Recent Utility Experience with High Impedance Fault Detection

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I. Abstract:

High-impedance fault detection technology – that is, detection of conductor arcing, or a conductor energized on the ground (downed conductor), has been available in digital relays since the mid 1990's. The IEEE Power System Relay and Control Committee (PSRCC) has recognized the issues surrounding this problem and has published both a guide and a consumer presentation of the associated issues and dangers. One implementation of this technology has been adopted by Potomac Electric Power Company (PEPCO) and has been in service since the early 2000's over most of their system. Note that on detection of a Downed Conductor on the PEPCO system, this protection function will Trip the associated feeder. Over the past 8 months, PEPCO has conducted a detailed monitoring study on the efficiency of the High Impedance fault technology installed on their system. This paper will provide a short overview of the implemented technology as well as the findings of this 8-month study.

Key Words:
High Impedance fault detection, HiZ, Downed Conductor (DNC);

II. Introduction:

High-impedance fault detection technology has been available in Digital Relays since the mid to late 1990's. Various technologies and techniques have been employed, however, the devices deployed on the PEPCO system make use of current signatures present in arcing faults. Specifically, it has been identified that arcing faults exhibit a significant increase in odd, even, and non-integer half-harmonics. The subject algorithm computes Harmonic Energy through the implementation of a 2-cycle Fast Fourier Transform (FFT) that decomposes the aforementioned harmonic content. Computing the sum of the squares of the various harmonic energies results in values of odd, even, and non-integer harmonic energies. A dynamic level of the harmonic energy is computed and "positive" indication of arcing is provided if any of the harmonic energy categories exceeds the dynamic threshold.

A second identifiable characteristic of an arcing fault is the "variance" in harmonic energy. Figure 1 below shows one of the harmonic energy components. Of note is the randomness of the energy pattern. The detection algorithm evaluates the high to low to high transitions of the computed energy and asserts a "positive" if such a pattern is identified. If the harmonic energy and randomness arcing characteristics are present in a series of data windows, an ARCING DETECTED alarm is issued by the relay.

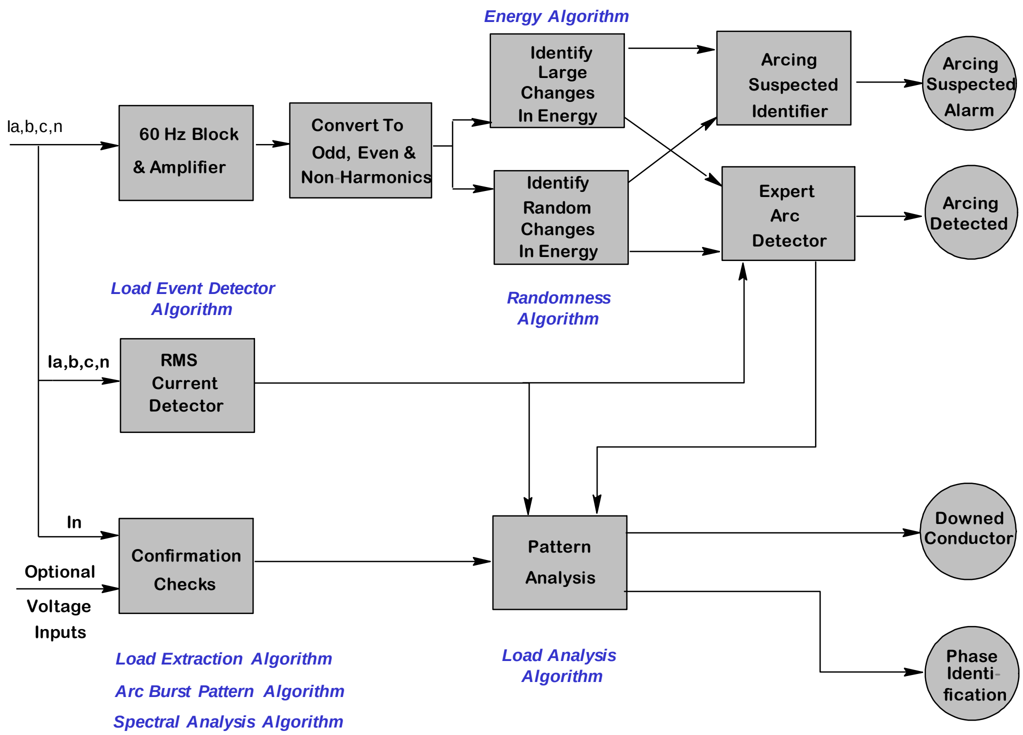


Figure 1. Flow chart of the employed algorithm

There are number of power system events in addition to downed energized wires that also exhibit ARCING characteristics – for example, a contaminated insulator, malfunctioning arrester, etc. Another example is the switching of capacitor banks, occurring multiple time per day and creating significant and sustained high-frequency current and voltage transients.

