Comparative Analysis of the Distribution Lines Falling Conductor Protection Methods

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Abstract

A broken power-line conductor on the ground can ignite the vegetation underneath the line and poses a great danger and safety problem for people, livestock, and property. The ideal solution is to detect the falling conductor and de-energize the conductor before it reaches the ground. Recently, this challenge has been heavily investigated and, in some regions, government agencies have introduced incentives to their utilities for developing solutions for falling conductor protection (FCP). The efforts for detecting a broken conductor before the conductor touches the ground have led to multiple electronic techniques that can be classified as current-based, voltage-based, and impedance-based methods. Each of these methods has its own merits and challenges that make these applicable on certain distribution feeders and challenging to apply on others. Impedance-based algorithms take advantage of both current and voltage measurements at multiple locations along the feeder. A real-time controller calculates the impedance change ratio (ICR) for each measurement point and detects a broken-conductor condition if the calculated ICR reaches a setpoint.

This paper evaluates the effectiveness of existing FCP algorithms for broken-conductor detection in different scenarios including the existence of distributed energy resources (DERs) on distribution feeders, the coordination requirements, and the impact of transformer configurations on the algorithm. Moreover, the paper presents the results for impedance-based, high-speed, falling-conductor protection (HFCP) in a utility feeder. The test results are obtained using Real-Time Digital Simulator (RTDS) and a real-time controller, evaluating the performance of the impedance-based HFCP algorithm with DER presence on distribution feeders and with different configurations.

I. Introduction

A broken conductor can occur anywhere along a power-distribution system. The cause can be severe weather, natural disaster, hardware failure and utility-pole collapse and are not detected by conventional protection methods. Conventional line protection detects large, short-circuit, overcurrent faults to prevent equipment damage. Reclosers and sectionalizers isolate and minimize damage in the faulted zone while continuing service to unaffected circuits. Conventional protection methods do not detect a broken conductor because there are very small fault currents from the large impedance to a line touching the ground; these small currents do not activate conventional protection. High-impedance-fault (HIF or Hi-Z) detection methods have been applied to detect a downed conductor, but the effectiveness of these methods is compromised for complex distribution networks [1]. This is especially problematic in power systems with distributed energy resources (DERs). It is important to detect and disconnect the line quickly because a downed conductor produces arcing, which can ignite the vegetation under the line and cause wildfires.

II. Falling-Conductor Methods

Traditional, electrical, falling-conductor protection methods are current based, or voltage based. These methods in distribution systems use negative-sequence current to positive-sequence current (I2/I1), phase-voltage measurements, and capacitive current [2]–[4]. Recent methods are rate of change of phase voltage, negative-sequence voltage, zero-sequence voltage, voltage harmonic distortion and 3rd-harmonic power, or a combination of these methods [5]–[7]. However, traditional and new methods do not address the complexity of modern distribution systems and the increased penetration of DERs; sensitivity and speed are compromised.

This paper discusses these traditional and new methods, and presents a new, practical, and scalable solution for detecting falling conductors before they touch the ground—the high-speed, falling-conductor (HFCP) algorithm to detect a broken conductor. This method employs a rate of change of load impedance calculated with synchrophasor data from phasor-measurement units (PMUs) distributed throughout the power-system network. A PMU at the substation source provides protection for the entire feeder and a majority of the branches. Adding downstream PMUs increases coverage for outlying branches with smaller loads. Adaptive setpoints increase security for detection in the downstream branches.

III. Current-based FCP, I2/I1

A traditional method to detect the broken conductor is to measure the ratio of negative-sequence current, I2, to positive-sequence current, I1. It works on the principle that a broken phase conductor produces unbalanced current, I2. An advantage of this method is that modern, numeric, protection relays calculate these sequence components; the method is readily available at the point where the current transformers are applied in the power system. When the affected phase current drops to zero, the I2/I1 ratio can be calculated from the line impedances Z0/(Z1+Z0). However, the assumption that the phase current falls to zero is valid only for two-terminal transmission lines.

For three-terminal lines and distribution lines there are other factors that affect the I2/I1 ratio measured at a protective relay. These factors include the network impedance, pre-fault load flow, break location, and distributed energy resource (DER) connections. Unbalance from line loading affects the sensitivity of the I2/I1 method. Typical I2/I1 settings are 0.2 per unit and greater to accommodate for system standing imbalance. For a typical pickup setting ratio of 0.2, studies show that it is required to drop 50% of the single-phase load for the I2/I1 element to assert [3]. A disadvantage of the I2/I1 method is that response is delayed for tens of seconds to coordinate with phase/ground overcurrent protection.

To investigate I2/I1 sensitivity a simulated distribution system was constructed that has a recloser R in the middle of the feeder downstream of the main circuit breaker CB, as well as three load branches L1, L2, and L3, with a possible distributed generation (DG) connection (see Fig. 1).

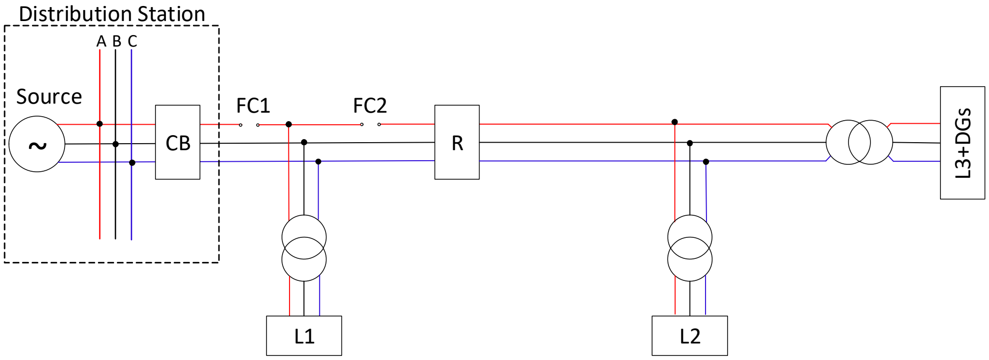


Fig. 1 Conductor break and open-phase faults on a simplified distribution feeder

Simulation results were developed for a close-in, falling conductor on Phase A (FC1), shown in Fig. 2, and a falling conductor behind L1 (FC2), shown in Fig. *3*. A distribution-station relay running the I2/I1 method can detect the break at FC1 because the ratio is 0.63. However, this relay cannot detect the break at FC2 because the measured ratio is 0.2. Therefore, if a falling conductor happens at FC2 or downstream of the feeder the probability of detecting it is very small. This situation affects the coverage significantly. The variable load flow compromises the dependability of the protection for a distribution line with many branches.

