# Practical Experience With High-Impedance Fault Detection in Distribution Systems—Continued

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# Practical Experience With High-Impedance Fault Detection in Distribution Systems—Continued

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***Abstract*—Downed conductors and other high-impedance faults (HIFs) pose utility personnel and public safety concerns when left energized and unaddressed on distribution systems. Energized lines with HIF conditions can also result in equipment damage and prolonged outages. Traditional protective relaying may be unable to detect and isolate the faulted sections. This paper serves as a follow-up to "Practical Experience With High-Impedance Fault Detection in Distribution Systems," which detailed the desire of PPL Electric Utilities to implement the HIF detection algorithm on a pilot system and use the results of staged fault testing to improve their use of HIF detection. The paper also provided an analysis of a real-world event and recommended future HIF detection and system enhancements.**

**In this paper, we present how PPL has furthered their use of HIF detection on their distribution system following additional application experience. This includes insight into the informed remote tripping decisions that system operators perform based on alarm and supervisory control and data acquisition (SCADA) outputs from intelligent electronic devices (IEDs), loss of voltage, HIF detection decisions, and load loss. We explain the automatic isolation logic that PPL has developed based on their HIF detection and reclosing philosophies. The event analysis of successful manual and automatic isolation operations of downed conductors is provided. Lastly, we document examples in which the HIF detection at PPL detected other system conditions, such as failed power system equipment that resulted in electrical arcing.**

## I. Introduction

The detection of high-impedance faults (HIFs) on power distribution systems continues to be an endeavor that challenges both the sensitivity and security of protective relays and recloser controllers. Electric utilities must be careful to set protection settings so that they provide the most fault resistance coverage but do not create the possibility of false trips for heavy load conditions. To account for this gap in traditional protection, utilities can use HIF detection, which uses characteristics other than overcurrent level, to detect an HIF. Typically, HIF detection is not as familiar to protection engineers. HIF detection tends to require more time to understand and observational experience before it can be put into practice reliably and securely. Because HIF detection is still an imprecise science, utility personnel often need the effectiveness of the protection validated before being confident enough to implement it into a system. It is important that in addition to effective protection, HIF detection does not contribute to an increase in false alarms or trips.

PPL Electric Utilities performed a successful pilot of an HIF algorithm [1] during which they familiarized themselves with HIF protection and evaluated its effectiveness. The HIF algorithm in use is integrated into microprocessor-based protective relays and recloser controllers that use odd- and interharmonics to detect electrical arcing caused by HIFs, such as downed conductors [2].

With a successful pilot and practical application experience, PPL became confident enough in the operation of the HIF algorithm and its capability to detect conditions beyond those of downed conductors that it implemented HIF protection within its distribution system. PPL's practical experience has allowed them to use the HIF algorithm in a way that best compliments their existing system.

This paper details PPL's experiences and lessons learned as the HIF detection algorithm has been implemented systemwide. These experiences include a successful automatic trip of a recloser controller for a downed conductor and the unexpected detection of other system conditions where arcing was present.

Section II introduces PPL's implementation philosophy, expected operation for alarming, and automatic isolation. This section also provides a summary of PPL's HIF detection experiences.

Section III provides event analyses and lessons learned from successful manual and automatic operations of the HIF algorithms, including a trip function for automatic isolation and alarms for downed conductors.

Section IV documents the unexpected detection by the HIF algorithms of conditions beyond downed conductors, including the detection of a failing distribution transformer and a failing capacitor bank.

## II. Expected Operation and Detection Summary

PPL uses the HIF algorithm for alarms and manual and automatic isolations. This section introduces the HIF algorithm and provides further details of how system operators use the alarm functions to inform manual operations. It details how the tripping logic is built into protective relays and recloser controllers to provide automatic isolation for events that are likely caused by downed conductors.

### *A. HIF Algorithm*

The HIF algorithm employs odd- and interharmonic signatures that observe the randomness of arcing that occurs during HIF conditions. There are two independent subsets of the algorithm for HIF detection: HIF Algorithm 1 (HIF1) that uses the odd-harmonic content and HIF Algorithm 2 (HIF2) that uses the interharmonic content. In this paper, only HIF2 is discussed as it is the only algorithm available in the recloser controllers and because there has been minimal experience with HIF1 in substation relays at PPL.

The HIF2 algorithm works on a per-phase basis and establishes a tuning threshold of the total interharmonic content of each phase known as the sum-of-difference current reference (SDIREF). The sum-of-difference current (SDI) is compared to the SDIREF plus additional margin to determine if the change is large enough to indicate an HIF condition. The margin allows for slight changes in SDI current during load changes.

The HIF algorithm requires a minimum phase current of 0.05 • nominal current secondary to begin tuning. When a 1000:1 CTR is used with a recloser controller, the minimum threshold required for tuning is 50 A primary. The threshold must be exceeded for a 24-hour initial tuning period to learn expected trends. If the current drops below the minimum threshold, the 24-hour timer restarts. This process can be monitored in a device by observing the ITUNE_*n* (*n* = Phase A, B, or C) digital bits. During the ITUNE process, the HIF output for the phase in ITUNE is defeated and HIF2_*n*/HIA2_*n* cannot assert. After 24 hours, ITUNE_*n* desasserts and NTUNE_*n* asserts, which shifts a device to normal adaptive tuning that slowly tunes the SDIREF to changes in normal load over the course of normal operation.

The algorithm has HIF2_*n* fault outputs that operate for large changes in SDI over a short period and HIA2_*n* alarm outputs that operate for smaller changes in SDI sustained over a longer period. The operation of these outputs is determined by counters that track the difference between the SDI and SDIREF plus margin reference values. These counters can be monitored with the analog quantities, T7CNT*n* for the HIF2_*n* outputs and T8CNT*n* for the HIA2_*n* outputs. The HIF algorithm also contains supervisory logic to block the HIF2/HIA2 outputs for three-phase conditions (3PH_EVE). The supervisory logic drives decision clearing logic, which drives the T7/T8 counters to zero so that they do not assert for undesired conditions.

The last part of the HIF algorithm that PPL uses is the high-sensitivity mode (HIFMODE). This setting allows the user to define conditions where there may be a higher probability of an HIF condition occurring and increases the probability of an HIF assertion by requiring fewer counts for an output to assert.

### B. *Alarming Logic and Manual Isolation*

The HIF algorithm outputs are passed through a series of logical filters and are then latched and sent as DNP3 binary inputs to the system operator. This creates a static alert that an HIF may be present.

HIF_A_PHASE_ALARM_LATCH is set by the Phase A HIF alarm HIF_A_PHASE_ALARM_SECURE_INPUT and resets under three-phase or Phase A close conditions or a target reset. This logic ensures that once an alarm is established, it remains asserted until it is manually reset.

HIF_A_PHASE_ALARM_LATCH_SET := HIF_A_PHASE_ALARM_SECURE_INPUT_TIMER

HIF_A_PHASE_ALARM_LATCH_RESET := R_TRIG (CLOSE_A OR CLOSE_3_PHASE) OR LOCAL_TARGET_RESET OR REMOTE_TARGET_RESET

Security is built into the alarming scheme to ensure that only a single phase alarms within a period of 150 cycles.