In order to further "securely" classify a downed conductor event, the status of the fundamental current is analyzed by the relay. Specifically, when a conductor breaks, there is typically a loss of load followed by arcing. Additionally, as the conductor falls, there is often an overcurrent event associated with conductor coming into contact with other phases or objects on its way to the ground. Identification of either of these two conditions – prior to arcing detected – results in the classification of an arcing event as a downed conductor. It should be noted that in the previous report on PEPCO's experience with downed conductor detection [1], it was noted that 70% of the downed conductor classifications were preceded by an overcurrent trip followed by a high-speed reclose that held.

These are utility requirements and expectations for the successful high-impedance fault detection system:

- Operate only if a high-impedance fault is truly present. Do not operate for anything else.
- Detect both intact downed conductors (conductor still maintain continuity but laying on the ground) and broken downed conductors (conductor is physically broken and laying on the ground).
- Detection speed is important but not critical. There must be an opportunity for conventional overcurrent protection to operate first and sectionalize the fault first, operating only if conventional protection does not operate with HiZ fault pattern still present.

- Use additional sources of information including voltage, breaker operation, pattern of current changes in all 3 phases to further distinguish HiZ faults securely.
- Employ given power system learning to learn the typical baseline feeder background noise and harmonic content to adjust algorithm sensitivity accordingly.
- Allow fine tuning of the HIZ algorithm functionality with settings to achieve optimal performance.
- Bias the system toward security. Significant false alarms or trips will cause the system to be shut down.

III. PEPCO HiZ Implementation and Experience

First incorporated in 1909, Pepco provides electric distribution service to the Washington DC area along with its adjacent Maryland suburbs, serving a population of over 2.3 million people over 640 square miles of service territory. Its distribution system consists of nearly 1,500 13kV feeders, nearly half of which are overhead in 4-wire multi-grounded wye configurations.

Beginning with an initial deployment of several hundred GE UR-F60 relays utilizing a second specialized DSP module in the relay for high impedance fault detection, Pepco began its pilot of high impedance downed conductor detection in the early 2000s by providing alarm-only indications via SCADA for suspected downed wires. Having observed a positive correlation between alarms and field reports of downed conductors, tripping was implemented into the relays soon after to provide protection against high impedance faults involving downed wires.

Pepco now has over 750 GE UR-F60 relays equipped with high impedance fault detection capability providing downed conductor protection on nearly all Pepco overhead feeders. Each relay is programmed to trip its respective feeder breaker and provide SCADA targets for detected downed conductors. The algorithm and its configurable settings have remained unchanged since its initial deployment with the factory recommended settings still in use today.

High impedance downed conductor protection schemes operate in conjunction with traditional overcurrent relaying and auto-reclosing schemes deployed on overhead feeders. Pepco's feeder overcurrent protection standard includes both time and varying levels of instantaneous overcurrent elements to provide both effective clearing of faults and to minimize damage.

A significant number of downed wire events begin with an operation of the traditional feeder overcurrent protection followed by a successful auto-reclose that holds. This results in an energized downed wire condition that cannot be detected by conventional overcurrent means. The GE UR HiZ detection algorithm continuously monitors the feeder for signs of arcing and one of two triggering conditions (Overcurrent or loss-of-load). Once a downed conductor is declared by the relay a trip command is sent to the feeder breaker and it remains locked out until the feeder is patrolled.

Energized Downed Conductors are difficult to detect but pose a safety hazard to both employees and the public along with creating the potential for property damage. As a type of High Impedance Fault, downed conductors may only provide fault currents on the order of 0-100 Amps, making them indistinguishable from load current and making them invisible to conventional overcurrent protection schemes. For this reason, FLISR (Fault Location, Isolation and Service Restoration) schemes are unable to locate and isolate high impedance downed conductors due to their reliance on overcurrent targets.

It is understood that downed wire detection is an inherently challenging task and that no present technology can achieve 100% accuracy. With that challenge there is a balance between safety and reliability that must be considered. Given the monumental importance of safety to employees and the public, an evaluation of downed conductor detection was performed on the Pepco system with the aim of improving the algorithm and its settings to provide maximum security while preserving reliability.