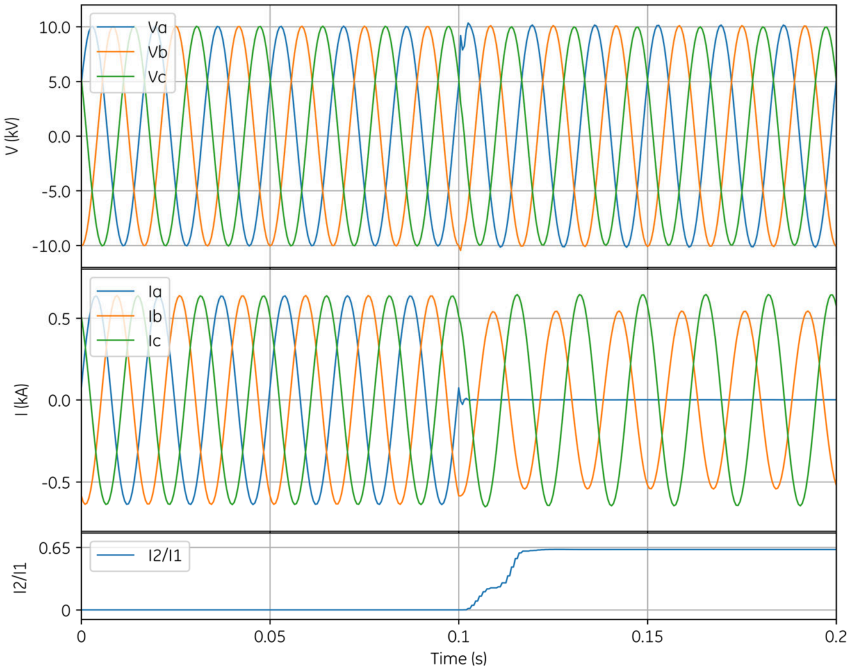


Fig. 2 Close-in conductor break/open-phase fault at FC1

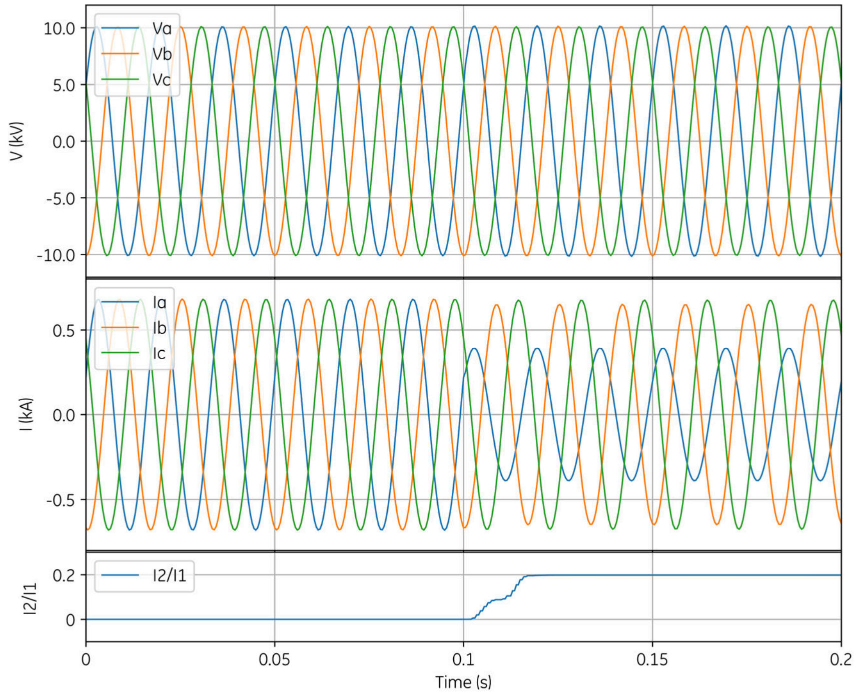


Fig. 3 Conductor break/open-phase fault behind L1 (FC2)

IV. Voltage-Based FCP

Voltage-based FCP methods detect a loss of voltage/rate of change of voltage using sequence-voltage magnitudes and voltage angles. FCP based on the loss of voltage uses pre-determined thresholds to detect falling conductor events. Voltage measurements at multiple locations of the distribution network are required (upstream and downstream). A falling-conductor event is detected when the downstream voltage quantity collapses below the pre-set threshold.

The following subsections present the most common, voltage-based FCP methods and the study results obtained for use cases on the distribution system shown in Fig. 4.

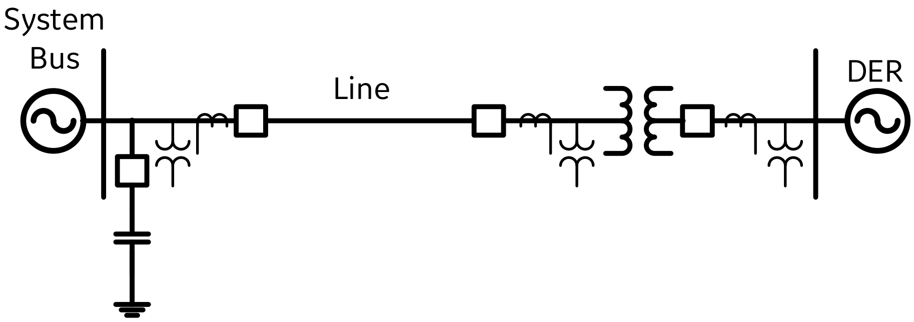


Fig. 4 Study system for voltage-based methods

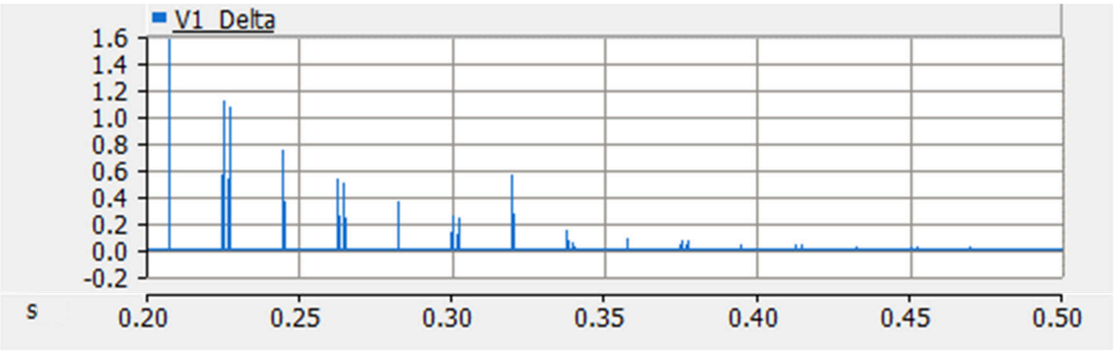
A. Positive-Sequence Voltage Observations

The FCP method based on the rate-of-change-of-voltage calculates the rate at which the measured, phase-voltage magnitude is changing with respect to time (dV/dt).

Typically, this FCP algorithm uses a pre-determined threshold and the polarity of the calculated dV/dt to detect a falling-conductor event. The measured dV/dt on opposite sides of a broken circuit will have opposite polarities. Once the calculated dV/dt is greater than the threshold a supervision check is performed using the rate-of-change-of-zero-sequence voltage (dV0/dt) before a trip signal is issued to the appropriate circuit breakers.

Fig. 5 shows the results obtained for full-load, 50% loading, and light-loading conditions, with and without integrated DERs. For the use cases considered, the rate-of-change of positive-sequence voltage (V1 delta) detected the falling-conductor event correctly. The performance of this FCP method did not deteriorate in the presence of DERs and for light loading.

The method is simple and is deployed easily. However, it depends on the availability of voltage measurements (voltage transformers) and PMUs at both ends of a single distribution line. The installation of PMUs at both ends of a single distribution line, and the associated costs, make this method impractical for distribution systems. Also, the performance of this method has not been demonstrated for dynamic reactive power (VAr) compensators, inverter-based DERs, voltage regulators, tap-changing transformers actions, etc. The presence of these devices in distributions systems causes the voltage to vary even under normal operating condition and this could result in the failure of voltage-based methods.