HIF_A_PHASE_ALARM_SECURE_INPUT := (HIA2_A OR HIF2_A) AND NOT (HIA2_B OR HIA2_C OR HIF2_B OR HIF2_C)

HIF_A_PHASE_ALARM_SECURE_INPUT_TIMER := HIF_A_PHASE_ALARM_SECURE_INPUT

HIF_A_PHASE_ALARM_SECURE_INPUT_TIMER_PU := 150 cycles

Alarm latches, secure inputs, and timers on Phases B and C follow similar logic.

When an HIF alarm is received, the operator takes no immediate action but is "on notice" to look for other indications of an HIF. These indications include the following:

- Sudden load reduction, including total loss of load
- Loss of voltage on a downstream device, but voltage on an upstream device
- End user calls about sparking wires or poor voltage
- Emergency services call(s)

If operators receive any of these indications, they initiate a ping of all the devices downstream from the recloser controller that sent the HIF alarm, make an educated determination as to the location of the downed conductor based on the presence of voltage, and then open the device closest to the location.

If no indications are reported within a certain amount of time after the initial alarm, the system operator manually resets the HIF alarm. If an alarm reoccurs, the operator notifies the engineering department that a persistent alarm is present, and engineering personnel investigate the root cause.

### C. *Automatic Isolation*

For automatic isolation, additional decision logic is applied to the HIF alarms. The decision flow is shown in Fig. 1:

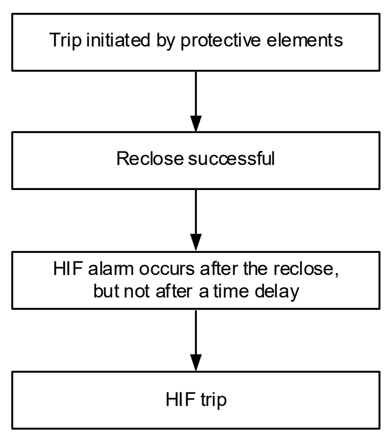


Fig. 1. Automatic isolation decision flow.

PPL implemented an enable condition with a dropout timer in which an HIF trip only occurs if there is an HIF alarm(s) 15 minutes after reclosing. The condition is set as follows:

HIF_TRIP_ENABLE := ((R_TRIG RECLOSE SHOT 1 OR 2) AND (RECLOSER IN CYCLE MODE)) AND NOT HIF_SUPERVISION_TIMER AND REMOTE_ENABLE

HIF_TRIP_ENABLE_TIMER := HIF_TRIP_ENABLE

HIF_TRIP_ENABLE_TIMER_DO := 15 minutes

The HIF_SUPERVISION_TIMER logic serves as a supervisory check that defeats the HIF_TRIP_ENABLE if there is a traditional (non-HIF) protective trip up to 10 minutes after an HIF alarm.

HIF_SUPERVISION := R_TRIG
HIF_A_PHASE_ALARM_LATCH OR R_TRIG
HIF_B_PHASE_ALARM_LATCH OR R_TRIG
HIF_C_PHASE_ALARM_LATCH

HIF_SUPERVISION_TIMER := HIF_SUPERVISION

HIF_SUPERVISION_TIMER_DO := 10 minutes

REMOTE_ENABLE is a latch set and reset by SCADA operators. REMOTE_ENABLE allows remote operators to enable or disable automatic HIF tripping of a recloser controller via SCADA.

The HIF TRIP logic includes the individual phase HIF alarms that are supervised by the REMOTE_ENABLE and HIF_TRIP_ENABLE logic.

HIF_TRIP := (R_TRIG
HIF_A_PHASE_ALARM_LATCH OR R_TRIG
HIF_B_PHASE_ALARM_LATCH OR R_TRIG
HIF_C_PHASE_ALARM_LATCH) AND
REMOTE_ENABLE AND
HIF_TRIP_ENABLE_TIMER

PPL's logic was developed over several years of observational and then practical experience with the HIF algorithm. The basis for the logic is the assumption that a falling conductor contacts the neutral, causes a fault that operates typical overcurrent protection, hits the ground, and then re-energizes when the recloser controller recloses, at which time the HIF alarms activate and initiate an automatic trip with no reclose. If no HIF alarm occurs after the 15-minute time delay, the tripping element self-resets and the HIF algorithm is only able to alarm.

PPL enables HIFMODE for a period after the first reclosing shot is attempted. Based on PPL's field experience, HIFs most commonly occur in the 5 minutes following a reclose. Because this reclosing state is logically available in the relay, PPL enables the HIFMODE for 5 minutes after the first reclosing shot is issued to help detect HIFs.

HIFMODE := ((R_TRIG RECLOSE SHOT 1) AND
(RECLOSER IN CYCLE MODE)) AND NOT
HIF_SUPERVISION AND REMOTE_ENABLE

### D. *HIF Detection Experience Summary*

PPL has investigated 33 known cases of HIFs (including downed conductors, arcing conditions, and equipment failures) and they were able to take immediate isolation action on 94 percent of the HIFs. The remaining two cases were not detectable by the HIF algorithm due to low current levels that did not allow the HIF algorithm to tune prior to their occurrence.

Since the implementation of automatic tripping logic in 2019, PPL's results have been as shown in Table I:

TABLE I
HIF DETECTION SUMMARY AFTER 3 YEARS OF EXPERIENCE

| HIF Outcome | Number of Events | Percent of Total |
|---|---|---|
| Successful automatic HIF operations | 10 | 30% |
| Successful manual HIF operations | 21 | 64% |
| HIFs that were unable to be detected | 2 | 6% |

In addition to the 33 cases of known HIFs on PPL's system, there were 8 HIF algorithm operations where no associated HIFs were found. The primary contributing factors for undesired HIF alarms and trips were Mylar balloons contacting lines and cases where 3PH_EVE was unable to properly secure the HIF algorithm outputs. The protective relay manufacturer has developed firmware enhancements to further secure HIF algorithm outputs for these cases that PPL has not yet implemented.

## III. HIF EVENT ANALYSES AND LESSONS LEARNED

This section provides detailed analyses of successful manual and automatic isolation of HIF conditions and the lessons learned from each one.

### A. *System Operators Manually Isolated a Circuit After an HIF Alarm Due to a Downed Conductor Caused by a Car Accident*

The event occurred shortly after the initial pilot and prior to the development of the automatic logic described in Section II. PPL system operators received HIF alarms and began to look for indications of an open phase. When additional indications were found, system operators remotely operated the recloser controller. PPL was later informed that there had been a downed conductor after a vehicle crashed into a utility pole.

### 1) *Event Analysis and Alarms*

A review of the event reports revealed that the HIF alarm spanned two event reports because a previous HIF event trigger had asserted and started recording prior to the HIF occurring. Combining the events revealed that the T7 counters for Phases A and B counted towards alarm and that HIF2_A and HIF2_B asserted, as shown in Fig. 2.

