Practical Experience With High-Impedance Fault Detection in Distribution Systems

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Revised edition released October 2019

Originally presented at the
46th Annual Western Protective Relay Conference, October 2019

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***Abstract*—High-impedance faults (HIFs) on distribution systems, such as those caused by downed conductors, continue to be difficult to detect using traditional protective relaying because low fault currents are often masked by load conditions. HIFs are a public safety concern if the faults go undetected. This paper documents how PPL Electric Utilities improved HIF detection on their distribution system by adding an HIF detection algorithm and updating metering technology while still using their existing protective relaying. We describe why PPL wanted to enhance their HIF algorithm, and we discuss the HIF detection algorithm. We document live downed conductor detection testing and the associated findings along with lessons learned from the initial pilot and subsequent enhancements to the system, including adding HIF tripping logic. We also provide event analysis of HIF conditions that occurred on site during the pilot.**

I. Introduction

High-impedance faults (HIFs), such as those caused by downed conductors, are a public and employee safety hazard that has always troubled the electric utility industry. HIFs often draw low magnitudes of current and are masked by system conditions. The low fault current of HIFs makes it difficult for protection engineers to set traditional protective relays with enough sensitivity to detect HIFs. The required overcurrent settings would need to be set so low that they would encroach on load current values, which would sacrifice security. Because traditional protective relays typically cannot be set to detect HIFs without misoperating for heavy loads, there are often blind spots in protection that can result in potentially dangerous conditions (e.g., fire or electrocution hazards), for employees and the public.

PPL serves over 1.4 million homes and businesses in 26 counties in southeastern Pennsylvania and maintains approximately 50,000 miles of line. Their service territory includes densely populated urban settings and remote rural areas. PPL integrated HIF algorithms in their substation microprocessor-based protective relays and line recloser controllers on their 12.47 kV distribution feeders.

This paper examines the use of HIF algorithms to improve HIF detection and discusses PPL Electric Utilities' practical experience with HIF alarms and trips. PPL added an HIF detection algorithm to their existing distribution protective relays to improve HIF detection, fault resistive coverage, arc detection, and employee and public safety.

Section II describes the use of the HIF detection algorithm and the analog and digital quantities needed to interpret HIF event reports.

Section III details the initial implementation of HIF detection on the PPL system, including the initial settings, and discusses the PPL investigation into false assertions and the effect of the metering system in use at the time of the pilot.

Section IV provides a summary of live downed conductor and HIF algorithm performance testing performed by the Electric Power Research Institute (EPRI) and PPL.

Section V documents the proposed implementation of HIF algorithms in PPL protective relays and the alterations that PPL made to their alarm logic to prevent false assertions based on the findings in Section III. The section introduces and explains the HIF tripping logic.

Section VI provides event analysis and findings from the detection of HIFs on the distribution system during the pilot.

II. HIF Detection Algorithm

HIFs are difficult to detect with traditional overcurrent relays because of their small current magnitude and the randomness of current during arcing. This paper discusses a relay that uses the harmonic characteristics of HIFs to detect them. The relay uses two algorithms for HIF detection: HIF Algorithm 1 (HIF1) that uses the odd-harmonic content of the phase currents and HIF Algorithm 2 (HIF2) that uses the interharmonic content. The algorithms function independently but both work on a per-phase basis, and both have the same key elements in their design, such as an informative quantity detecting HIF signature, a stable pre-fault reference, an adaptive tuning function, and decision logic [1].

After a line is energized, the relay requires a 24-hour tuning process to monitor the line and learn expected trends that occur under a minimum phase current of 0.05 • nominal current secondary. During the initial 24 hours, the ITUNE_*n* (*n* = Phase A, B, or C) digital bits assert and no HIF alarm or fault bits will assert. Following the initial tuning, the relay shifts to normal adaptive tuning based on changes in ambient load conditions.

The HIF logic has three-phase event detection logic, which disables HIF outputs during conditions occurring on all three phases simultaneously. 3PH_CLR is the three-phase digital bit for HIF1, and 3PH_EVE is the three-phase digital bit for HIF2.

If the HIF event that occurs is the result of a downed conductor, then the fault may be accompanied by a load current reduction on that phase. Load reduction logic monitors for a decrease in current from a tuned current reference and asserts the LR*n* (*n* = Phase A, B, or C) digital bit.

A. Detecting HIFs Using Odd-Harmonic Content (HIF1)

HIF1 detects HIFs using total odd-harmonic content (ISM) as the operating quantity, which is derived from the phase currents using a specially designed finite impulse response (FIR) filter. The algorithm maintains short-term and long-term histograms of ISM, and if the difference between them is greater than the derived detection threshold, the algorithm increments a counter. The detection logic declares an HIF alarm if there are more accumulated deviations than the derived detection threshold setting value within a fixed time window. HIA1_A is the HIF1 alarm on the Phase A digital bit, and HIF1_A is the HIF1 fault on the Phase A digital bit. Phases B and C are similar.

B. Detecting HIFs Using Interharmonic Content (HIF2)

HIF2 uses the sum of difference current (SDI) as the operating quantity. SDI is the total interharmonic content of the phase currents. The algorithm establishes an SDI reference (SDIREF) and compares it to the measured SDI to detect an increase in SDI during an HIF [1]. The algorithm learns a margin above SDIREF for changes in ambient loads. When the SDI departs from SDIREF plus MARGIN, these deviations are automatically accumulated and mapped as analog counters in the decision logic.

T7CNT*n* and T8CNT*n* (*n* = Phase A, B, or C) are the counters for HIF2 fault and alarm conditions. T7CNT*n* and T8CNT*n* increment based on how much SDI deviates from SDIREF plus MARGIN and for how long [1]. The detection logic declares an HIF2 fault if the T7CNT*n* counter exceeds the threshold (determined by the calibration level settings) within a fixed time. The alarm logic works like the fault logic but detects smaller SDI differences over a longer period. HIF2_A is the HIF2 fault on the Phase A digital bit, and HIA2_A is the HIF2 alarm on the Phase A digital bit. Phases B and C are similar.

III. Initial HIF Detection Pilot

To learn how to use the algorithm in their system, PPL performed a pilot installation. This section details the setting considerations of the pilot and analyzes a rash of false alarms that occurred on the system.

A. Early Challenges

In 2015, PPL decided to pursue a microprocessor relay-based HIF detection solution to identify downed conductors. After evaluating the built-in HIF detection algorithms, PPL wrote initial alarm logic in the relay by mapping the HIF alarms to Distributed Network Protocol (DNP) binary points, which were sent through supervisory control and data acquisition (SCADA) to the system operators.