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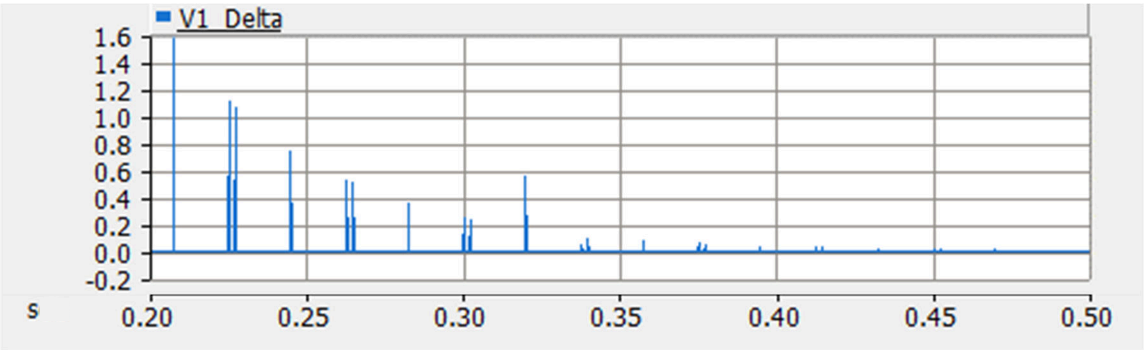

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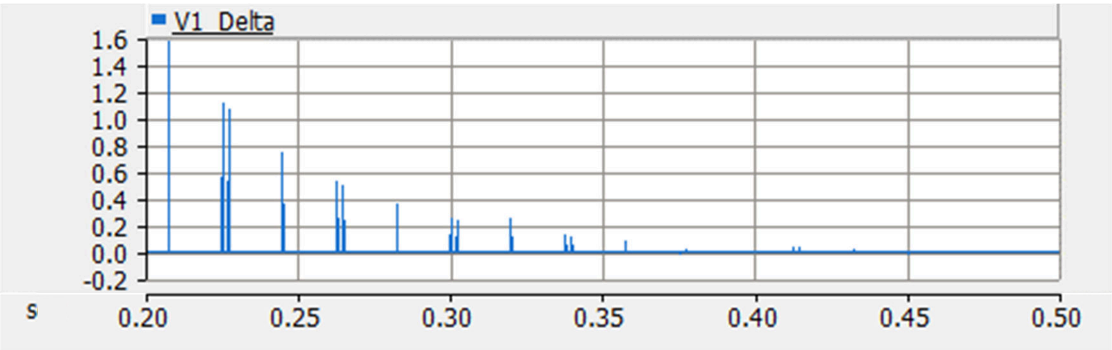
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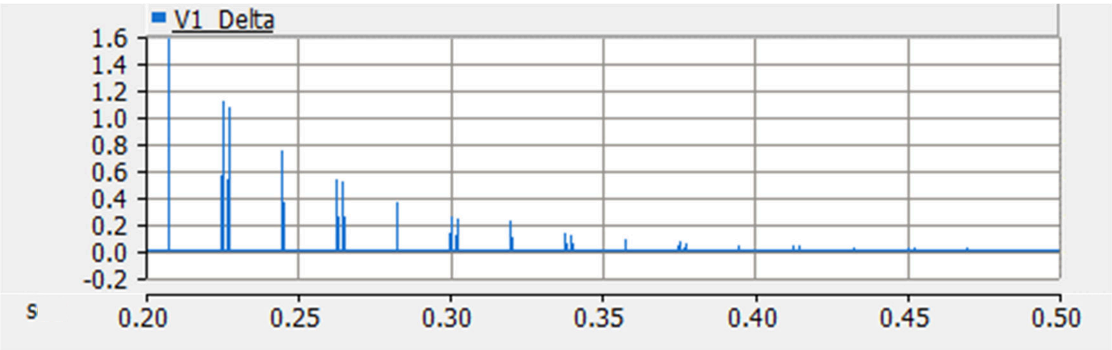
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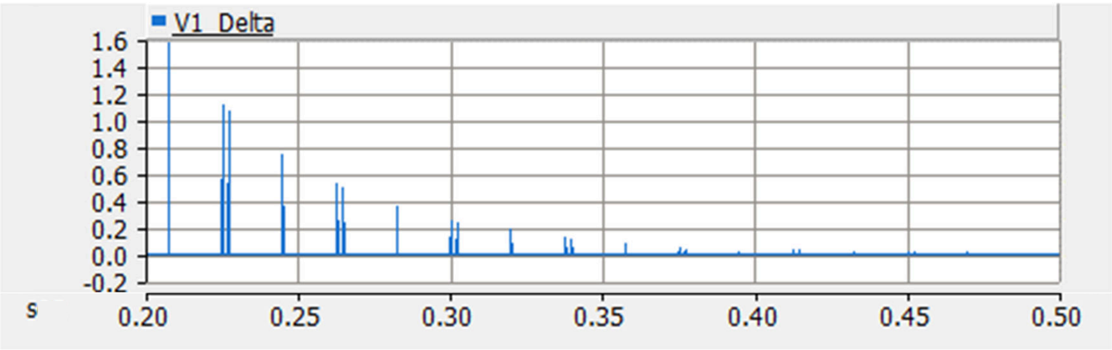
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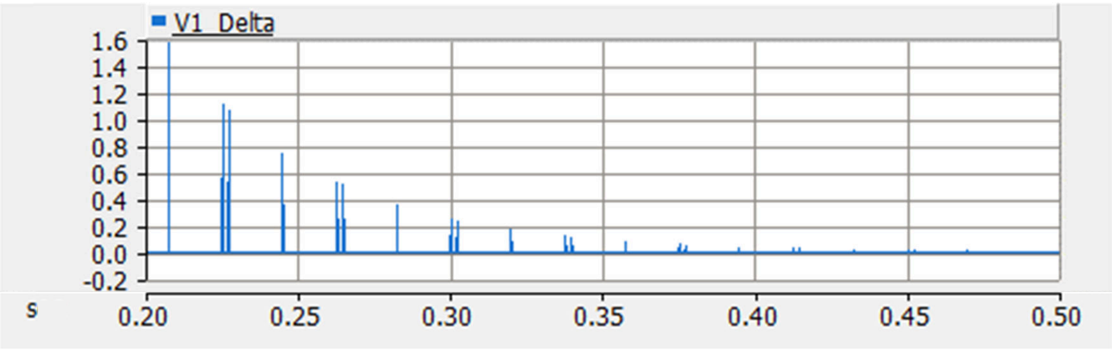
V1_Delta
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0.40
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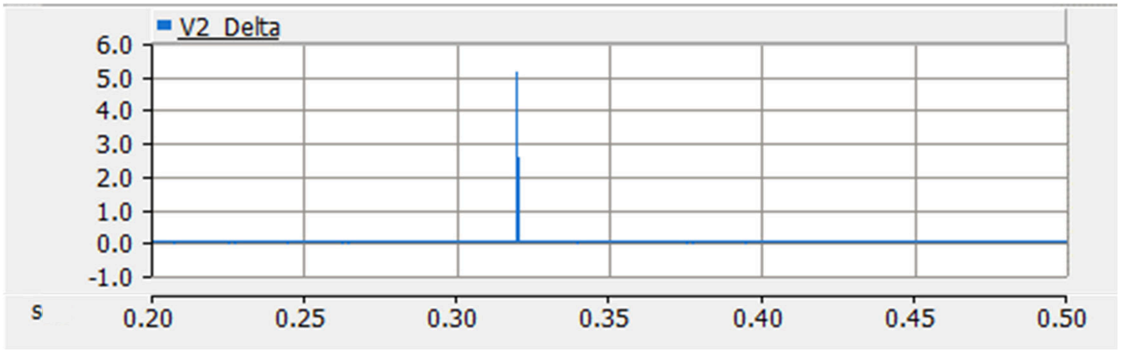
(f)

Fig. 5 Test cases for rate-of-change of positive-sequence voltage for a falling Phase A conductor (a) full load without DER, (b) full load with DER, (c) 50% loading without DER, (d) 50% loading with DER, (e) light loading without DER, and (f) light loading with DER

B. Negative- and Zero-Sequence Voltage Observations

Zero- and negative-sequence (V0 and V2) components can be used to detect a falling-conductor condition. A falling conductor is detected when V0 or V2 magnitude exceed predetermined thresholds for a fixed delay (e.g., 200 ms). The V0 and V2 magnitudes of a PMU further from the source end experience a steep increase compared to the V0 and V2 magnitudes measured by a PMU closer to the source. Similar to the voltage-magnitude the zero- and negative-sequence voltage angle detects a falling-conductor event on the circuit using the angular relationship obtained from the PMUs in the distribution system.