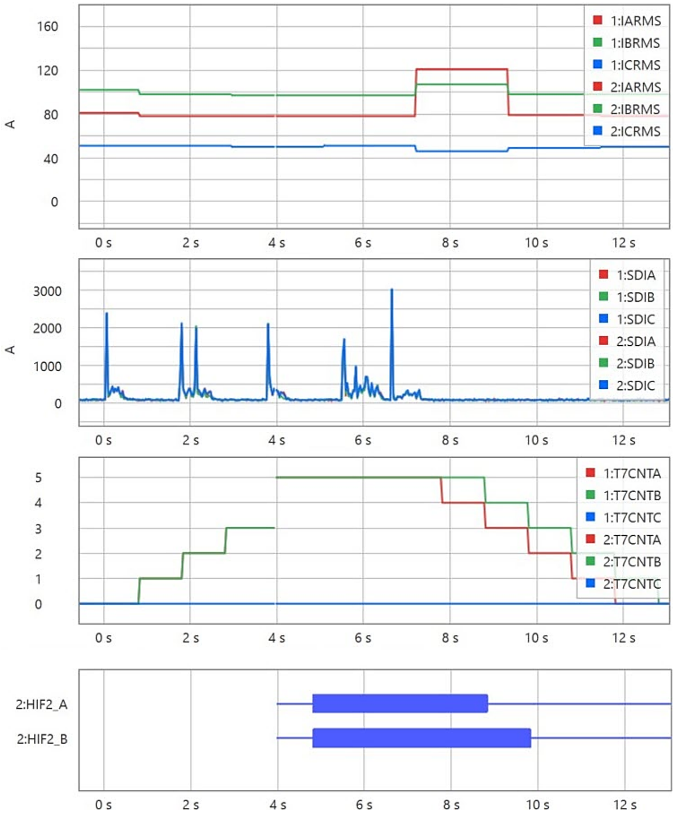


Fig. 2. HIF2 algorithm asserted on Phases A and B less than 5 seconds after SDI activity was detected.

A similar SDI signature was observed across all three phases. It was found that while Phases A and B were in normal tuning, Phase C was still in initial tuning, which resulted in the Phase C alarms not being active. The 3PH_EVE logic was still active and restrained the T7 counters from incrementing for three-phase activity. This can be seen 20 minutes before the alarm in Fig. 3.

Fig. 3 also shows an upstream recloser controller tripping and reclosing twice (labeled 1 and 2 in Fig. 3) when an increase of current was detected prior to the period of zero current flow. Approximately 20 minutes before the HIF alarm, ITUNE_C can be seen dropping out. This was due to the Phase C current dropping below the tuning threshold, which suggested the HIF algorithm was unable to complete 24 hours above the minimum tuning threshold to move the Phase C HIF algorithm into normal tuning.

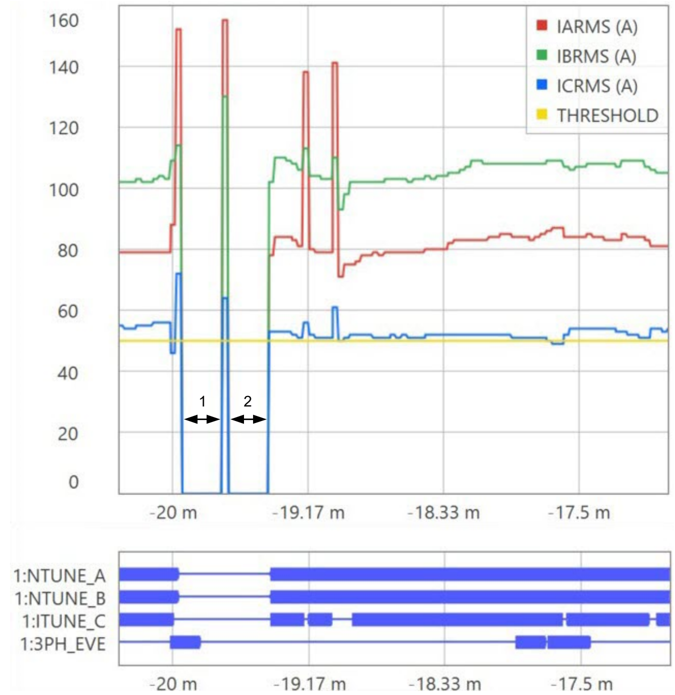


Fig. 3. HIF2 algorithm tuning behavior showed the Phase C initial tuning drop out as Phase C rms currents dropped below the minimum current threshold.

After reclosing, there appeared to be SDI activity and smaller current increases on Phases A and B. T7CNTA and T7CNTB count but no HIF output asserted, as shown in Fig. 4.

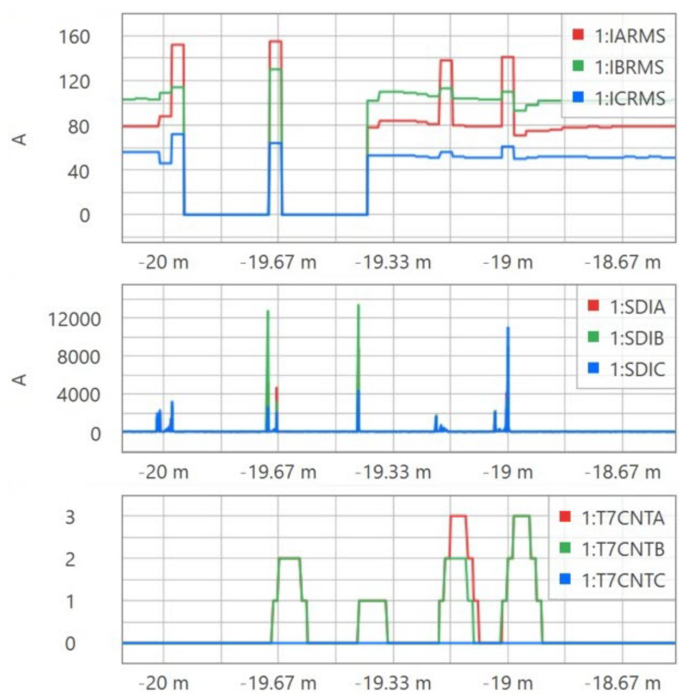


Fig. 4. SDI spike and the associated current change.

### 2) Lessons Learned

This event was considered the first successful field HIF detection at PPL because the alarms helped to locate a downed conductor that otherwise would have gone undetected until emergency calls reporting the accident reached the operators.

The SDI activity that caused the HIF alarm was close in magnitude to the spikes seen 20 minutes prior. Because it was known that this event was caused by an actual HIF condition, there was the possibility that the detection was delayed or that the algorithm was not sensitive enough to detect the HIF. Because the T7 counts were just one count away from HIF fault assertion, enabling HIFMODE would have resulted in an HIF alarm 20 minutes earlier.

Early in PPL's HIF algorithm experience, only HIF reports were retrieved. For all future events, all the event reports, including raw and filtered events, would need to be retrieved. Higher resolution event reports would allow for increased insight into future events.

## B. A Tree Limb Was Found on a Line by a Line Patrol

In this event, a recloser controller (Recloser 1 in Fig. 5) detected HIF assertions on Phases A and B over 3 minutes after a fault was isolated by a downstream device (Recloser 2 in Fig. 5).

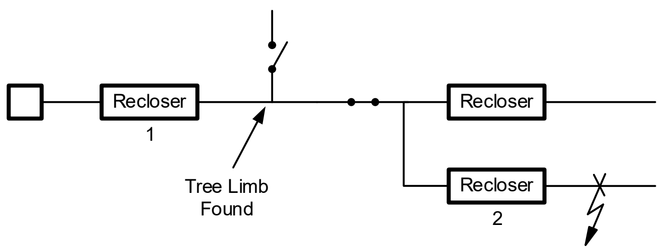


Fig. 5. Circuit diagram and sequence of operation.