Approximately 50 feeders equipped with HIF detection-capable relays with alarm logic mapped to SCADA were placed in service simultaneously. The goal of the initial rollout was to pilot the technology as a proof of concept to see if the algorithms would detect downed conductors or whether they would misoperate.

PPL encountered unexpected challenges and results because of limited background information, development of the alarm logic, and false HIF detections.

1) Limited Background Information

At the outset, there was little knowledge of how the HIF detection algorithms would behave practically. The functionality was described in the relay manual, but only limited detection rates were available. The testing that had been done was on a limited scale, and only relative detection rates had been recorded, so the statistical effectiveness of HIF detection was unknown, which provided no basis for predicting success with HIF detection at PPL [2].

2) Developing Alarm Logic

Because of the limited proven success of the HIF algorithms, PPL decided to retain the existing ground relay functionality as the primary form of HIF detection. The HIF detection algorithm would then act as a backup to the ground relay protection and would only alarm. A system operator would respond to the alarm and isolate the fault location. With this baseline established for expected operation and relay functionality, PPL developed relay logic that was mapped to the SCADA points.

PPL developed the following alarm logic:

LATCH SET := HIF2_A + HIF2_B + HIF2_C

LATCH RESET := NOT (HIF2_A + HIF2_B + HIF2_C)

The HIF alarm was set as a latch because it was assumed that a successful HIF detection by the algorithm would remain sealed in, the same way that a successful overcurrent detection is sealed in with the continual assertion of a 50/51 element while the current is above pickup. This proved to be an incorrect assumption because the latch would reset during HIFs because of the intermittent arcing.

To further improve detection rates when system conditions indicated a potential downed conductor, the high-sensitivity mode was enabled for the algorithm. PPL used the following logic for the high-sensitivity mode:

High-sensitivity mode activation := 51G pickup AND SHOT_0 AND NOT (TRIP OR 51P pickup)

This logic increased the sensitivity of the algorithm in scenarios where a conductor may break and fall to the ground but not trip the relay. It was assumed that a combination of the downed conductor alarm and the 51G element would indicate that an energized, downed conductor was the cause of the alarm and trip, which would stop the system operator from re-energizing a downed conductor.

3) Analyzing False HIF Detections

Upon activation of the HIF-related SCADA points, the system operator was inundated with false HIF detection alarms. Several feeders at three substations were in continuous alarm states.

Initial event analysis showed that the HIF2 elements were asserting and deasserting regularly as well as alternating phases, as shown in Fig. 1. During several of the events, the 3PH_EVE logic asserted and blocked the HIF2 elements; however, 3PH_EVE did not stay asserted, which allowed the HIF2 elements to assert.

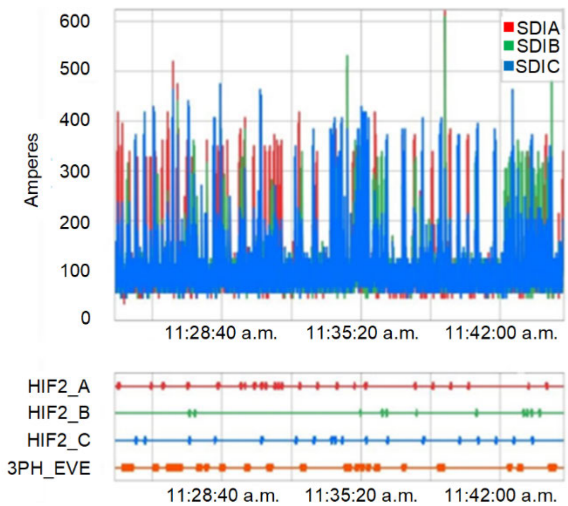

Fig. 1. Initial pilot HIF event showed false alarming of the HIF2 elements across all three phases.

In reviewing the SDI values, a pattern emerged that showed square wave shapes that lasted for approximately 3.5 seconds that were spaced 0.8 seconds apart, as shown in Fig. 2. There was a consistent order of increased SDI current starting on each phase and then across two phases at a time until all the phase combinations were met.

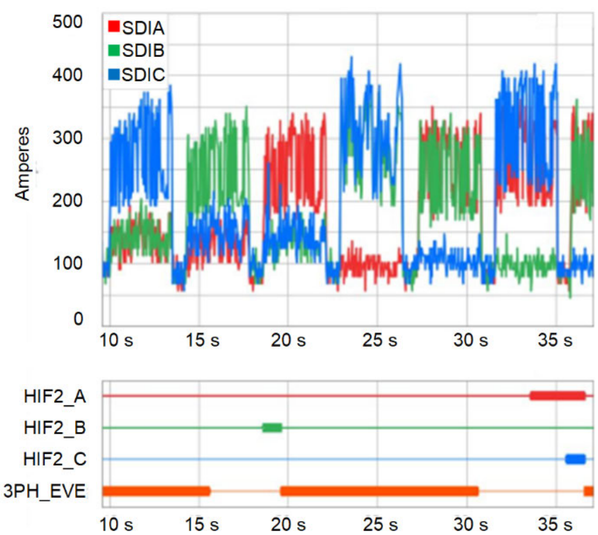

Fig. 2. SDI current increases on Phases C, B, A, CB, BA, and AC caused each HIF2 element to assert within 20 seconds; 3PH_EVE only blocked assertion for part of the event.

The counters for HIF2 incremented over the time that the waveform existed, as shown in Fig. 3. T7CNT*n* caused the HIF2 element for each phase to assert just as the SDI waveform on that phase returned to normal levels.

Fig. 4 shows the SDI, SDIREF, and MARGIN on a per-phase basis over the same time frame shown in Fig. 3. The first SDI excursion is on Phase A. SDIAREF and MARGINA start to tune toward the SDIA excursion. However, the SDIA excursion exceeds MARGINA and is sustained for long enough that HIF2_A asserts. SDIA then returns to its pre-excursion level, and SDIAREF begins to tune back to the pre-excursion level. Phases B and C experienced the same excursion after Phase A returned to normal levels. At no point in the portion of the event shown in Fig. 3 or Fig. 4 did all three-phase SDI increases overlap, which avoided the assertion of the 3PH_EVE logic. This is unlike Fig. 2 where there was enough three-phase activity to temporarily shut down the elements at multiple points during the event, but not the entire duration of the event.