Fig. 6 shows the results obtained for the rate-of-change of negative-sequence, voltage-magnitude, FCP method for full load, 50% loading, and light loading conditions, with and without DERs. Note the magnitude variability in the cases. The results show that this FCP method is adversely affected by system loading. Therefore, it is difficult to determine the appropriate pick-up threshold to use for dependable element assertion. Also, similar to the rate-of-change of positive-sequence, voltage-magnitude, FCP method, the rate-of-change of negative-sequence, voltage-magnitude, FCP method depends on the availability of voltage measurements and PMUs at both ends of a single distribution line; it is impractical for multi-line distribution systems. In addition, the performance of this method has not been demonstrated for dynamic VAR compensators, various inverter-based DERs, voltage regulators, and transformer tap changers, etc.



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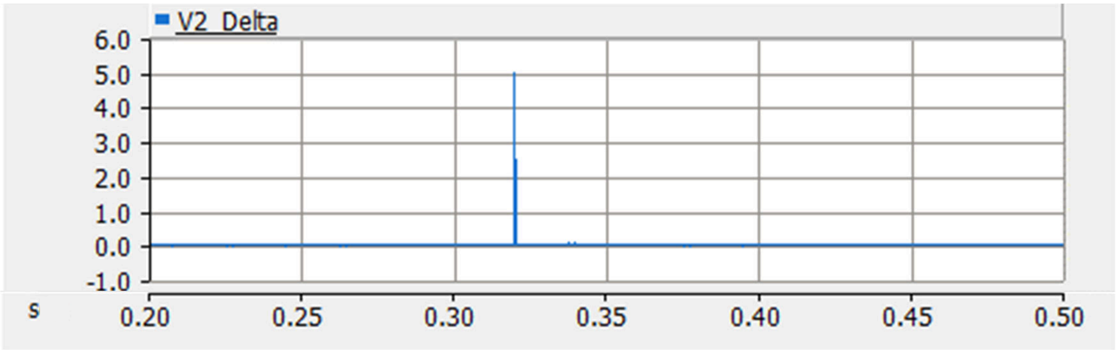

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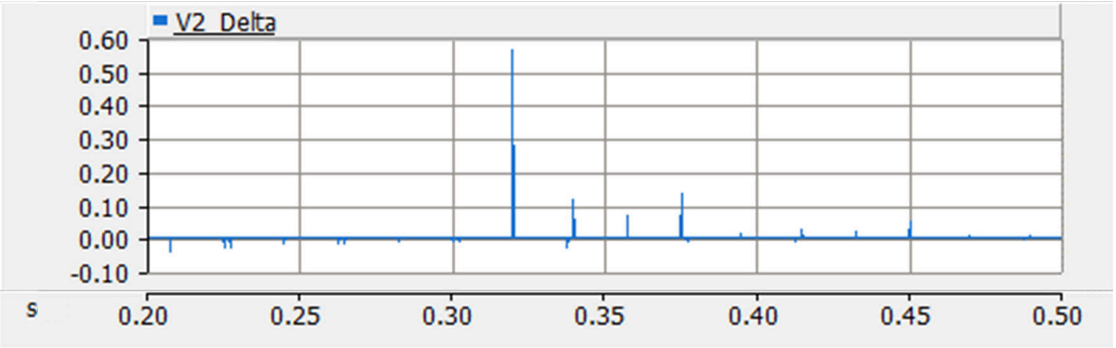
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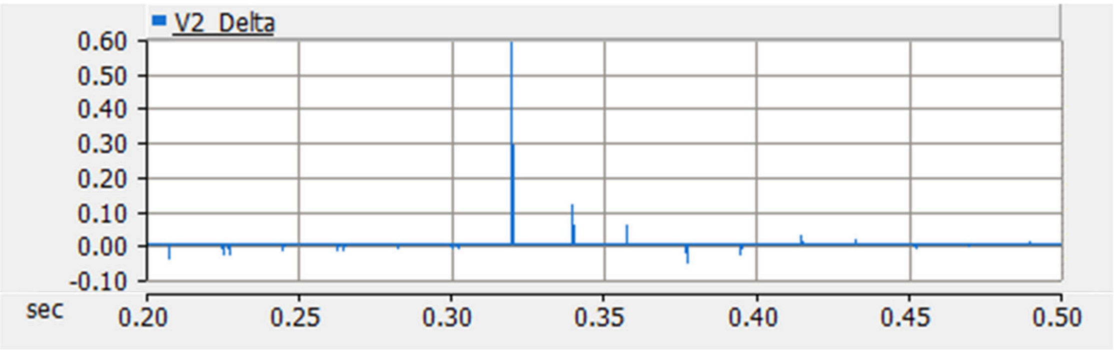
(c)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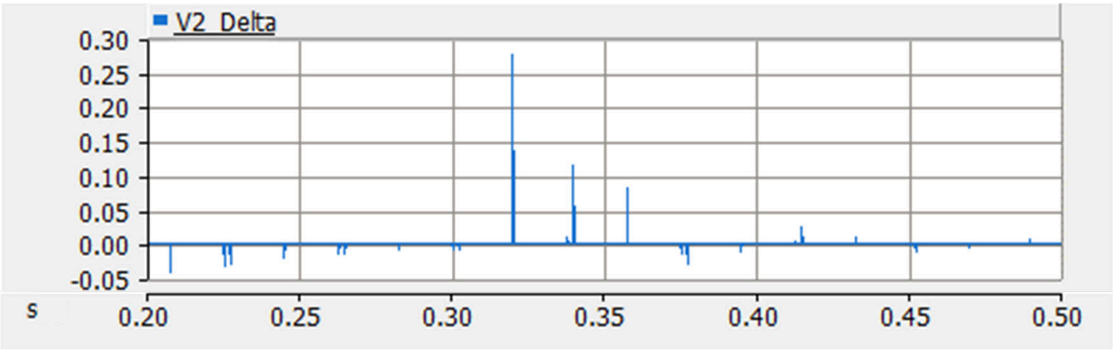
(d)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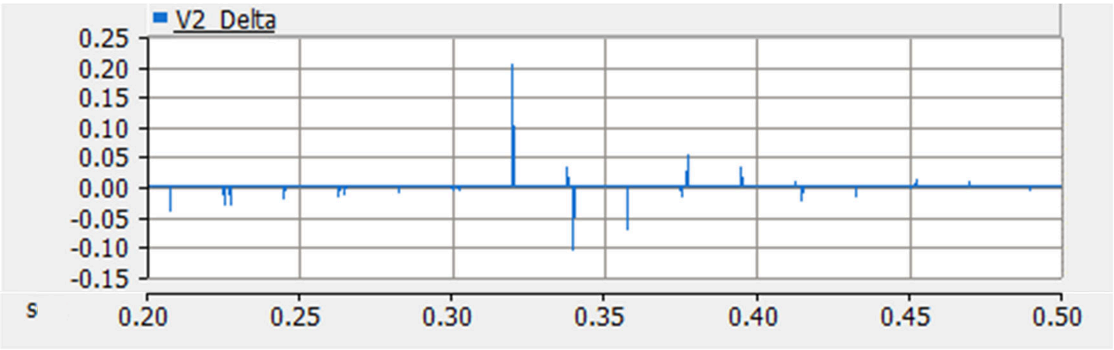
V2_Delta
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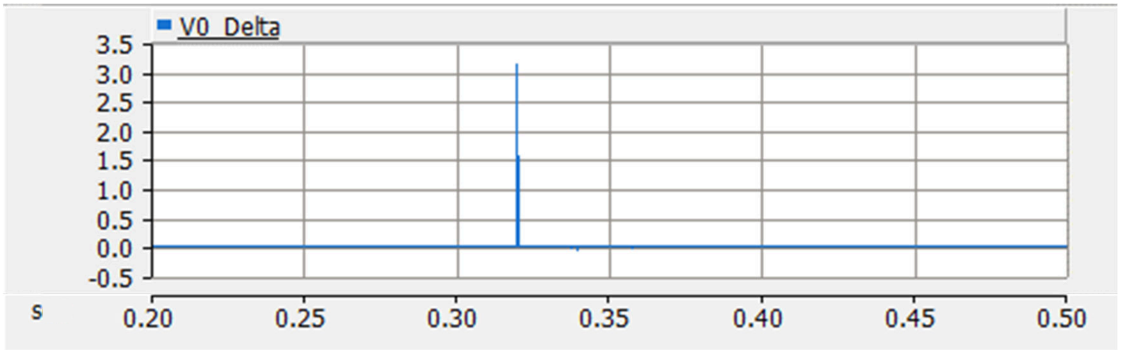
0.40
0.45
0.50