Pepco's evaluation involved approximately 780 relays over a seventeen-month timeframe. This represents 1105 relay-years of operation. Like the 2006 study, the 2020 study had the following criteria: 1) having an indication from an operator log or from a target report and 2) having relay data to support analysis and from which to draw conclusions about the relay's operation. By cross-referencing the operator log comments and relay data Pepco recorded 42 downed conductor indications on the feeders instrumented with high-impedance fault relays.

The 42 events were further classified into three classifications: successful operation, non-downed conductor HiZ operation, and unsuccessful operation. A successful operation indicated that the relay tripped for downed conductor and the corresponding operator log mentioned wires on the ground when the site was visited. A non-downed conductor HiZ operation indicated that the relay tripped for downed conductor and the corresponding operator log does not mention the wires on ground found. Examples of a non-downed conductor HiZ operation included a burnt off tap, tree interference, balloon interference, a cable fault, and a failed splice. Lastly, an unsuccessful operation indicated that the relay tripped for downed conductor and the operator log mentioned that no fault or no wires down was found. Table 1 depicts two examples of each classification.

Target	Distribution System Operator Comments	Classification	Reason
DNC-B	At 1009, circuit tripped with DNC. At 1012, customer reports wire down. At 1111, OH Lineman reported AØ primary down due to primary making contact with a tree limb. At 1238, OH Lineman reported blown BØ fuse & a burnt up BØ cutout. OH Lineman reported BØ primary was off insulators at two poles. At 1241, OH Lineman reported BØ primary is back up. OH Lineman installed a cutout with dead blade. At 1348, OH Lineman reported BØ primary was secured to insulators.	Successful	Wires Down
DNC-A	At 1651, circuit tripped with DNC. At 1656 MCFB reported multiple broken poles and wire down due to large tree. SF6 switch will not open via supervisory for sectionalizing purposes. Close via supervisory, restoring partial load. At 1825, OH Lineman reported broken pole and 10 spans of wire damaged and hanging low due to large tree. The next day, Mobile Operator reported 2 operations at AØ, CØ, ground, and time.	Successful	Wires Down
DNC-C	At 1451, circuit tripped with CØ DNC. Received a report of wire arcing. At 1514, OH Lineman reported nothing found at call location. At 1522, OH Lineman reported burnt off over the arm tap. At 1541. OH Lineman reported tap remade. Closed by supervisory; restoring all load. The next day DNC CØ targets were reported.	Non-downed Conductor HiZ	Burnt Arm Tap

DNC-A	At 1518, OH Trobleman reported balloons on AØ that got into BØ and tracked in the rain. At 1545, OH Trobleman reported balloons removed. At 1606, received NL calls. At 1628, Mobile Operator reported targets of AØ DNC and HiZ with 5 operations. At 1647, OH Lineman reported customer saw sparking and was investigating. At 1659 OH Lineman reported the AØ Tie and AØ IC on feed through with the IC not having a dust cover leaving it open to water was the cause for it to arc. Nothing was plugged into the module. OH Trobleman reported all 3Ø energized where BØ and CØ have open cutouts, AØ continues and is energized to cable. At 1734, OH Lineman reported AØ elbow closed on feed through (IC in field, Loop Tie on feeder print) is testing de-energized, fuse likely blown.	Non-downed Conductor HiZ	Balloon Interference
DNC-B	Circuit tripped with DNC. At 1739, no reports form PGFB. At 2011, OH Lineman reported he patrolled de-energized portion of circuit, with no fault found. Close via supervisory, restoring all load. At 2028, Mobile Operator reported targets of zero operations CØ and ground time with DNC ground operation. Operation.	Unsuccessful	Nothing Found
DNC-C	Circuit tripped with CØ DNC. At 0023, OH Lineman patrolled feeder and reported nothing found. Closed by supervisory restoring all load.	Unsuccessful	Nothing Found

Table 1. Operation classification examples

The 42 events consisted of 29 successful downed conductor operations, 6 non-downed conductor HiZ operations, and 7 unsuccessful operations. This results in a 70% successful operation detection rate and an 83% overall HiZ detection rate, which combines successful operations and non-downed conductor HiZ operations.

IV. Analysis and Examples of HiZ Operations

A. Successful DNC Operation

The case under consideration is an actual Pepco event where the Hi-Z algorithm correctly declared a "Hi-Z Downed Conductor-A" (i.e., downed conductor in phase A) on a 13kV overhead radial distribution feeder. For this event, downed wires were found on the feeder with the conductor down on the ground in a right-of-way.