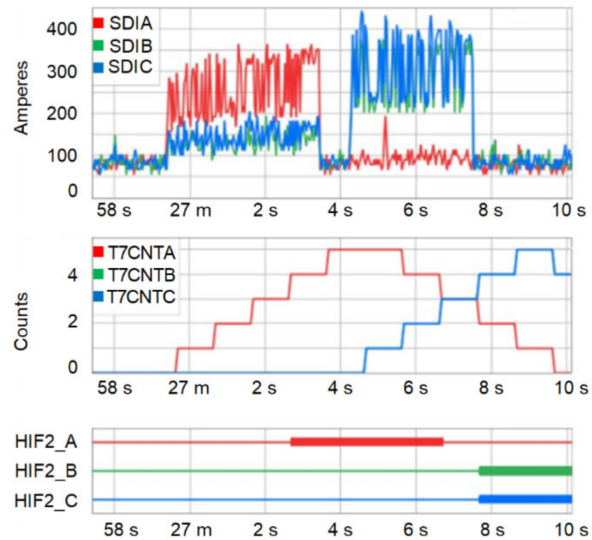

Fig. 3. T7CNT*n* counters incremented 5 counts in the 5 seconds that the SDI excursion existed, which caused the HIF2 elements to assert and falsely alarm.

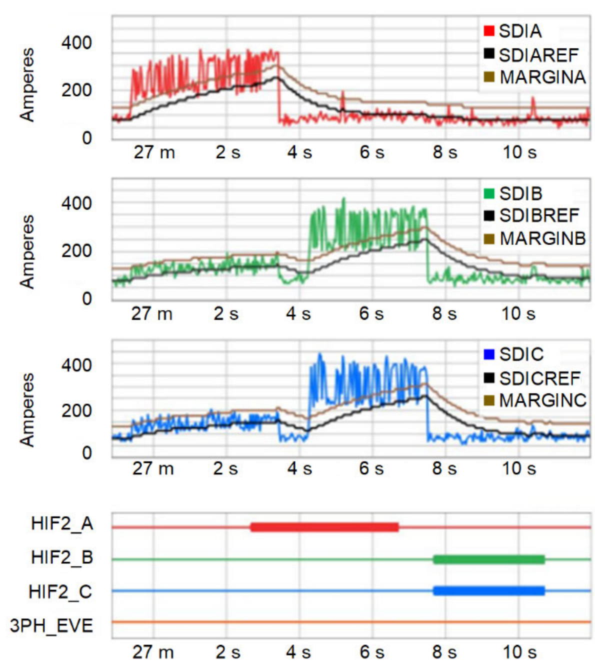

Fig. 4. SDI reference currents on each phase began to tune to SDI excursions; however, the excursions were too large and asserted the individual HIF2 elements.

The root-mean-square (rms) line currents in Fig. 5 were within expected ranges, with no obvious deviations that would trigger an HIF alarm. The rms line current showed brief spikes of small current magnitude that were directly correlated with the square-shaped HIF algorithm signatures but only varied by 2 amperes or less.

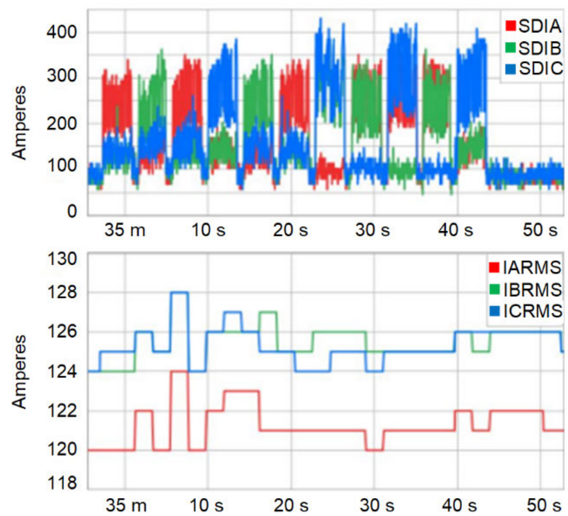

Fig. 5. RMS currents appeared to be of expected load values with brief increases that correlated with the SDI signatures.

An event from a different feeder showed a similar SDI waveform; only that time, one Phase C HIF2 element asserted, as shown in Fig. 6. The same waveform appearing on different feeders in different regions eliminated any one device or load characteristic as the root cause. That meant that the root cause was either a flaw in the HIF2 algorithm or a system-wide issue.

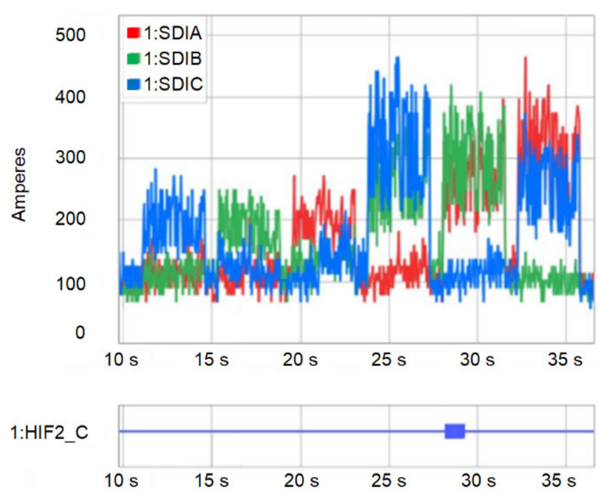

Fig. 6. Event showed a single instance of three-phase behavior that only asserted one HIF element.

The harmonic content of the HIF2_C assertion appeared to match normal levels with a total harmonic distortion of 13 percent, as shown in the 16-sample/cycle raw event report in Fig. 7. Based on this, PPL did not believe the false alarms were being caused by unusual loads on the system.

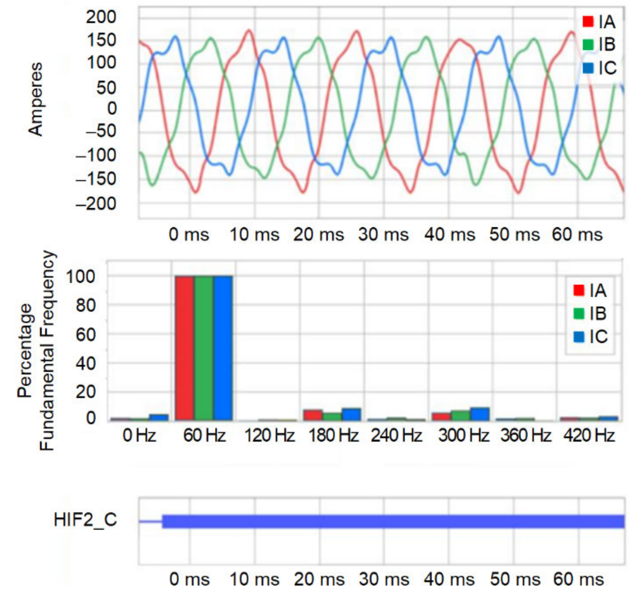

Fig. 7. Raw event capture showed normal harmonic levels during the HIF2_C assertion.