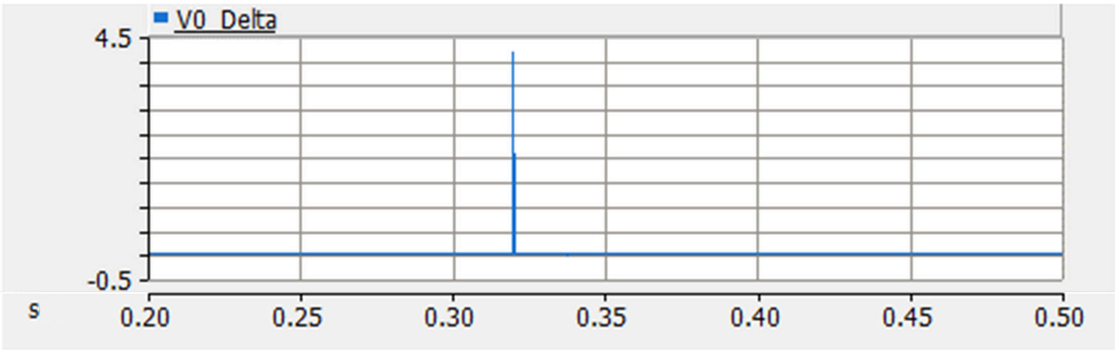
(f)

Fig. 6 Test cases for rate-of-change of negative-sequence voltage for a falling Phase A conductor (a) full load without DER, (b) full load with DER, (c) 50% loading without DER, and (d) 50% loading with DER, (e) light loading without DER, and (f) light loading with DER

Fig. 7 shows the results obtained for the_rate-of-change of zero-sequence voltage_FCP method for_full-load, 50% loading, and light-loading conditions, with and without DERs. Note the magnitude variability in the cases. The results show that this FCP method is affected adversely by system loading and it is difficult to determine the appropriate pick-up threshold to use for dependable operation. Also, similar to the rate-of-change of positive-sequence voltage FCP method, the rate-of-change of zero sequence voltage FCP method depends on the availability of voltage measurements and PMUs at both ends of a single distribution line; it is impractical for multi-line distribution systems. In addition, the performance of this FCP method has not been demonstrated for dynamic VAR compensators, various inverter-based DERs, voltage regulators, and transformer tap changers, etc.



(a)



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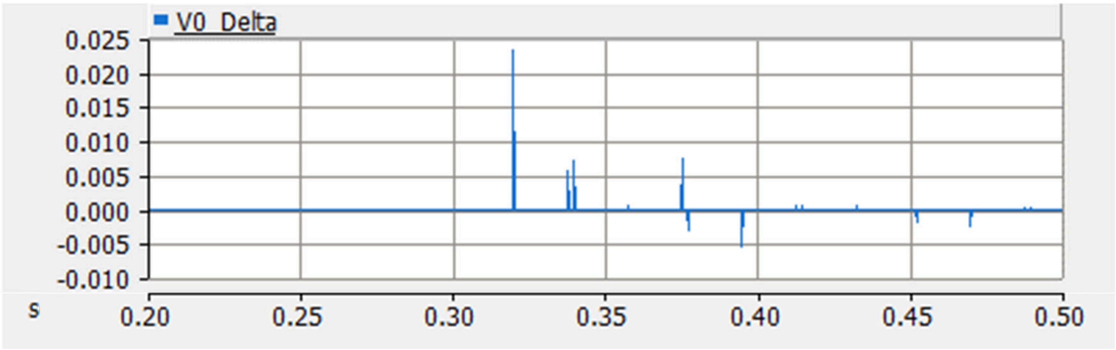

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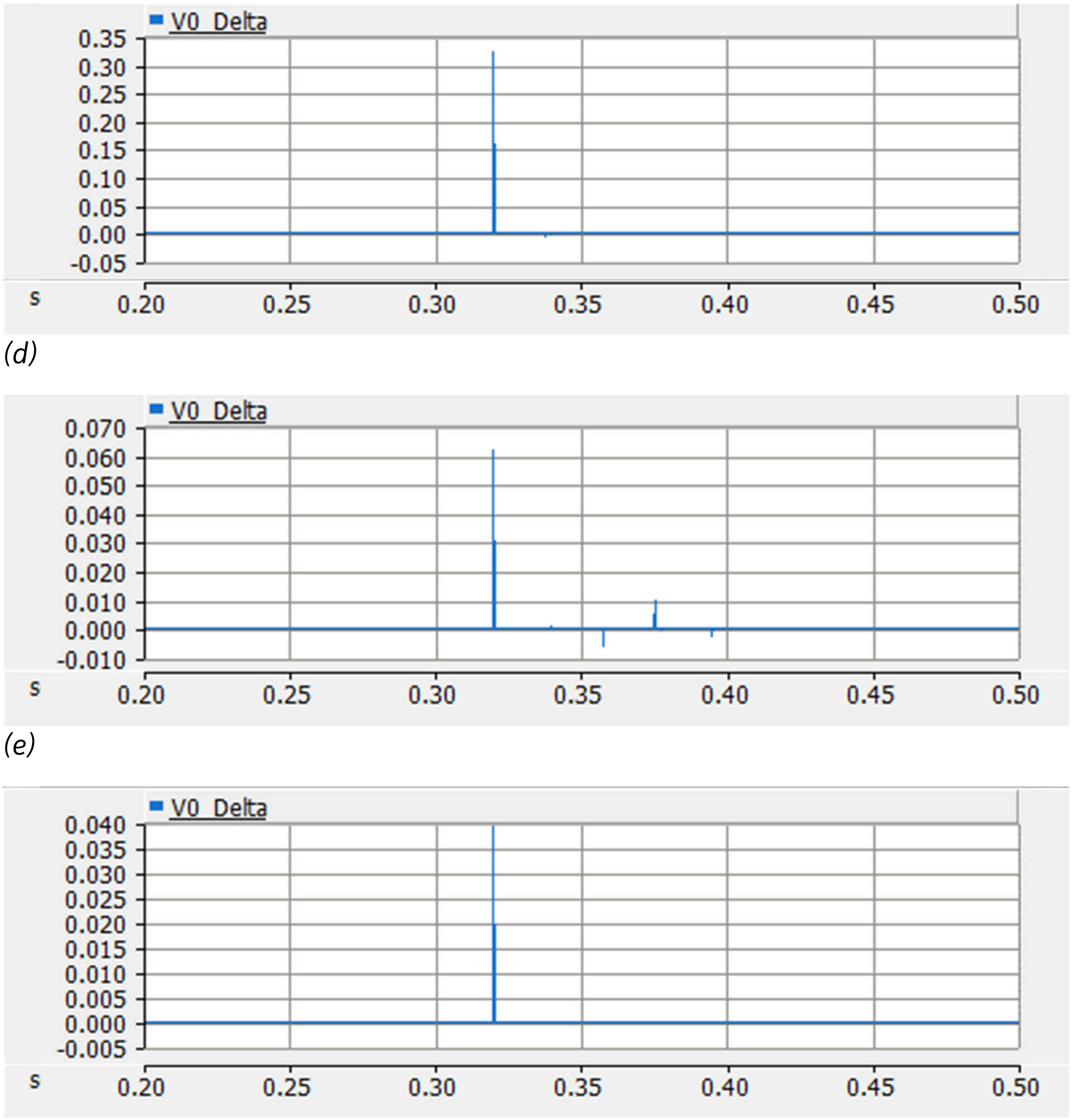

(d)

(e)

(f)

Fig. 7 Test cases for rate-of-change of zero-sequence voltage for a falling Phase A conductor (a) full load without DER, (b) full load with DER, (c) 50% loading without DER, and (d) 50% loading with DER, (e) light loading without DER, and (f) light loading with DER

V. Impedance-based FCP

Impedance-based FCP provides a reliable solution to detect and isolate broken overhead-line conductors prior to the conductor touching the ground for both transmission and distribution networks. This is a substation-centric solution that employs impedance-change ratios, ICRs [8].