### 1) Analysis of Initial Fault and Trip Event

Fig. 6 shows the downstream fault rms current on Phase A along with the HIF2 assertion 3 minutes and 47 seconds later.

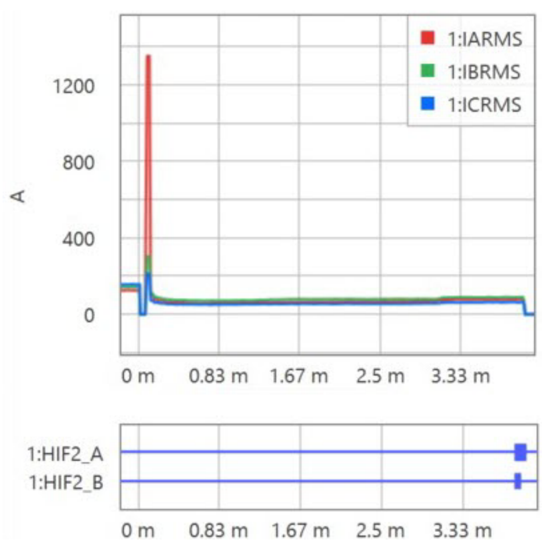


Fig. 6. HIF2 fault outputs asserted 3 minutes after a downstream fault was cleared.

Further inspection of the SDI current showed spikes of activity that were sustained only on Phase A. The T7CNTA of the Phase A HIF2 algorithm was sustained long enough to allow HIF2_A to remain asserted past HIF2_B, which allowed the HIF trip (SV50T) to occur, as shown in Fig. 7. This illustrates the security of the tripping logic. The logic does not respond when multiple phases alarm; the three-phase activity was seen several seconds before the Phase A only activity. The logic dependability is displayed by the five bursts of SDIA after 234 seconds that keep T7CNTA sustained to maintain the HIF2_A assertion.

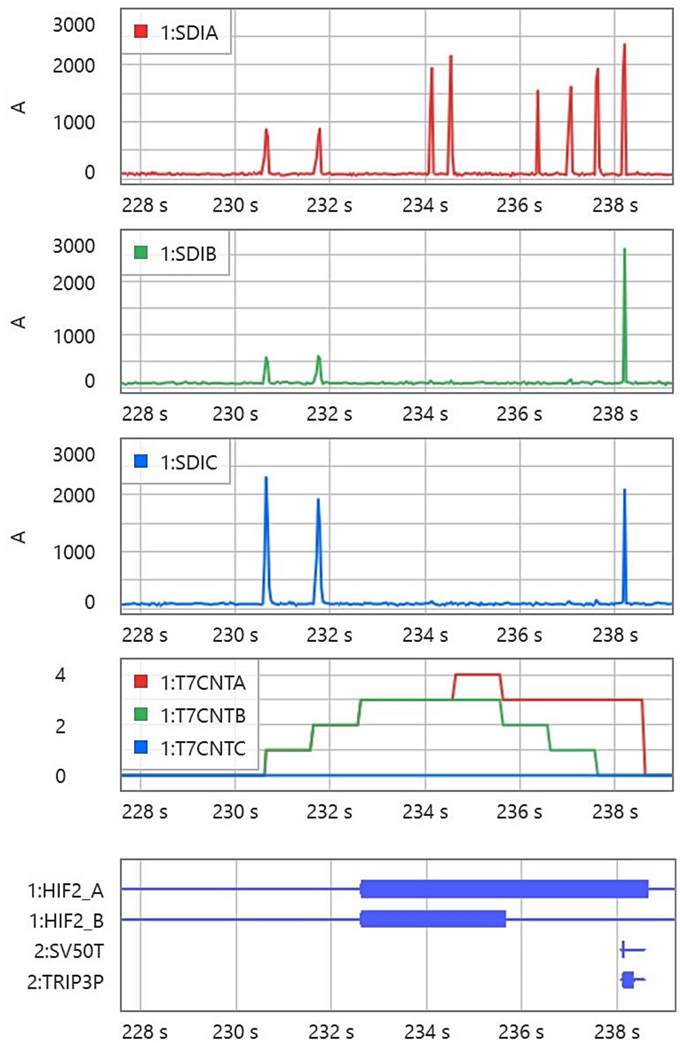


Fig. 7. Recloser controller tripped on SV50T.

The recloser controller tripped and locked out. A line patrol was dispatched to investigate, and they located and removed a tree limb from the line approximately an hour later. The line was closed approximately 10 minutes later and no additional alarms or trips occurred.

### 2) Lessons Learned

Because no downed conductor was found, it was speculated that this event was indicative of what arcing from a tree limb caught in a line could look like in terms of an SDI signature.

The event occurred early in the tripping experience of PPL and crews that initially dispatched to investigate were specifically searching for a downed conductor. PPL determined that a trip should result in further investigation of the line because more than a downed conductor could result in a trip.

### C. *Detection of Tree Encroachment on a Distribution Line*

In this event, a tree made repeated contact with a medium-voltage line, which caused frequent arcing events that did not draw enough current to trip a protective device but did cause enough transient voltage sag for end users to continually complain of flickering lights. Eventually, the contact had become severe enough that overcurrent was detected, the fault location was found, and upon investigation, it was determined that the HIF algorithm had identified arcing going back at least 2 years. This knowledge indicated the possibility of proactive tree trimming via arc-detection algorithms if the arcing detection could be correlated with a phase and location.

#### *1) Fault Detection and HIF Event*

Table II shows the event history on the day solid contact occurred and resulted in an alarm being sent to the system operator to indicate a potential HIF event.

TABLE II
EVENT HISTORY

| Time | Phase | Magnitude |
|---|---|---|
| 18:24:34.334 | BG | 800 |
| 18:24:39.610 | BG | 795 |
| 18:24:40.868 | BG | 808 |

Fig. 8 through Fig. 10 show the oscillography for each of the BG events.

These three events occurred in rapid succession on the same day with no final outage occurring. The system operator alerted engineering personnel to perform an investigation. The phase and location were correlated using oscillography. During the investigation, engineering personnel noticed that the HIF function had counted, which was similar to an occurrence from 2 years prior.

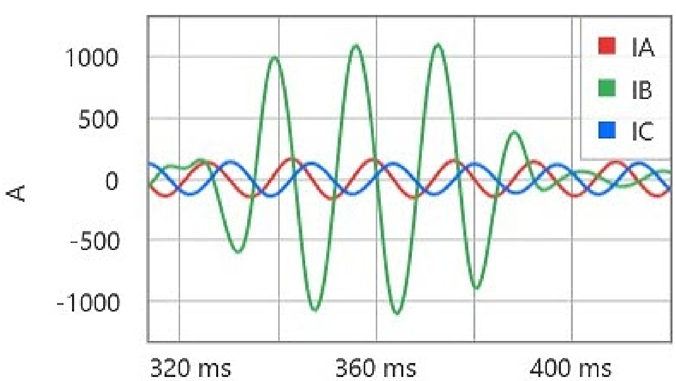

Fig. 8. First BG detection.