4) *Determining the Root Cause of the False Assertions*

After the false alarms, the pilot was paused so that the HIF algorithm, SCADA alarm points, and line equipment could be analyzed. Before restarting the pilot, PPL wanted to understand the HIF detection algorithm function and the resulting operational outcomes.

Following the false alarms, PPL met with the relay manufacturer and subject matter experts (SMEs) to discuss the false assertions and waveforms. The HIF algorithm includes calibration level settings that determine how long and how much SDI must deviate from SDIREF plus MARGIN to increment the HIF counters as well as how many counts assert the HIF fault and alarm outputs, as discussed in Section II. It was proposed that the false assertions could be avoided by adjusting these settings; however, changes to these settings would reduce HIF sensitivity and delay HIF algorithm assertion on legitimate HIFs. Reduced HIF sensitivity and delayed HIF assertion were not acceptable to PPL, but PPL agreed to adjust these calibration settings on a small test basis to see if assumptions about the resultant operation were accurate. However, even after the calibration settings were adjusted, the HIF false alarms continued.

False alarms were seen across the PPL distribution system. Substation-based feeder relays had such a high rate of false assertions that false alarms were continually being sent to the system operators. This made the HIF alarming functionality useless for HIF detection. PPL disabled transmission of HIF alarms through SCADA until a correction could be made. The increased false alarms on the substation-based relays were unusual because HIFs are typically masked by load current, which makes them more difficult to detect on substation-based relays. This led PPL and the SMEs to hypothesize that the cause of the false assertions was at the system level.

To test the hypothesis, a data acquisition (DAQ) device was tied into the current transformer (CT) and potential transformer (PT) circuits on a feeder with false HIF alarms (Fig. 8). The DAQ device was installed in the breaker to retrieve high-resolution sampling data in multiple formats over 24 hours so that the HIF algorithm development team could analyze the data to determine if corrections needed to be made to the HIF algorithms.

Fig. 8. DAQ device installed in the breaker at the PPL substation.

The initial data collected did not reveal the cause of the SDI excursions or how to adjust the HIF algorithms to ignore or tune out the excursions. It was discovered over the initial part of the pilot that PPL was transitioning to a wireless smart metering system that was replacing a power line carrier (PLC)-based metering system that transmitted metering information over the distribution system. To test whether the metering system was a potential cause of the false alarms, additional data were collected while the metering system was disabled.

Prior to the experiment, the feeder relays had been alarming approximately every 20 minutes. After the metering system was shut down for over an hour, there were no HIF alarms and SDI levels appeared flat, as shown by the triggered event in Fig. 9.

Upon reenabling the metering system, the metering transformers were heard transmitting metering information and these transmissions directly correlated to the relays producing an HIF alarm, as shown in Fig. 10. The pattern was the same as those seen in Fig. 2 and Fig. 6.

Alarms continued every 20 minutes thereafter. At this point, the root cause of the false assertions was attributed to the metering system, as verified by both the relay and the modeling of the data captured by the DAQ device.

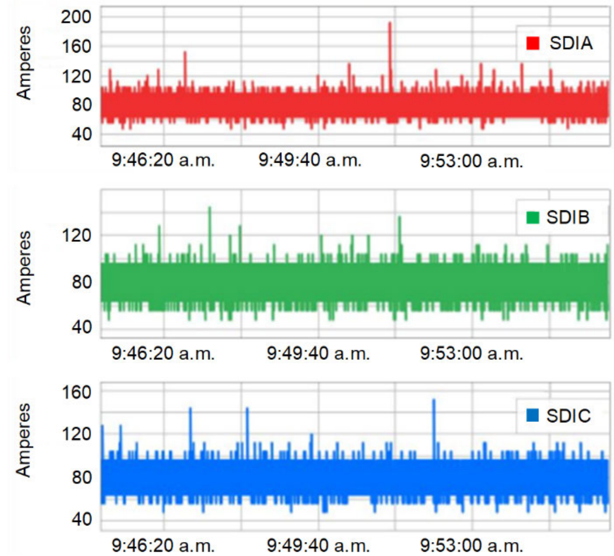

Fig. 9. HIF event triggered while metering system was disabled showed no SDI excursions

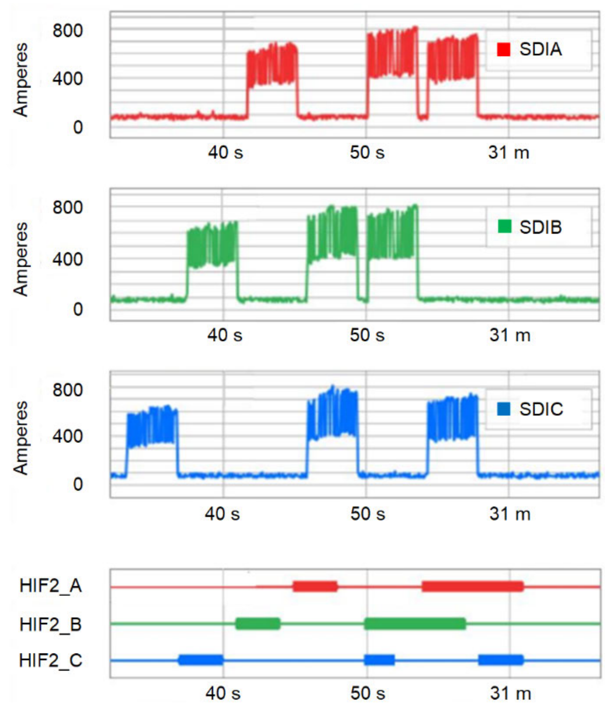

Fig. 10. HIF event capture triggered while the metering system was energized showed systematic SDI excursions similar to those seen in other false assertion events.

B. *Understanding the HIF Algorithm*

Having seen the system response following the initial implementation of the HIF algorithm, PPL took the following actions to use the HIF detection algorithm more effectively:

- Tested energized, downed conductors to better understand the algorithm response, as described in Section IV.
- Met with the relay manufacturer to better understand the HIF algorithm. It was agreed upon that more practical experience with the HIF algorithm was needed to use the HIF detection in the manner that PPL desired, as described in Section V, Subsection A.

