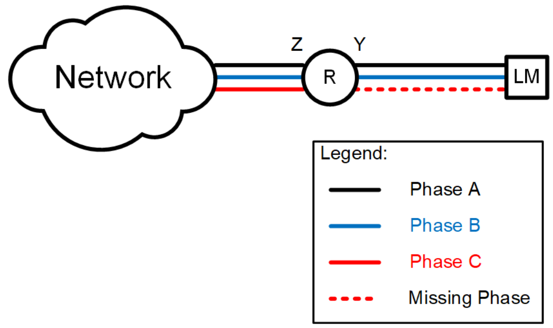

Figure 5 Two-Phase Lateral

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_{LM} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_{A_{LM}} \\ V_{B_{LM}} \\ V_{C_R} \end{bmatrix} \quad (5)$$

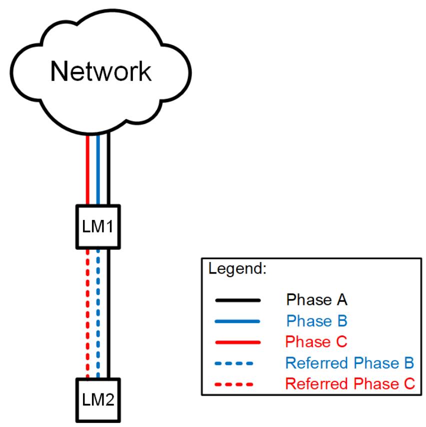

Figure 6 Single-Phase Lateral

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix}_{LM2} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_{A_{LM2}} \\ V_{B_{LM1}} \\ V_{C_{LM1}} \end{bmatrix} \quad (6)$$

D. Communications Network Protocol

In this centralized, wide-area FCP scheme, the communications network and protocols play a vital role. To de-energize the affected section of the network before the broken conductor touches the ground, detection of the falling conductor needs to happen at protection speeds. The IEEE C37.118 Synchrophasor Protocol and IEC 61850 GOOSE protocol are used to perform the high-speed detection and isolation operation.

1) IEEE C37.118 Synchrophasor Protocol: The IEEE C37.118 Synchrophasor Protocol is increasingly used not only in wide-area monitoring systems but also in protection and control applications. The Synchrophasor Protocol transmits current and voltage phasors along with digitals and analogs in real time with high accuracy over a wide area [14]. Synchronized data with high accuracy of time helps in processing the incoming data from various PMUs over a wide geographical area. The demodulated IRIG-B000 format provides the time source accuracy of ±10 µs for high-accuracy measurements.

2) IEC 61850 GOOSE protocol: IEC 61850 GOOSE is an Ethernet-based protection-speed protocol that utilizes a publish-subscribe communications model for high-speed communications. Once the algorithm detects the falling conductor condition using the IEEE C37.118 synchrophasor data, the affected section needs to be de-energized before it can hit the ground. For this reason, Ethernet-based protection-speed IEC 61850 GOOSE protocol is used. Distribution networks may already have an Ethernet-based communications network available for SCADA protocols like Distributed Network Protocol (DNP3) and Modbus. However, SCADA protocols typically only require communication latencies ranging from seconds to minutes while IEC 61850 GOOSE protocol requires communication latencies measured in milliseconds. In cases where low-latency communications, such as Ethernet radios, direct fiber, or pLTE, are already in use, IEC 61850 GOOSE communications for FCP can be more easily integrated in the existing communications network.

With the IEEE C37.118 and the IEC 61850 GOOSE protocols, the FCP algorithm is capable of detecting and isolating falling conductors well within 500 ms [4] after the conductor break, which is fast enough to prevent a public safety hazard by de-energizing the broken conductor before it touches the ground.

IV. REAL-TIME DIGITAL SIMULATOR AND HIL TESTING

The real-time digital simulator with HIL capability was leveraged to test the FCP solution in a laboratory environment. The real-time digital simulator runs electromagnetic transient (EMT) simulations of the power system in real time. The distribution circuit was modeled including distribution line parameters, breakers, reclosers, fuses, and PMUs along with the conductor break to mimic real-world scenarios in a draft environment. Physical equipment, such as IEDs or PMUs and automation controllers, was included in the test rack to perform closed-loop testing with the simulated distribution network. A high-accuracy IRIG signal is provided to the real-time digital simulator network for time-aligned data [4] [12] [13]. The real-time digital simulator environment was set up to support IEEE C37.118 and IEC 61850 GOOSE protocols for the simulated PMUs. The testing included the following scenarios [4]:

- Simulating falling conductors at various locations on the distribution circuit.
- Performing maintenance tests with loss of communications or one or more PMUs out of service.
- Conducting approximately 200 automated tests for average trip timing calculation.
- Running contingency tests to validate the security of the FCP algorithm, such as power system faults, bad voltage sensors, blown fuses, external voltage disturbances, manual or automatic closing and opening of breakers, and device power cycling.