The FCP algorithm, as shown in the block diagram of Fig. 8, uses the ICRs calculated from synchrophasor measurements streamed from feeder-protection relays. The algorithm declares a falling conductor condition when the ICRs for a distribution feeder exceed a threshold (an adjustable setpoint, defaulted at 0.18). Only single-phase falling conductors that create an open phase before falling are detected with this algorithm. To prevent an incorrect alarm/trip when a fuse is blown (for example, in one of the feeder laterals) the FCP function operates only when no fault is detected prior to the falling-conductor condition within an adjustable time, counted in seconds before the FCP operated. The FCP logic is blocked for the following conditions:

- Any phase current is less than or greater than a threshold
- Any phase voltage is beyond the defined healthy level
- A single-phase fault condition is identified
- A PT secondary fuse is blown
- A feeder power fuse is blown because of a short-circuit fault

Additionally, a voltage-based detection scheme is employed for PMUs located along the feeder. It detects open phases upstream of the PMU by measuring a small voltage and small current on one phase, and healthy voltages on the other two phases. This improves the coverage of the overall solution and provides a rough estimate as to where the fault is located, for coordination with upstream PMUs, e.g., the PMU at the substation.

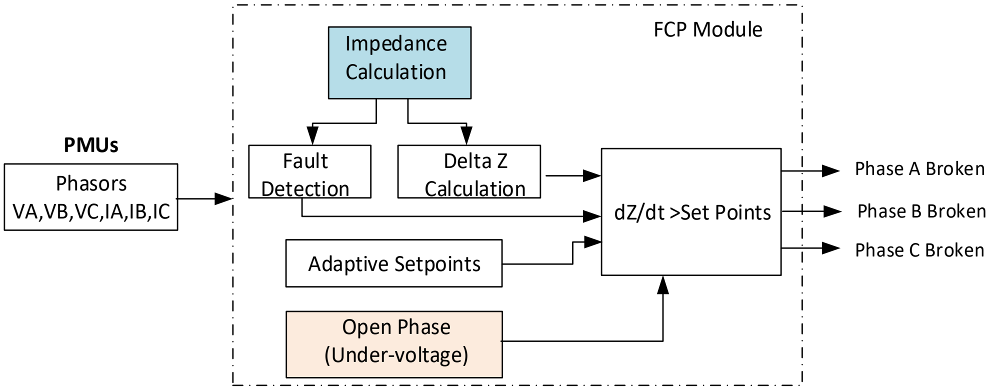

Fig. 8 Block diagram of FCP algorithm

Arcing and similar transient incidents prior to the conductor starting to fall can affect the calculation of the impedance. To avoid this the program stores 10 previous phasors with a moving window as shown in Fig. 9. The number of phasors to calculate the impedance Z is user adjustable (setting range: 1–10). It is recommended to keep four samples between the present impedance Z and the previous impedance Z'; therefore, the default value is 4 for a PMU frame rate of 60 samples/s and 8 for 120 samples/s. Fig. 10 shows the concept of moving windows for reliable falling-conductor detection.

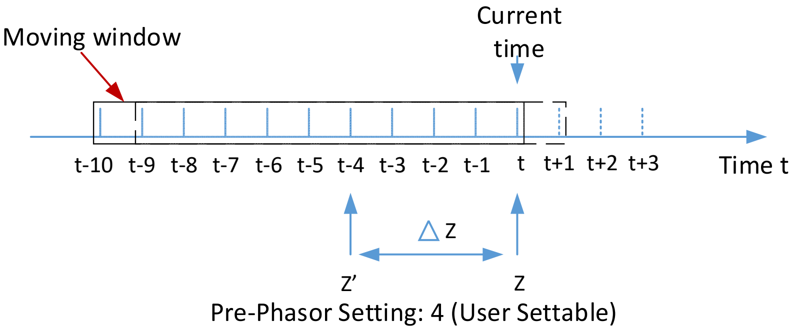

Fig. 9 Moving window of the ICR calculation

The setpoint/threshold for ratio of δ_Z in FCP logic is adjusted adaptively based on the feeder loading (current) as indicated in Fig. 10. Note that the setpoint is inversely related to the feeder load current. Thus, as the feeder load reduces, a larger ICR (δ_Z) detects a broken-conductor condition. Assuming a fairly constant voltage at the substation, Fig. 11 shows the minimum approximate current (percentage of maximum load) that a branch needs to carry such that the proposed FCP logic can detect reliably broken conductors on this branch/lateral. The figure illustrates a feeder with the rating of 300 A and ratio of δ_Z_setpoint (δ_{Z_Sp}) of 0.18 at the rated load. It is recommended to study PMU placement and setpoints based on the load flow for each feeder and its branches to optimize the sensitivity and maximize the coverage.

Security features such as blown potential transformer (PT) and power fuse detection, PMU data integrity check, and single-line-to-ground (SLG) fault detection are also implemented. Fuse-blown detection blocks the operation of the FCP function when a fault is first detected, prior to the open-phase detection caused by the blown fuse (within a period defaulted at 1 second). A SLG fault is detected once the impedance enters the mho characteristic (setpoints) of the FCP logic. For this case, only a single-phase fault can operate (combined with overcurrent disturbance detection 50DD); thus, the SLG fault detection module blocks the FCP algorithm when a fault is first identified.

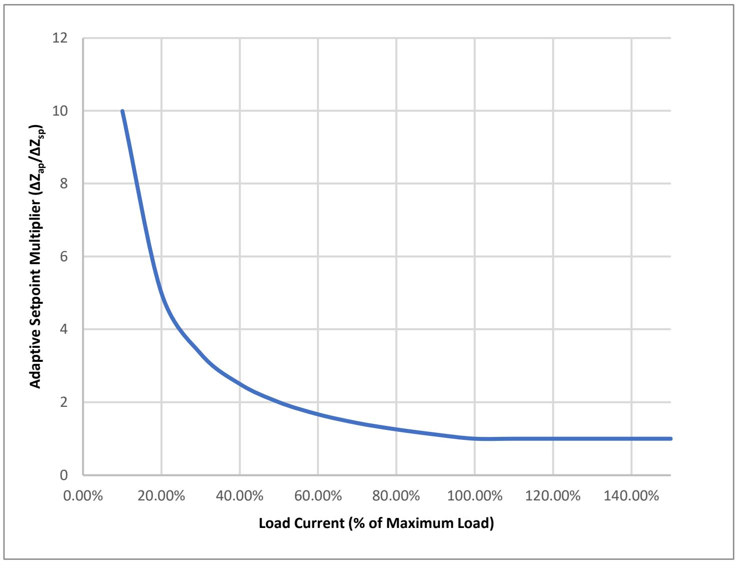

Fig. 10 Ratio of Delta_Z setpoint (setpoint at rated feeder load 300 A is 0.18)