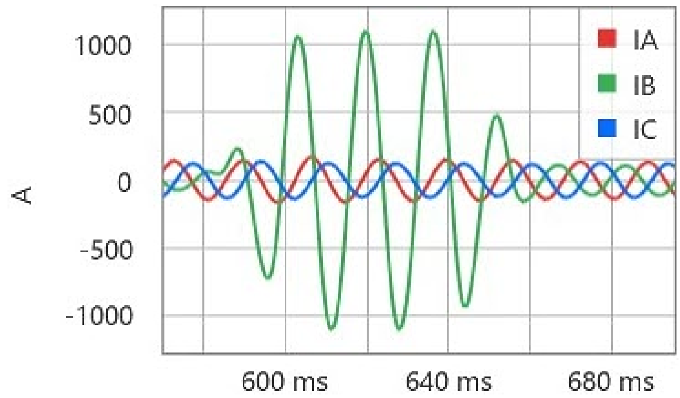

Fig. 9. Second BG detection.

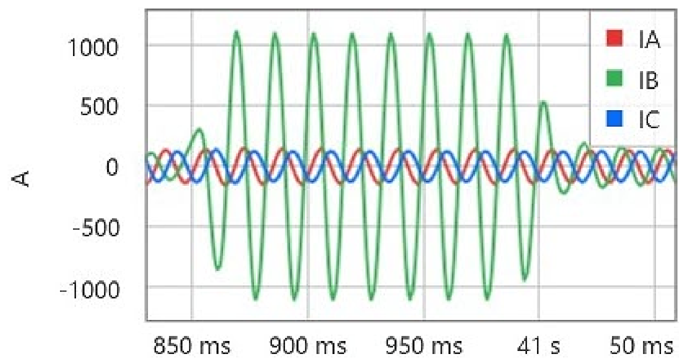

Fig. 10. Third BG detection.

Fig. 11 shows each of the SDI spikes seen during the fault that correspond to Fig. 8 through Fig. 10. The SDI spikes were directly related to the initial fault current and did not provide HIF alarm outputs because arcing was not sustained.

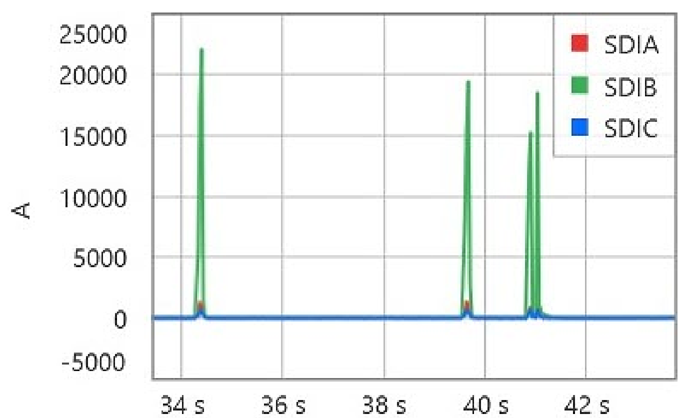

Fig. 11. Close-up of third HIF event.

Fig. 12 shows the SDI activity from the operation that occurred 2 years prior. The SDI shows three separate events with a shorter window between each event and on a different phase (Phase A) than the more recent event.

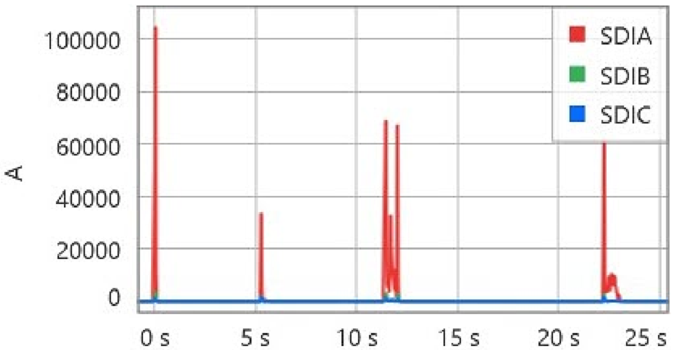


Fig. 12. Previous HIF event.

### 2) *Lessons Learned*

A line patrol found burn marks and tree encroachment and an engineering investigation also revealed arcing residue, which indicated that arcing had occurred. Further investigation showed that the HIF algorithm had recorded arcing 2 years prior; however, the corresponding event record showed a transient, BG fault with similar magnitude, leading the team to conclude that the tree encroachment was at least 2 years in the making and that the HIF algorithm had correctly detected this encroachment via arcing. PPL believes this knowledge can be leveraged to develop a proactive tree-trimming strategy using arc-detection algorithms.

## *D. A Downed Conductor Was Detected by Multiple Recloser Controllers*

This event provided insight into the coordination of multiple relays or recloser controllers equipped with the HIF algorithm and how they can coordinate for the distribution circuit shown in Fig. 13, which includes a distribution substation circuit breaker and recloser controllers. Recloser 1 was operating as a midpoint recloser and Recloser 2 was operating as a normally open tie.

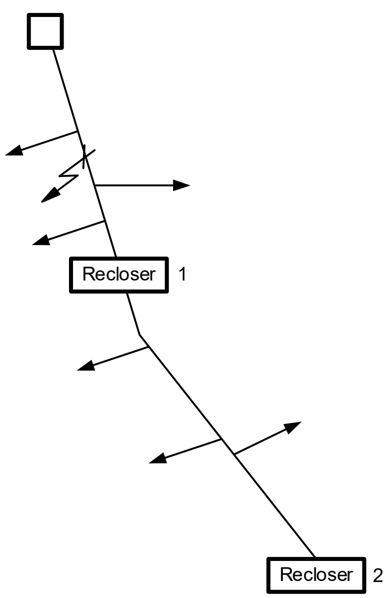


Fig. 13. Distribution circuit diagram.

### 1) *System Operation*

An initial fault that was upstream from Recloser Controller 1 resulted in a substation circuit breaker trip. The fault was a downed conductor downstream of the substation circuit breaker that caused the circuit breaker to trip to lockout. These reclosing operations occurred when the power source potential transformer on the source side of the recloser controller dropped out for each trip and reasserted with each close, which can be seen in Lines 15 through 20 of the Sequential Events Recorder (SER) in Fig. 14.