- Studied the event records to find a solution to the false assertions while the metering system was in service, as described in Section V, Subsection B.

These actions allowed PPL to better understand how the HIF algorithm detected downed conductors and how to improve detection rates and filter out the false assertions. PPL then tested these assumptions and developed tripping logic that automatically detected and isolated HIFs.

IV. HIF Live Downed Conductor Testing

PPL performed HIF live downed conductor testing to verify that the HIF algorithm would operate in the necessary physical conditions. This section summarizes the HIF live downed conductor testing that was performed at EPRI as part of EPRI's program investigating modern solutions for downed conductor detection [3].

A. Test Procedure and Setup

Initially, PPL considered isolating a portion of their distribution system to do the testing, but finding a location where the relay and DAQ device could be installed and provided with load was logistically unrealistic. As a member of the EPRI team working on downed conductor detection, PPL chose to stage faults at an EPRI test site.

PPL provided a 200 kVAR three-phase capacitor bank to supply standing load current. Care was taken to ensure that the MVA rating of the capacitor bank at the 12.47 kV line voltage and the current transformer ratio would provide enough current to meet the 0.25 amperes secondary current required to tune the HIF algorithm. With a capacitor bank providing 9.3 amperes primary and a CT ratio of 100:5, load levels were 0.45 amperes secondary.

EPRI provided a 12.47 kV step-up transformer and pole-mounted recloser so that the downed conductor test site could be energized. Fig. 11 shows the test setup with the relay and DAQ device installed in a pole-mounted enclosure (located between the source transformer and the capacitor bank). This ensured the relay would always detect load current from the capacitor bank and that closing the recloser would only energize the downed conductor.

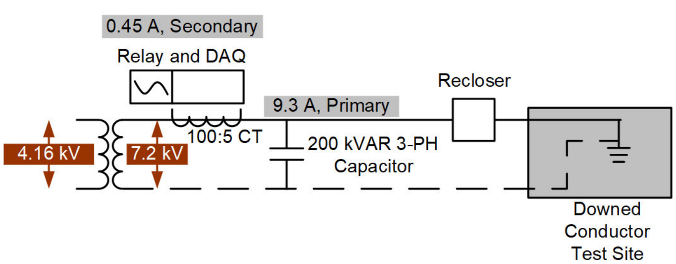

Fig. 11. Staged HIF setup included a 200 kVAR capacitor bank that provided load current that allowed the HIF algorithm to tune prior to the downed conductor testing.

The test plan steps were as follows:

1. Energize the capacitor bank 24 hours prior to the downed conductor testing to allow the HIF algorithms to tune.
2. Verify that the relay was in normal tuning mode by retrieving an event report for baseline SDI levels of capacitor bank load.
3. Set up the downed conductor with the test conditions (e.g., surface, length of conductor, and moisture). Test conditions are detailed in Table I.
4. Start recording on the DAQ device and then manually trigger an HIF event.
5. Energize the downed conductor by closing the recloser.
6. Monitor the relay for assertions (opening the recloser breaker once an assertion occurred or after no more than 10 minutes if no assertion occurred).
7. Retrieve the events from the relay and stop recording on the DAQ device.
8. Wait 10 minutes to allow SDI tuning to return to baseline SDI levels before repeating Step 3–Step 8 for subsequent tests.

B. Results

The retrieved event report (from Step 2) indicated that the SDI reference was approximately 12 amperes. The first test was of a downed conductor where most of the conductor was in contact with asphalt and approximately 11 ft was in contact with grassy ground. The surface contact is shown in Fig. 12.

Fig. 12. HIF Test 1 with the downed conductor lying primarily on asphalt with secondary grassy contact.

Following energization, the HIF2 element asserted in 2.233 seconds and HIA2 asserted in 19.233 seconds. SDI spiked randomly with peaks reaching over 100 amperes. Fig. 13 shows the SDI current waveforms and the behavior of the T7CNT*n* and T8CNT*n* counters during the event. Fig. 14 shows the pre-fault rms current at 12 amperes, with the fault current measuring as high as 24 amperes. Evidence of arcing that followed the event is shown in Fig. 15.

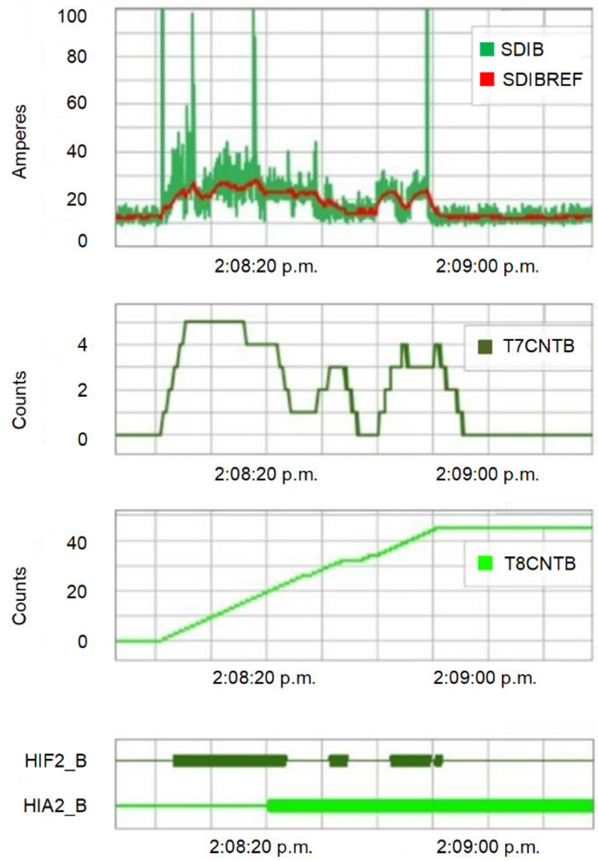

Fig. 13. HIF event capture for Test 1 showed alarm and fault assertions of HIF2 on Phase B.

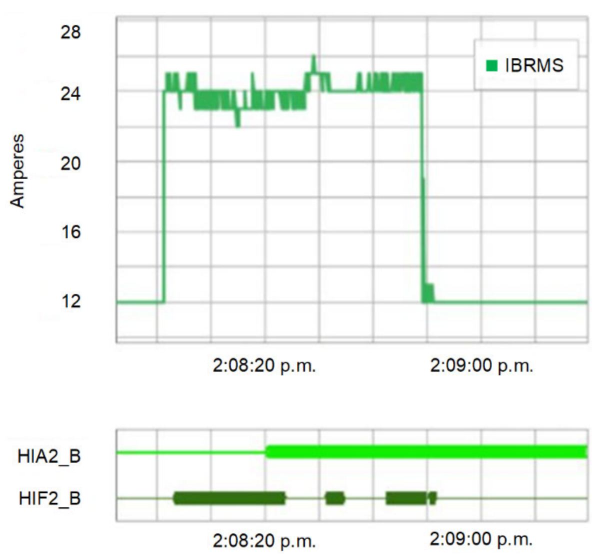

Fig. 14. HIF event capture for Test 1 showed only a small increase of fault current compared to the load current.