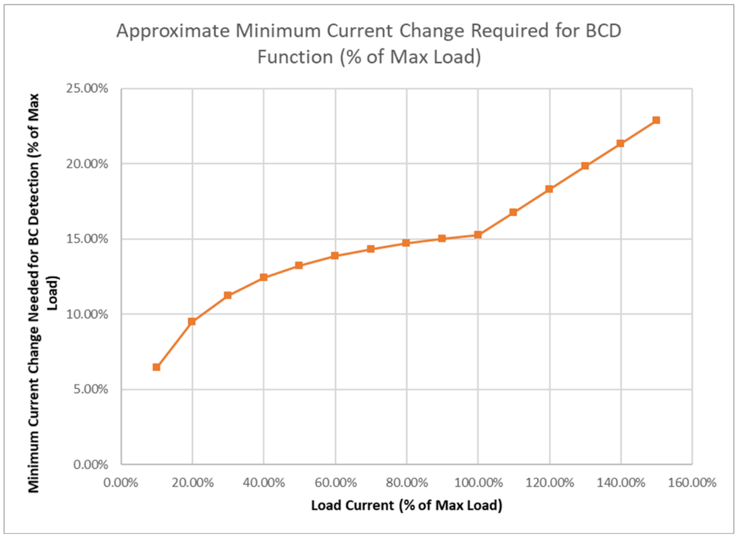

Fig. 11 Minimum branch current for successful FCP as a function of the feeder loading (rated load is 300 A with ratio of delta_Z_setpoint = 0.18)

The following cases are real-time digital simulator (RTDS) simulations performed for different scenarios, testing impedance-based FCP performance. Fig. 12 is the 12-kV study system architecture.

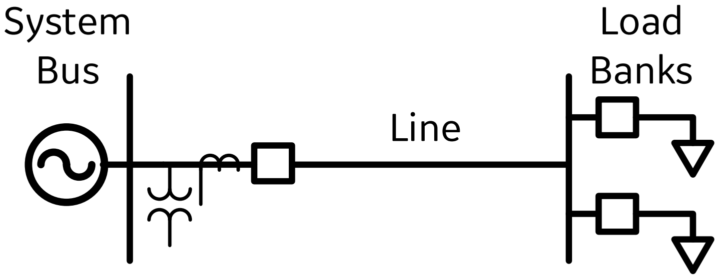

Fig. 12. Impedance-based FCP study system

A. Case 1: Small-Current Phase-A Line Open

Fig. 13 shows the waveforms for a Phase-A conductor break with small current draw from one load bank. The impedance-based FCP detects this Phase-A conductor break in less than 200 ms. The impedance change ratio in this case (Fig. 14) is greater than 30.87 with a typical setting of 0.20. This method works on lightly loaded lines.

Fig. 13 Case 1: small-current Phase-A line open RTDS playback for impedance-based FCP

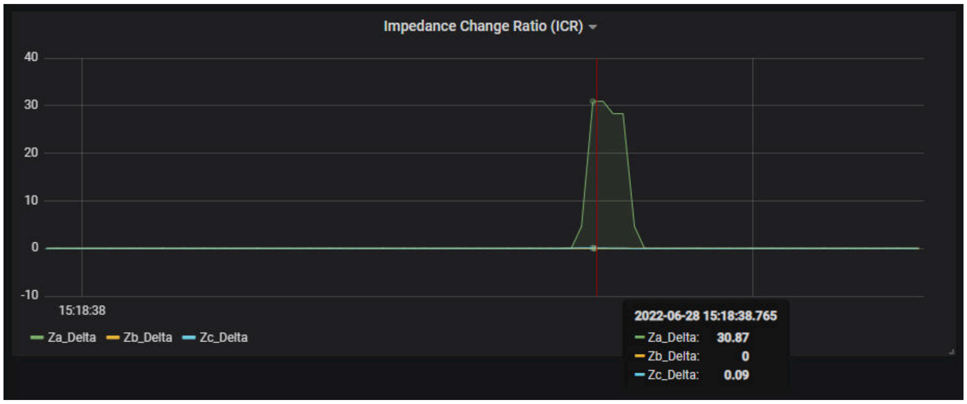

Fig. 14 Case 1: small-current Phase-A line open ICR change measured by impedance-based FCP

B. Case 2: Three-Phase Load Drop

Case 2 is a test case for a three-phase load drop, shown in Fig. 15 . The impedance-based FCP is secure for a three-phase load drop (e.g., CB open). The impedance change ratio in this case (Fig. 16) is greater than 30 for all three phases. Security is important to avoid false falling-conductor assertions.