| | | | | |
|---|---|---|---|---|
| 20 | 12/22/2020 | 05:16:39.109 | PWR_SRC1 | Deasserted |
| 19 | 12/22/2020 | 05:16:40.296 | PWR_SRC1 | Asserted |
| 18 | 12/22/2020 | 05:16:42.985 | PWR_SRC1 | Deasserted |
| 17 | 12/22/2020 | 05:16:59.269 | PWR_SRC1 | Asserted |
| 16 | 12/22/2020 | 05:17:27.202 | PWR_SRC1 | Deasserted |
| 15 | 12/22/2020 | 05:17:46.359 | PWR_SRC1 | Asserted |
| 14 | 12/22/2020 | 05:20:10.150 | PWR_SRC1 | Deasserted |
| 13 | 12/22/2020 | 05:23:02.877 | TRIP3P | Asserted |
| 12 | 12/22/2020 | 05:23:02.877 | OC3 | Asserted |
| 11 | 12/22/2020 | 05:23:02.881 | OC3 | Deasserted |
| 10 | 12/22/2020 | 05:23:02.915 | 52A3P | Deasserted |
| 9 | 12/22/2020 | 05:23:02.915 | 52AC | Deasserted |
| 8 | 12/22/2020 | 05:23:02.915 | 52AB | Deasserted |
| 7 | 12/22/2020 | 05:23:02.915 | 52AA | Deasserted |
| 6 | 12/22/2020 | 05:23:03.077 | TRIP3P | Deasserted |
| 5 | 12/22/2020 | 05:24:13.257 | LT06 | Deasserted |
| 4 | 12/22/2020 | 05:24:13.791 | OREDHIF2 | Asserted |
| 3 | 12/22/2020 | 05:24:15.792 | OREDHIF2 | Deasserted |
| 2 | 12/22/2020 | 06:57:24.471 | TRIP3P | Asserted |
| 1 | 12/22/2020 | 06:57:24.671 | TRIP3P | Deasserted |

Fig. 14. Recloser 1 Sequence of Events report.

This can also be seen in the HIF events where the rms currents dropped to zero. Large SDI spikes were seen across all three phases at the same time as the rms current step changes in Fig. 15. This activity was caused by the breaker operating, and the HIF alarms were correctly blocked by the 3PH_EVE logic.


Fig. 15. HIF2 event showed upstream CB operation and 3PH_EVE restraint.

System operators opened the recloser controller to isolate the fault, which is shown by the TRIP and OPEN commands in SER Lines 11 through 13. The TRIP and OPEN commands were followed by the recloser controller breaker contact opening (Lines 6 through 10). This is verified by the lack of current seen in at the beginning of Fig. 16.

When operators closed Recloser Controller 2 (tie point), both Recloser Controller 1 and Recloser Controller 2 indicated a Phase C HIF alarm. As illustrated in Fig. 16, there was a brief, large SDI spike around the time the tie was closed, followed by SDIC activity over a minute later, which resulted in an HIF2_C assertion.

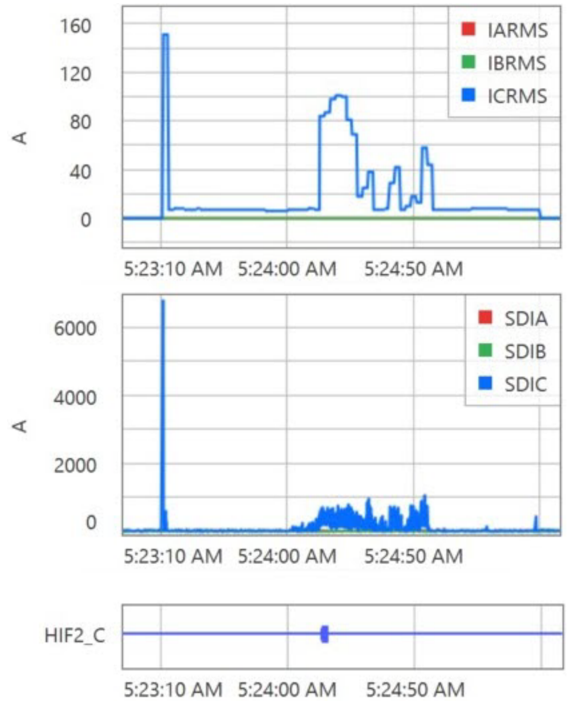


Fig. 16. HIF2 event showed SDI activity after breaker closure, which resulted in the operation of HIF2_C.

Because Recloser 1 was supposed to be open, system operators expected not to see any current. The SDI and rms current also existed on only Phase C. Further investigation revealed that this recloser controller had only a single 52A contact for all three phases. The only way current could have flowed is that the recloser was not actually open on Phase C when it was supposed to be. This was later verified in the field.

Fig. 17 looks in more detail at the SDI that resulted in the energization of the downed conductor on Phase C. SDIC experienced sustained random activity but only counted at the start of the event. The energization of this downed conductor by the tie breaker resulted in enough current to start to tune the algorithm. The current was below the threshold needed for automatic retuning long enough that the algorithm would automatically retune the next time current was higher than the minimum threshold.

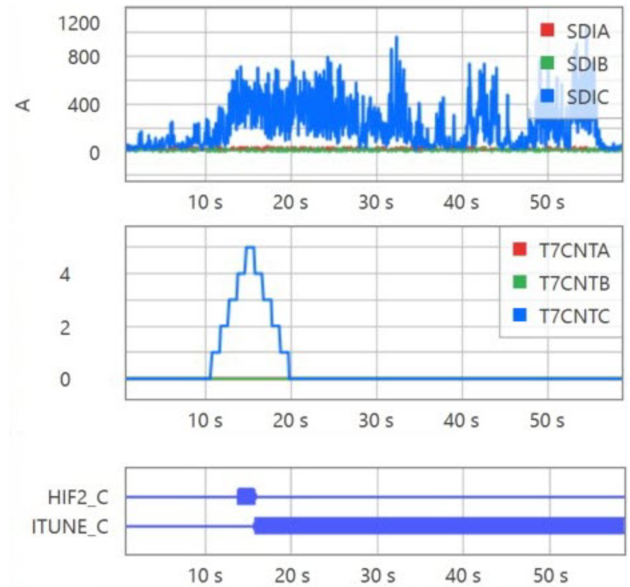


Fig. 17. HIF2 event showed HIF2_C assertion and initial tuning restart.

### 2) *Lessons Learned*

This event provided an example of how multiple recloser controllers can detect the same HIF and how they can be coordinated or polled to help operators make informed decisions. It is not always the case that multiple devices will detect an HIF. HIFs are more difficult to detect the further away a device is from the HIF because of increased load and the attenuation of the high-frequency components of SDI over longer feeder distances.

Investigating the events and device locations and determining current flow helped determine the location of the downed conductor. Having multiple devices (e.g., substation circuit breaker relay, recloser controller, and the tie recloser controller) enabled with HIF detection also helped call attention to a recloser controller in need of maintenance. Without the HIF detection indicating arcing, the continued current flow would not have been detected with other standard recloser controller settings, and the breaker contact would have mistakenly reported the recloser breaker as open.

## IV. HIF Algorithm Detection of Failing Power System Components

This section provides a discussion of events where the HIF algorithm detected HIFs caused by conditions other than downed conductors or tree contact.

### A. *HIF Algorithm Detected a Failing Transformer*

In this section, we discuss the detection of a failing overhead transformer that was caused by internal arcing within the transformer. After a successful trip and reclose by an upstream relay, the recloser controller HIF algorithm detected an incipient fault and asserted an alarm. This was a critical operation because the transformer fuse had not opened and there was no visible indication of a failure on the transformer. The alarm allowed the issue to be discovered before the transformer experienced a catastrophic failure.

#### 1) *Trip and HIF Event*

A relay upstream from the transformer detected the fault via a fuse-saving curve, tripped to save the fuse, and initiated an HIF algorithm count. The fault on Phase A of approximately 400 A, peak, was cleared in 3 cycles. This was an expected operation; the relay correctly detected a fault and tripped on the fuse-saving curve to save a fuse from a transient fault.