Thorough testing of the proposed FCP algorithm in a controlled laboratory environment allowed for shorter commissioning times onsite and prevented the need for extended system outages. Scenarios that are challenging or impossible to simulate in the field were easily tested in the laboratory environment to cover corner cases. Onsite testing and commissioning further validated the FCP algorithm.

V. FIELD IMPLEMENTATION

As of the writing of this paper, the FCP solution has been successfully implemented on seven distribution circuits, utilizing a mix of Ethernet radios and pLTE networks. Onsite commissioning is followed by a wide-area synchrophasor-based monitoring system that provides real-time data and the falling conductor location down to a single zone of protection. This allows the operations team to locate the broken conductor and dispatch the crew to the accurate location instead of patrolling the circuit for long hours. The field results have been very promising, and the authors are actively engaged in ongoing projects to implement FCP on more circuits. The authors continue to learn from field experience and adapt and enhance the FCP algorithm, validated by the real-time digital simulator testing, as needed. Detailed test results are included in [4] and [12].

VI. CONCLUSION

Downed or broken energized conductors on the ground and the associated HIFs pose significant wildfire risks, especially in dry vegetation areas, and they pose a public safety hazard. This paper reviews the solutions and methods available to detect a HIF condition caused by a downed or broken conductor. These special algorithms are based on ground fault current magnitudes, harmonics and interharmonics in fault currents, SCADA integration, ANN, and decision tree.

This paper dives deeper into the wide-area FCP solution based on IEEE C37.118 and IEC 61850 GOOSE protocols to detect and isolate falling conductors in midair before they touch the ground. The detection and isolation are within 500 ms of the break, which ensures that when the conductor touches the ground, it is de-energized, thereby mitigating the wildfire risk and also preventing a public safety hazard. The FCP solution is applicable to three-phase circuits as well as circuits with two-phase and single-phase laterals that may be in high fire threat areas. Broken or downed conductors are low probability but high-risk events that require dedicated algorithms for detection and isolation by leveraging the existing IEDs or PMUs in the distribution circuit. The FCP solution applies to radial circuits as of the writing of this paper and only operates if there is a physical break in the conductor.

It is important to note that there is no single protection and control scheme that operates for all possible scenarios. The FCP method can be added to existing system protection or advanced HIF detection methods such as the harmonic- and nonharmonic-based solution to provide as much coverage as possible and to avoid blind spots. It is paramount to have a layered approach to system protection by using multiple solutions in parallel to increase dependability and security.

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IX. VITAE

Tanushri Doshi received her MS degree in electrical engineering from Arizona State University and her BTech in electrical engineering from the Visvesvaraya National Institute of Technology, Nagpur. Tanushri joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2011 as an associate protection engineer. Presently, she is working as an engineering manager for the protection group in the SEL Engineering Services, Inc., division. Tanushri has experience in power system protection design, relay settings, wildfire mitigation solutions, synchrophasors, commissioning, and testing. She has designed and implemented protection and control schemes with hardware-in-the-loop testing using a real-time digital simulator. She is a registered professional engineer (PE) in the state of Arizona and a senior IEEE member.

Rohit Sharma is a project engineer in the protection group in the SEL Engineering Services, Inc., division of Schweitzer Engineering Laboratories, Inc. (SEL). He joined SEL in 2021. He has experience in power system modeling, hardware-in-the-loop testing using real-time digital simulators, power system protection design, event analysis, and relay settings. He earned his MS degree in electric power system engineering from North Carolina State University in 2020 and a BSEE degree from Sardar Patel College of Engineering in Mumbai, India, in 2017.

Anthony Rahiminejad graduated with a BSEE degree from North Carolina State University and is a registered professional engineer in the state of North Carolina. Anthony is an application engineer who joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2015 as an industrial solutions engineer. He has since held roles as an application engineer, sales engineer, and most recently, a lead product sales manager in Research and Development, supporting wireless sensors and fire mitigation solutions. Prior to joining SEL, he held a position as a senior power system engineer for Eaton Engineering Services.

Charlie Cerezo graduated with a Bachelor of Science in electrical engineering from California State Polytechnic University, Pomona and is a licensed professional engineer in the state of California. He is a system protection and controls engineer with San Diego Gas & Electric Company (SDG&E). Presently, he is one of the project engineers for the SDG&E Advanced Protection Program (APP), which develops and implements advanced protection technologies within electric substations and on electric distribution systems.

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