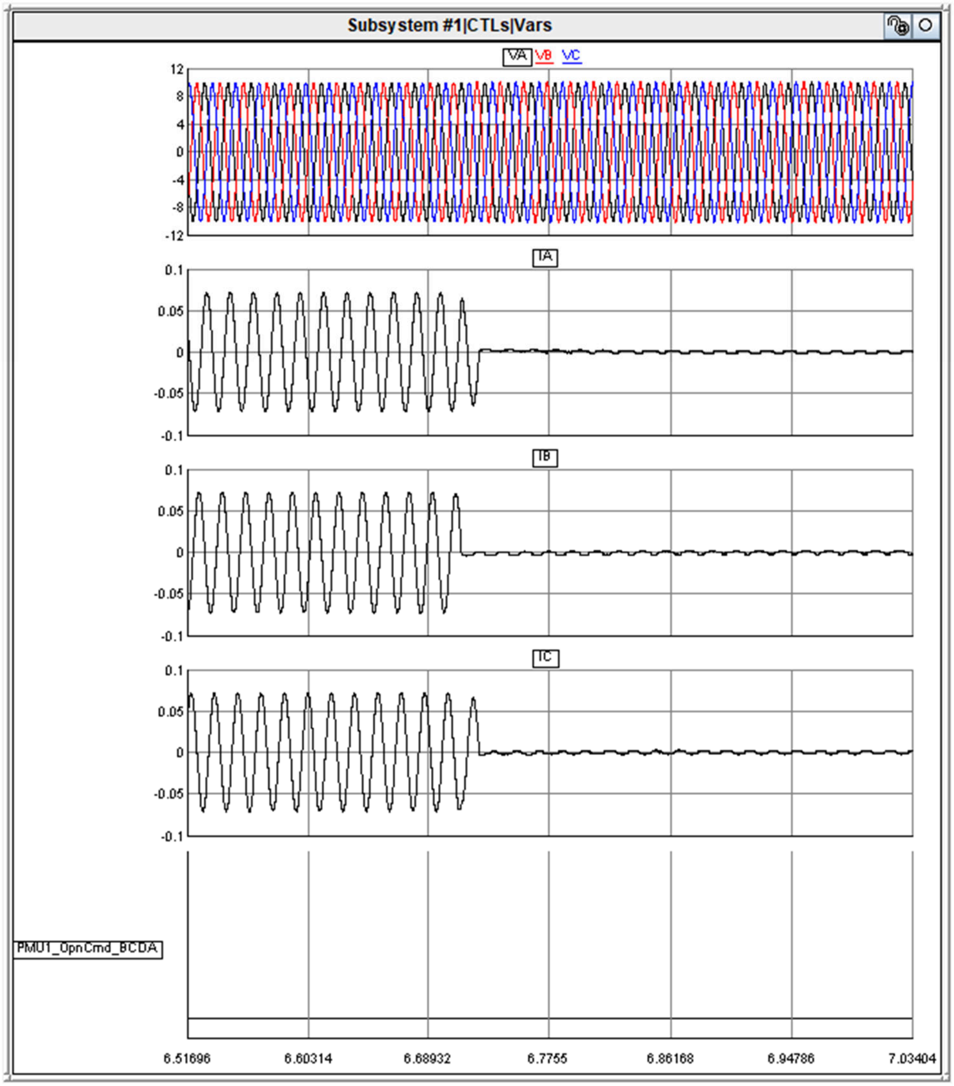

Fig. 15 Case 2: three-phase load-drop RTDS playback for impedance-based FCP

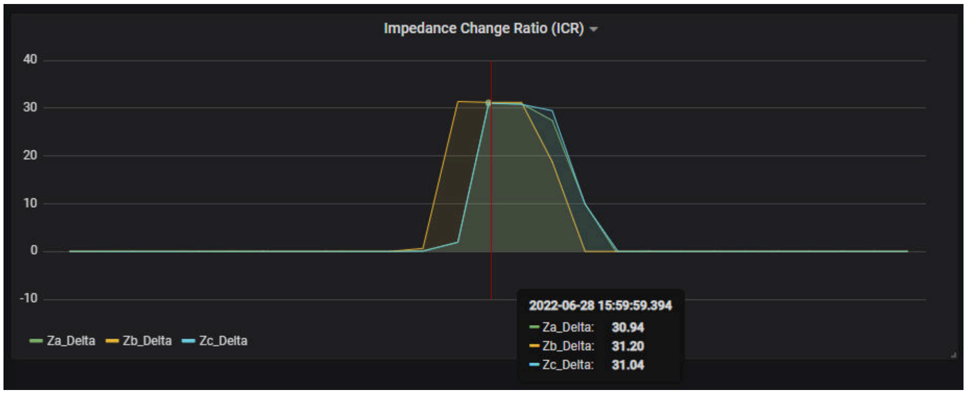

Fig. 16 Case 2: three-phase load-drop ICR change measured by impedance-based FCP

C. Case 3: Larger Load Current on Phase-A Open

Fig. 17 shows the waveforms for a Phase-A conductor break with larger load current (two load banks), however, the current remains relatively small. The impedance-based FCP detects this Phase-A conductor break in less than 200 ms. The impedance change ratio in this case (Fig. 18) is approximately 60 with a typical setting of 0.2. Again, this case demonstrates that the impedance-based FCP method works on lightly loaded lines.

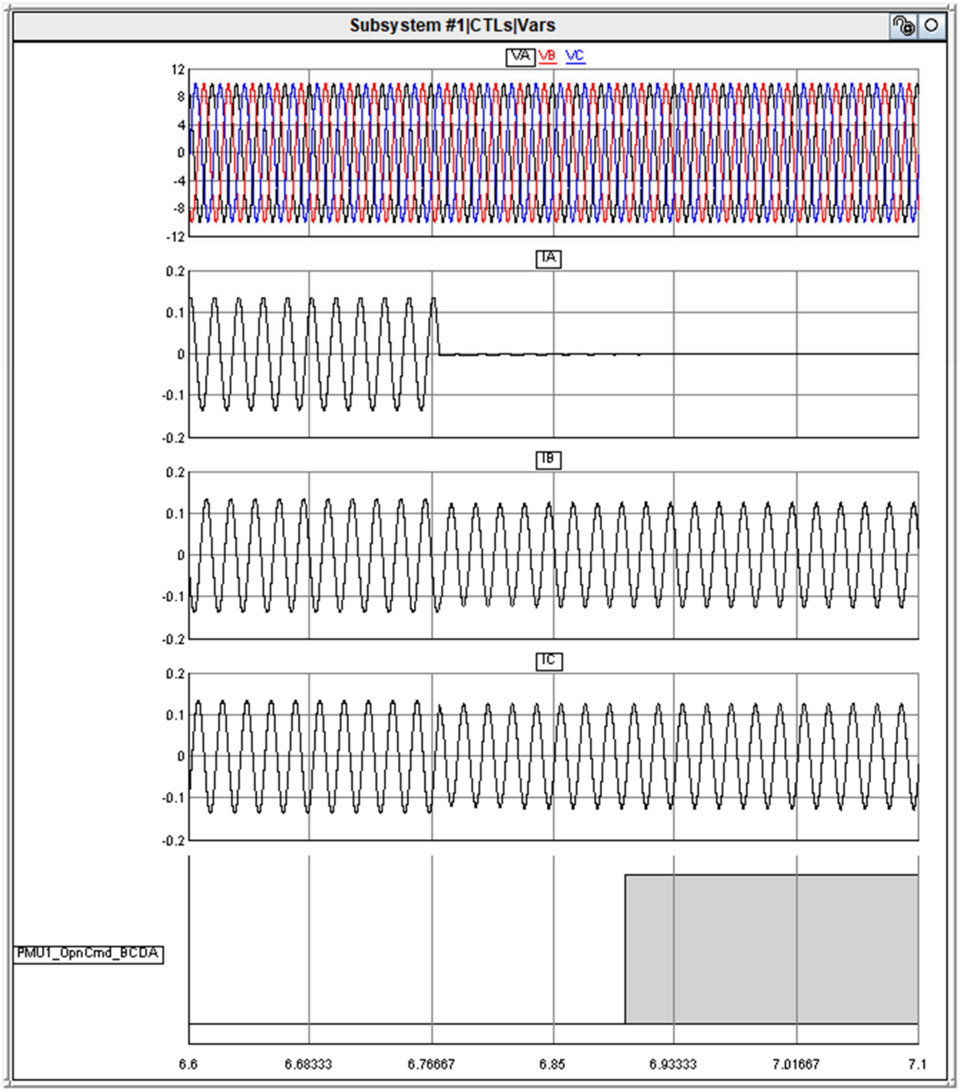

Fig. 17 Case 3: larger current RTDS playback for impedance-based FCP

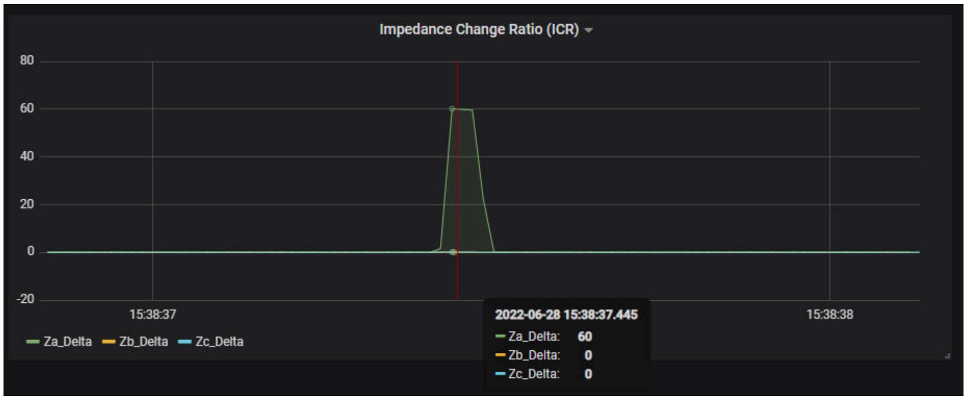

Fig. 18 Case 3: larger current ICR change measured by impedance-based FCP

VI. Conclusions

Detecting a broken conductor quickly can reduce damage to property (from wildfires) and improve human safety. Efforts for detecting a broken conductor before the conductor touches the ground have led to multiple techniques such as current-based, voltage based, and impedance-based methods. This paper presented disadvantages of the current-based and voltage-based methods, including application with DERs. Current-based I2/I1 does not detect well, especially with varying feeder load. The positive-sequence voltage method does not deteriorate in detection with light loading and DER presence. However, the three sequence-voltage broken-conductor detection methods depend on the availability of voltage measurements/PMUs at both ends of a single distribution line; it is impractical for multi-line distribution systems. It was shown that impedance-based algorithms are effective at detecting a falling conductor in different scenarios on distribution feeders and in lightly loaded distribution-system configurations.

VII. References

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