The most efficient fault clearing operation would have been the opening of the transformer fuse, which would have affected the fewest end users. The oscillography shows enough current after the initial fuse-saving trip and reclose that the fuse could operate; however, the failure was not sustained long enough to operate the fuse. The HIF algorithm was able to detect arcing during the period after the initial reclose. The line patrol found the failure via infrared scan while on patrol and was able to decommission and replace the transformer before a catastrophic failure occurred. The fuse cutout was also replaced as a precaution.

#### 2) *Lessons Learned*

A line patrol found no downed conductor; however, the line patrol did find the failing transformer via infrared scan. After an inspection of the transformer, the line patrol believed the transformer would have catastrophically failed, which would have created a possible public safety hazard. It is not clear if the fuse failed to operate or dropped out of the cutout.

PPL considered this a correct operation. While it would have been desirable for the transformer fuse to operate during the initial fault or after the first reclose when the fuse-saving scheme was blocked, neither of these occurred, and the fuse did not operate.

### B. *HIF Algorithm Detected a Failing Capacitor Bank*

This event was caused by a broken throttle on a fuse cutout on a downstream capacitor bank. The recloser controller tripped on an HIF alarm after a successful reclose operation that traditional overcurrent protection would not have detected.

#### 1) *Analysis of Recloser and Capacitor Bank Operation*

There was a Phase A-to-ground fault in which the recloser controller tripped on the 51G1T ground time-overcurrent element, as seen in Fig. 18.

Five seconds after the traditional protection trip, the recloser controller closed in and successfully held. As discussed in Section II, Fig. 19 shows the activation of SV47 (HIF_TRIP_ENABLE) when a device issues a reclosing shot (SH13P) after a protective trip. This enables an HIF tripping condition if an HIF alarm asserts after a device closes back in.

Fig. 19 shows an inductive system after the first protective trip. This is important to note as a capacitor bank was the direct cause for the HIF trip. The angle of the phase voltages was leading the angle of the phase currents by approximately 30 degrees. By adding a capacitor bank to the system, the difference between the angles can be lowered for a more efficient system.

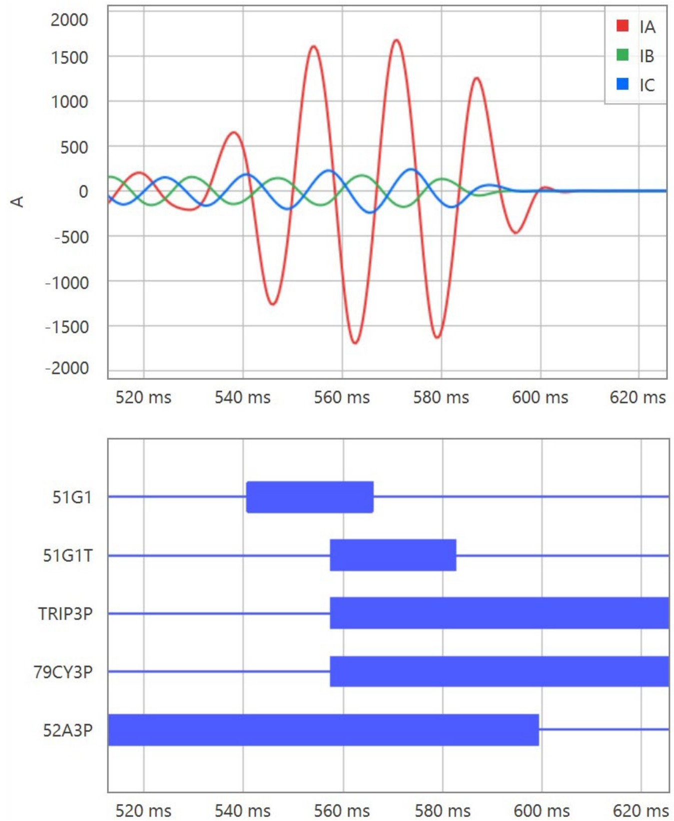


Fig. 18. Phase A-to-ground fault that initiated the reclose.

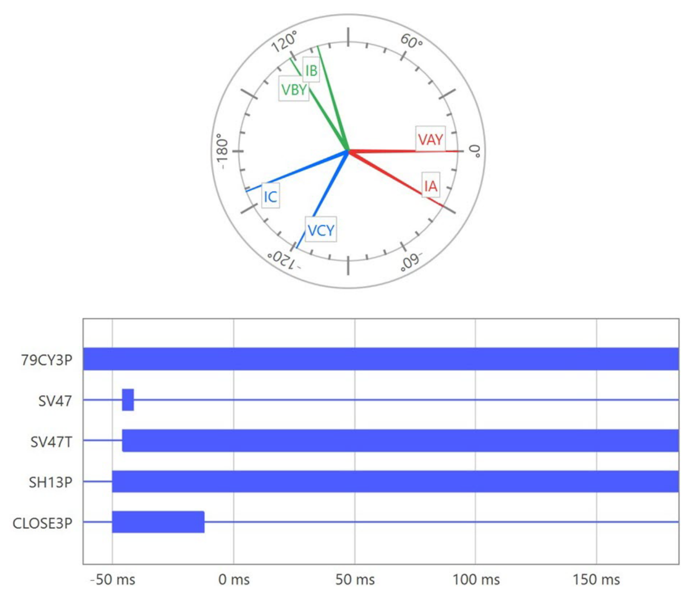


Fig. 19. First reclose shot into an inductive circuit.

Before the HIF trip, the system is suddenly capacitive, as shown by Fig. 20. This is indicative of a downstream capacitor bank being switched in. When the downstream capacitor was switched in, the failed throttle affected the current on the system.

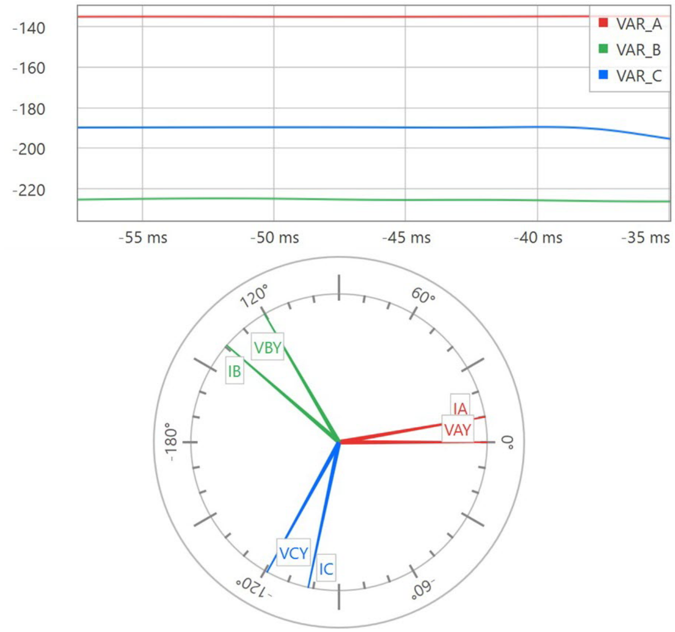


Fig. 20. VARs before drive-to-lockout.