Fig. 15. Staged HIF Test 1 showed arcing on the grass following the test.

PPL performed 16 individual tests, and the results are documented in Table I. Table I provides the details of each test and the performance of the HIF2 algorithm alarm and fault counters. Table I provides the maximum rms current detected by the relay.

C. *Conclusions From Testing*

Testing confirmed that detection rates are dependent on the surface and physical conditions with which the downed conductor is in contact. Of the 16 tests, the HIF algorithms detected 8 faults. However, in tests that included grassy surfaces, detection rates were approximately 90 percent.

PPL was satisfied with the results of the downed conductor testing. The tests verified that there was a high rate of successful detection on grassy surfaces, which constitutes much of the PPL service area. The tests were run for only a few minutes so that later tests were not affected by normal tuning. It was determined that the HIF algorithms had a higher rate of successful HIF detection than current protection methods, even if those tests in which no fault was detected were included.

TABLE I
HIF LIVE DOWNED CONDUCTOR TESTING RESULTS

Test Number	Conductor Contact Test Surface	Test Duration (minutes)	Time Until First HIF2 Assertion	HIF2 Max. Counts	Time Until First HIA2 Assertion	HIA2 Max. Counts	Max RMS Current (A)
1	11 ft on grass with some asphalt contact	0.798	2.233 s	5	19.233 s	37	26
2	1 ft on grass with the remaining on asphalt	3.363	2.102 m	5	2.352 m	73	16
3	1 ft on grass with the remaining on asphalt	2.672	—	2	—	8	17
4	5 ft on grass with the remaining on asphalt	7.257	6.571 m	4	—	28	18
5	51 ft on clay soil	6.592	—	1	—	0	18
6	Test 5 with a few feet wrapped in a tree	>10	—	1	—	1	16
7	51 ft in a downed tree/bush	5.762	—	1	—	3	16
8*	25 ft on rocky dirt	3.597	—	2	—	5	39
9	25 ft on rocky dirt	3.187	—	2	—	6	37
10	25 ft (coiled) on rocky dirt	4.466	—	1	—	1	21
11	10 ft on grass, 2 ft on asphalt, with the remaining on clay soil	7.251	6.769 m	4	—	21	25
12	3 ft on grass, 5 ft on gravel, and 13 ft on dirt	6.306	—	3	4.214 m	32	32
13	Test 7 with the ground wet	7.939	—	1	—	3	20
14	Test 1 with the ground wet	7.012	4.677 m	5	1.094 m	66	40
15	Test 14 with the capacitor bank offline	>10	3.402 m	4	1.818 m	46	40
16	Conductor laid on top of a tire (rubber) and grass while the capacitor bank was offline	1.143	—	0	—	2	9

* HIA1 asserted in 12.667 s.

V. HIF ALGORITHM LOGIC ENHANCEMENTS

As a result of the field tests, the team understood how the HIF algorithms worked and how they could make meaningful settings considerations and enhancements to the logic. This section details theoretical applications of the HIF algorithms, followed by the logic chosen to meet the needs of PPL.

A. HIF Algorithm Considerations

As discussed in Section II, the HIF algorithm operates on a single-phase basis and contains alarm and fault bits for HIF detection logic as well as load reduction logic. These bits toggle during HIF conditions based on the randomness of arcing but only have their statuses updated once a second. This means that they can be used to alarm back to SCADA or in device functions such as latches or logic equations with dropout timers.

For example, an alarm sent to SCADA could be set as a latch function that is programmed for each of the phase-specific HIF algorithm outputs. Two more latches could be programmed for the other two phases, and all three could be reset using the same remote bit, as follows:

A_PHASE_LATCH_SET = HIF1_A OR HIA1_A OR HIF2_A OR HIA2_A #A PHASE HIF ALARM

A_PHASE_LATCH_RESET = R_TRIG REMOTE_BIT_01

B_PHASE_LATCH_SET = HIF1_B OR HIA1_B OR HIF2_B OR HIA2_B #B PHASE HIF ALARM

B_PHASE_LATCH_RESET = R_TRIG REMOTE_BIT_01

C_PHASE_LATCH_SET = HIF1_C OR HIA1_C OR HIF2_C OR HIA2_C #C PHASE HIF ALARM

C_PHASE_LATCH_RESET = R_TRIG REMOTE_BIT_01

Tripping logic can be developed to be conservative in that it can require more than just an HIF algorithm assertion to detect arcing. An example is logic designed to only assert when a large amount of harmonics are detected in a short period of time (HIF fault algorithm) along with a loss of load on the same phase, as follows:

A_PH_LOGIC = (HIF1_A OR HIF2_A) AND LRA #A PHASE DOWNED CONDUCTOR SUSPECTED

B_PH_LOGIC = (HIF1_B OR HIF2_B) AND LRB #B PHASE DOWNED CONDUCTOR SUSPECTED

C_PH_LOGIC = (HIF1_C OR HIF2_C) AND LRC #C PHASE DOWNED CONDUCTOR SUSPECTED

LATCH_SET = A_PH_LOGIC OR B_PH_LOGIC OR C_PH_LOGIC #DOWNED CONDUCTOR SUSPECTED

LATCH_RESET = R_TRIG REMOTE_BIT_01 OR UNLATCH_TRIP #RESET DOWNED CONDUCTOR ALARM

By design, this tripping logic is biased towards security and against dependability. If an HIF occurs far from the relay and the loss of load is minimal, the relay load reduction logic may not operate.

Another use case is to only use the HIF algorithm elements after a relay has tripped (e.g., when an initial fault occurs and there is enough current magnitude to trip a relay or recloser on the overcurrent elements). Depending on the device programming during open interval timing between reclosing shots, a power line could fall and lose contact with the initial fault point. When reclosing occurs, the line could be lying on a high-impendence surface, limiting the fault current so that it is below the overcurrent settings. Tripping and logic settings could be set to trip only after the first reclosing shot (SHOT_1) and to drive to lockout, as shown by the following logic that uses HIF2:

A_PH_LOGIC = (HIF2_A OR HIA2_A) AND SHOT_1 #A PHASE DOWNED CONDUCTOR SUSPECTED

B_PH_LOGIC = (HIF2_B OR HIA2_B) AND SHOT_1 #B PHASE DOWNED CONDUCTOR SUSPECTED

C_PH_LOGIC = (HIF2_C OR HIA2_C) AND SHOT_1 #C PHASE DOWNED CONDUCTOR SUSPECTED

LATCH_SET = A_PH_LOGIC OR B_PH_LOGIC OR C_PH_LOGIC #DOWNED CONDUCTOR SUSPECTED AFTER TRIPPING

LATCH_RESET = TARGET_RESET #RESET DOWNED CONDUCTOR AFTER TRIPPING DETECTION

This logic could also be expanded to include other reclosing shots. This logic works well with the alarm elements of the HIF algorithm because lingering arcing could be used to trip a device after an initial fault is detected.

The relay includes a high-sensitivity mode that enables the algorithms to operate on fewer counts and harmonics when HIFs are highly probable. Enabling the high-sensitivity mode during reclosing shots or for a period following a reclose cycle could help improve sensitivity.

These example logical functions could also be used to drive reclosing relays to lock out and prevent permanent HIFs from being re-energized, which could mitigate fire risk. Resetting logic could be used to require a line crew to reset the relay alarm or trip locally after a line has been repaired following an HIF.

B. Updated PPL Alarm Logic and HIF Functions

As discussed in Section III, PPL had a unique harmonic signature that bypassed the built-in three-phase event logic appearing across their distribution system. To mitigate the risk of false alarms caused by this unique signature, PPL implemented the following alarm logic:

A_PHASE_LOGIC = (ANY PHASE A HIF ELEMENT) AND NOT (ANY PHASE B HIF ELEMENT OR ANY PHASE C HIF ELEMENT)

B_PHASE_LOGIC = (ANY PHASE B HIF ELEMENT) AND NOT (ANY PHASE A HIF ELEMENT OR ANY PHASE C HIF ELEMENT)

C_PHASE_LOGIC = (ANY PHASE C HIF ELEMENT) AND NOT (ANY PHASE A HIF ELEMENT OR ANY PHASE B HIF ELEMENT)

This logic only alarms for single-phase HIFs. PPL applied the developed logic to dropout timers that would delay alarming until a period after the typical false assertions could not be detected by the HIF algorithm built-in three-phase event logic, setting each of the above conditions with a delay timer of 2.5 seconds. This time requires the HIF algorithm to be processed and give an HIF output for 3 consecutive assertions of the HIF logic, preventing a single assertion from creating a false alarm. The HIF testing in Section IV showed that detectable HIF conditions asserted an HIF element for longer than 3 seconds; therefore, the risk of missing an HIF condition seemed minimal. The only drawback to this timer was that the detection would be delayed for legitimate HIF events. PPL was comfortable with this delay in return for heightened security.

For the high-sensitivity mode, PPL implemented a 30-minute window following the first reclosing shot, so that even if an initial fault is cleared, the extended time frame would allow for the detection of a downed conductor on a surface on which it is harder to detect.

C. PPL-Implemented Protective Trip Functions

The team had tested and analyzed downed conductor events and understood the conditions that created solid contact with the ground and the signatures of the resulting arcing current. The next logical step was to add the HIF detection algorithm to the relay trip equation to automatically isolate the downed conductor upon detection. Based on practical experience, the following factors were considered in writing the tripping logic.

1) Not All Detections Are Downed Conductors

It was clear that PPL equipment was causing most of the false alarms, but it was unknown if other equipment could cause false detections. Of all the false events analyzed, only one was not a PLC metering signal, and that was correlated with a customer starting a large motor. Even with the filtering built into the relay alarm logic, the HIF detection functionality was not deemed secure enough to trip on alone.

2) *Practical Experience With the Physics of a Falling Conductor*

The team considered the sequence of events that occurs when an energized, downed conductor occurs and compared that to the known downed conductor relay events and found that in every case a normal protective relay trip occurred before the HIF. This is indicative of solid contact made during the initial fault, such as a tree contacting the phase wire, or the phase wire breaking but contacting another phase or the neutral as it falls to the ground. With this knowledge, the team added relay logic supervision that only allowed HIF detection to initiate a protective trip and lockout if a normal protective trip occurred first, followed by the downed conductor alarm after the reclose, indicating the wire was on the ground.

As mentioned, this sequence of events was correlated with 100 percent of the known HIF events at PPL, so it was deemed a secure method for supervising the HIF detection logic to initiate a protective trip and lockout. As of this writing, PPL has investigated more than 20 downed conductors detected by the HIF algorithms. These detections have resulted in one successful HIF protective trip, no false trips, and several more events where the HIF detection logic would have tripped correctly if it had been enabled. PPL continues to enable HIF tripping logic on a programmatic basis as the PLC metering system is replaced.

VI. Practical Event Analysis

This section analyzes the first event where a downed conductor was detected by the relay closest to the HIF. PPL received reports of an outage and dispatched a line crew to investigate. The line crew found a downed conductor that had fallen across a road. When PPL polled the closest device, they found that the relay had accurately detected the HIF on Phase A.

The event report in Fig. 16 shows a slight increase in rms current for slightly less than 9 minutes. During the event, Phase A rms current hovered at approximately 200 amperes except for a small jump to just under 575 amperes for 2 seconds. The most sensitively set elements (phase and ground time overcurrent) in the recloser relay were set at 600 ampere pickups. Normal load levels prior to the event were under 80 amperes.

In Fig. 17, large SDI spikes well above the SDIAREF value were seen over the course of 9 minutes. This resulted in an initial HIF2 assertion and a HIA2 assertion.

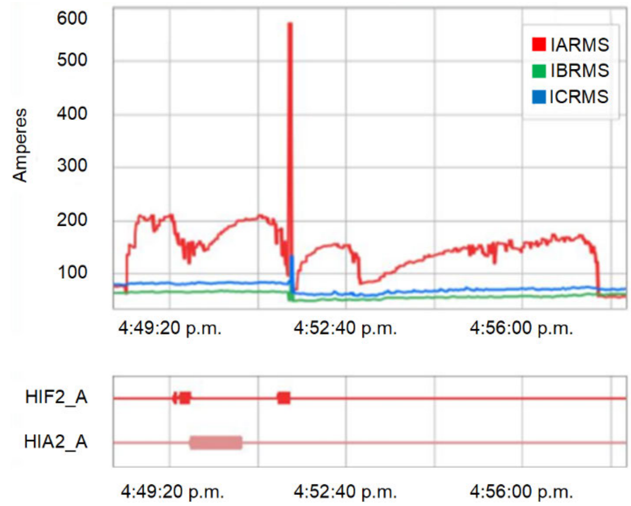

Fig. 16. HIF event capture of the downed conductor showed that the rms currents on Phase A were slightly elevated, but still below the 600 ampere pickup levels.