After the successful reclose, the recloser controller asserted an HIF alarm. As shown in Fig. 21, HIF TRIP ENABLE (SV47T) was still active while the B PHASE HIF_ALARM (SV45T) asserted. The HIF_B_PHASE_ALARM_SECURE_INPUT_TIMER expired, which ensured that only a single phase was in an alarm state. This set LT13 (HIF_B_PHASE_ALARM_LATCH), which then tripped the recloser through SV50T (HIF_TRIP).

The throttle was causing arcing across Phases B and C. This arcing can be seen in Fig. 22. This was the state of the system just before the recloser drove to lockout.

This event shows an instance where the HIA2 alarm function of the HIF algorithm asserted and resulted in the subsequent alarm and trip. The SDI levels are much smaller than other events presented and are sustained over 90 seconds. The delay in the start of the T8CNTB counting was due to decision clearing logic as a result of the breaker opening from the initial protective trip.

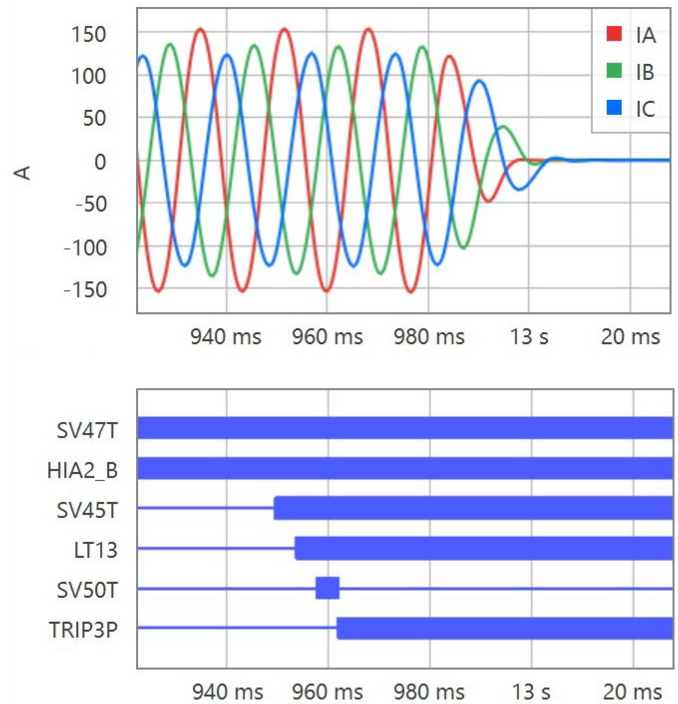


Fig. 21. Fundamental current HIF2 trip.

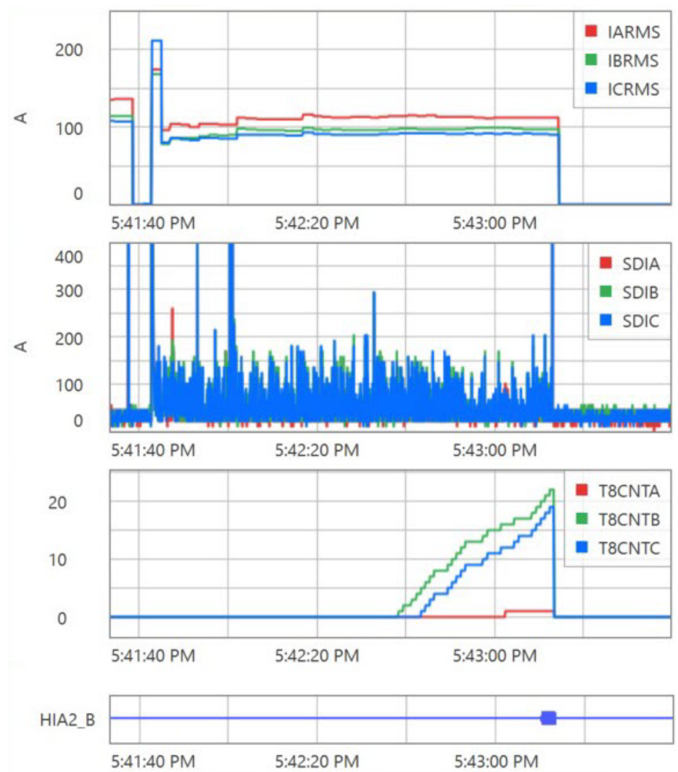


Fig. 22. HIF event showed Phases B and C simultaneously counting towards alarm.

### 2) Lessons Learned

By allowing an HIF alarm to trip the recloser controller, PPL found a broken throttle on a fuse cutout on a capacitor bank. This would have been a reoccurring fault that could have resulted in significant damage or possible safety risk if the line was continually re-energized. The change from negative-to-positive VARs on all three phases confirmed that the fuse on Phase B still had continuity and that the connection was not secure, which resulted in just enough arcing to be detected by the HIF logic. By detecting arcing, utilities can use it as a tool to detect equipment failures.

## V. Conclusion

These events show a cross section of successful events that PPL has experienced since the systemwide implementation of the HIF algorithm. Most of the HIF detections are energized, downed conductors that are detected via alarming or are automatically isolated via the trip algorithm and logic. The analysis of these events has enhanced PPL's confidence in this logic. PPL has observed an acceptable success rate for detection of HIFs across their system.

The HIF algorithm detects more than downed conductors, which is evidenced by the events where no downed conductors were found. This led to further insight into power system equipment failures that contained arcing, such as the transformer and capacitor bank failures and indications of arcing tree contacts. We believe this has uncovered a novel use that needs further exploration for arc-detection algorithms.

The goal of this paper is to provide the HIF detection experience of PPL to other companies in the industry to provide a basis for others looking to improve HIF detection rates and the detection of more than downed conductors.

## VI. References

[1] M. Kistler, F. Heleniak, and T. Varshney, "Practical Experience With High-Impedance Fault Detection in Distribution Systems," proceedings of the 46th Annual Western Protective Relay Conference, Spokane, WA, October 2019.

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## VII. Biographies

**Mychal Kistler** earned his BS in electrical engineering from Excelsior College. Mychal joined PPL Electric Utilities in 2007 and is a protection engineer. His responsibilities include protective relay settings and standards development. Mychal is a registered professional engineer in the state of Washington.

**Frank Heleniak** earned his BS in electrical engineering and BS in physics from Widener University in 2014 and MS in electrical engineering from Villanova University in 2018. Frank joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2014 as an associate application engineer in power system protection. He later became a regional technical manager, and his responsibilities included protective relaying application support and technical training. Frank currently serves as the sales and customer service director for the northeast U.S. Frank is a registered professional engineer in the state of Pennsylvania and a senior member of IEEE.

**Chad Kennedy** earned his BS in electrical engineering from the University of Dayton in Dayton, Ohio in 2006. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2012 and works as a protection application engineer in King of Prussia, Pennsylvania. Chad has been a local meter expert for the last 7 years. He has been an IEEE member for 13 years.

**Gabe Maday** earned his BS from Drexel University in Philadelphia, Pennsylvania in 2017. Gabe joined Schweitzer Engineering Laboratories, Inc. (SEL) as a protection application engineer in King of Prussia, Pennsylvania, focusing on transmission line protection and emerging technologies. He presently serves as the regional technical manager of the northeast U.S. Gabe has been an IEEE member for 6 years.


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