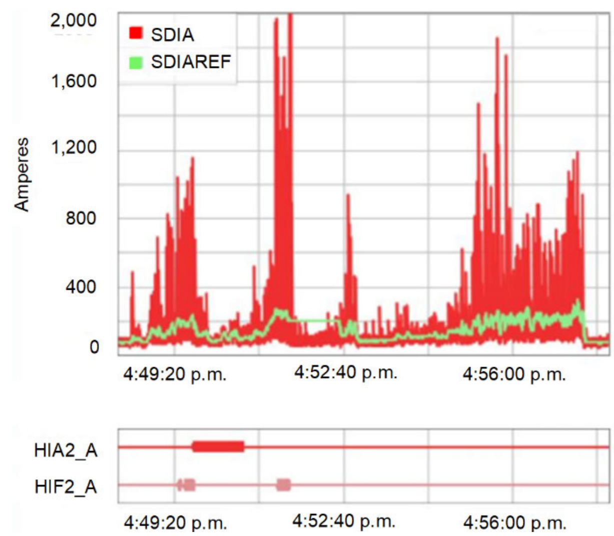

Fig. 17. HIF event capture of the downed conductor showed large SDI spikes on Phase A.

Between the first SDI excursion of SDIREF up to the initial assertion of HIF2, the algorithm took 57 seconds to assert, as shown in Fig. 17. Fig. 18 shows the T7CNTA count leading up to the HIF2_A assertion once T7CNTA reached 4 counts in 3 seconds.

HIA2 asserted in 1 minute and 14 seconds as the T8CNTA counter incremented to 30, as shown in Fig. 19.

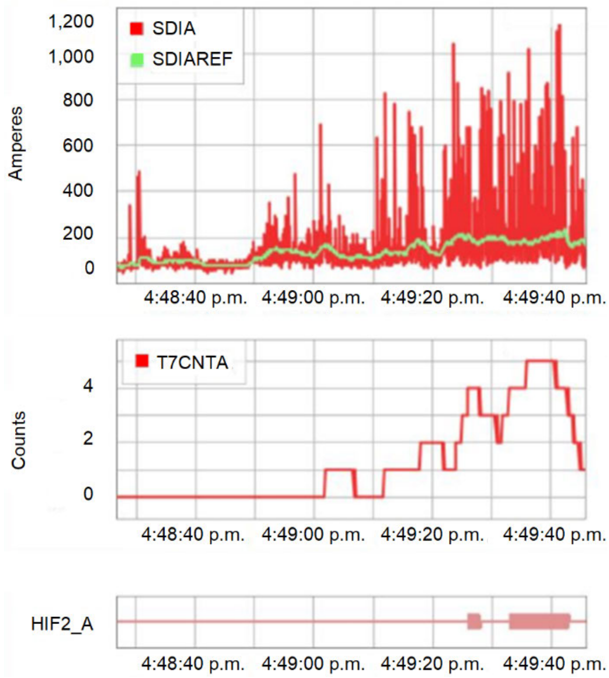

Fig. 18. HIF event capture of the downed conductor showed an HIF2 assertion as the interharmonic counter incremented 3 counts in 3 seconds.

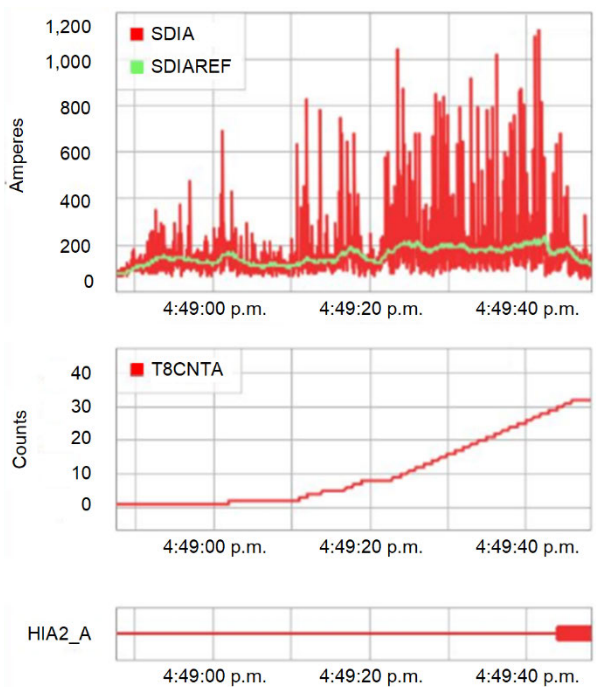

Fig. 19. HIF event capture of the downed conductor showed the HIA2 assertion as the interharmonic counter incremented 30 times.

VII. Conclusion

HIF detection continues to be a challenging and important venture for protection engineers and utilities. Detection methods can be susceptible to false operations based on various normal power system operations, such as arcing or harmonics from load or PLC-based metering. Care needs to be taken to understand the HIF detection principles used in protective relaying and use cases must be analyzed.

The PPL pilot application shows that an HIF detection algorithm that uses interharmonics can be successful in detecting HIFs both through staged fault testing and application on distribution feeders. This is especially true on grassy surfaces. There continues to be difficulty in detecting HIFs that only fully contact very good insulators that do not result in much arcing.

On its own, interharmonic analysis can detect HIFs and other power system occurrences. Using a system-based approach that brings in multiple inputs can help improve security and the confidence that HIF detection logic only asserts for HIFs. These inputs can include loss of load, metering communications loss, or other inputs.

PPL used HIF detection algorithms in their distribution protection devices successfully to improve the efficiency of their system. The HIF detection allows PPL to minimize the amount of time that energized HIFs are left on the system. PPL could also restore portions of their distribution system based on the more accurate isolation of HIFs to decrease customer impact. The implementation at PPL also improved the safety of employees and the public by decreasing the possibility of potentially dangerous conditions resulting from a downed conductor.

VIII. Acknowledgment

The authors gratefully thank Daqing Hou and Venkat Mynam for their support and expertise during the pilot. We would also like to thank Tom Short of EPRI for his support and insight on HIF detection during staged fault testing.

IX. References

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X. Biographies

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20191021 • TP6931-01