Figure 2. HiZ oscillography for a True Downed Conductor Operation of F60 Hi-Z element.

The downed conductor logic of the relay's Hi-Z element is armed only by either an IOC or a Loss-of-load (LOL) event. Once in the armed state it remains latched in the armed state for either 120 seconds or until a Hi-Z event is declared, whichever comes first.

The Hi-Z oscillography retrieved for this scenario is shown in Figure 2. It can be seen that Hi-Z element declared "Hi-Z Arc Detected-A" (Hi-Z State=5) three times within a window of one minute before declaring "Hi-Z Downed Cond-A" (Hi-Z State=9). More details about the outputs of F60 Hi-Z element to this scenario is explained with the help of Figure 3.

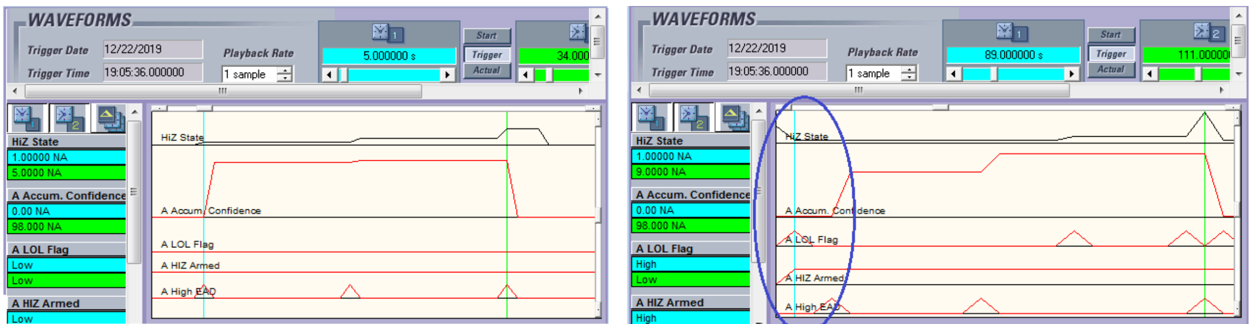
Figure 3 shows the sections of Hi-Z oscillography when: Hi-Z element output "Hi-Z Arc Detected-A" (a), Hi-Z element output "Hi-Z Downed Cond-A" (b). It can be seen from Figure 3 (a) that when Hi-Z element detected a signature of a Hi-Z event, the Hi-Z State went from 0 (Normal) to 1 (Co-ordination timeout) and then to 2 (Armed). Also, during this time period Hi-Z element started building-up the Accumulated Confidence.

Now, for any event to be declared a Hi-Z event, the two criteria must be met:

1. Accumulated Confidence equal or above Confidence Threshold.
2. The number of EADs equal or higher than EAD Threshold.

Confidence and EAD Thresholds are governed by the sensitivity setting of Hi-Z element. For this case the Confidence Threshold was 68% while EAD Threshold was 3.

It can be observed that the accumulated confidence built-up and crossed threshold rapidly. However, the Hi-Z event was only declared after the threshold of 3 EADS was met. The key point to note in Figure 3 is that Hi-Z State =1 (Co-ordination timeout) was triggered by a “HighEAD” in (a), while Hi-Z State =1 (Co-ordination timeout) was triggered by a Loss of Load (LOL) event in (b). It can be seen in Figure 3 (b) that when LOL triggered the Co-ordination Timeout state, it also armed the DNC logic of phase-A (A HIZ ARMED in the figure). That is precisely the reason why when conditions were met for declaring an Hi-Z event, the output in Figure 3 (a) was “Hi-Z Arc Detected-A” (Hi-Z State=5), while in Figure 3 (b) it was “Hi-Z Downed Cond-A” (Hi-Z State=9).



(a) (b)

Figure 3. Hi-Z element output “Hi-Z Arc Detected-A” (a), Hi-Z element output “Hi-Z Downed Cond-A” (b).

From the waveforms captured by F60 shown in Figure 4, it can be seen that the current in phase-A was relatively higher than the other phases. The phase-A current also had relatively higher harmonic content. The current waveform of phase-A also shows a typical Loss of Load (LOL) event in the region followed by green cursor line in Figure 4.

This figure gives us few important observations:

- Voltages do not show any distortion and appear normal
- Currents in healthy phases appear to be very steady with low harmonic content.
- The faulted phase current exhibits erratic behavior with a significant content of harmonics; 13.1% of the 2nd harmonic, 11.4% of the 3rd harmonic, 5.9% of the 4th harmonic, etc.

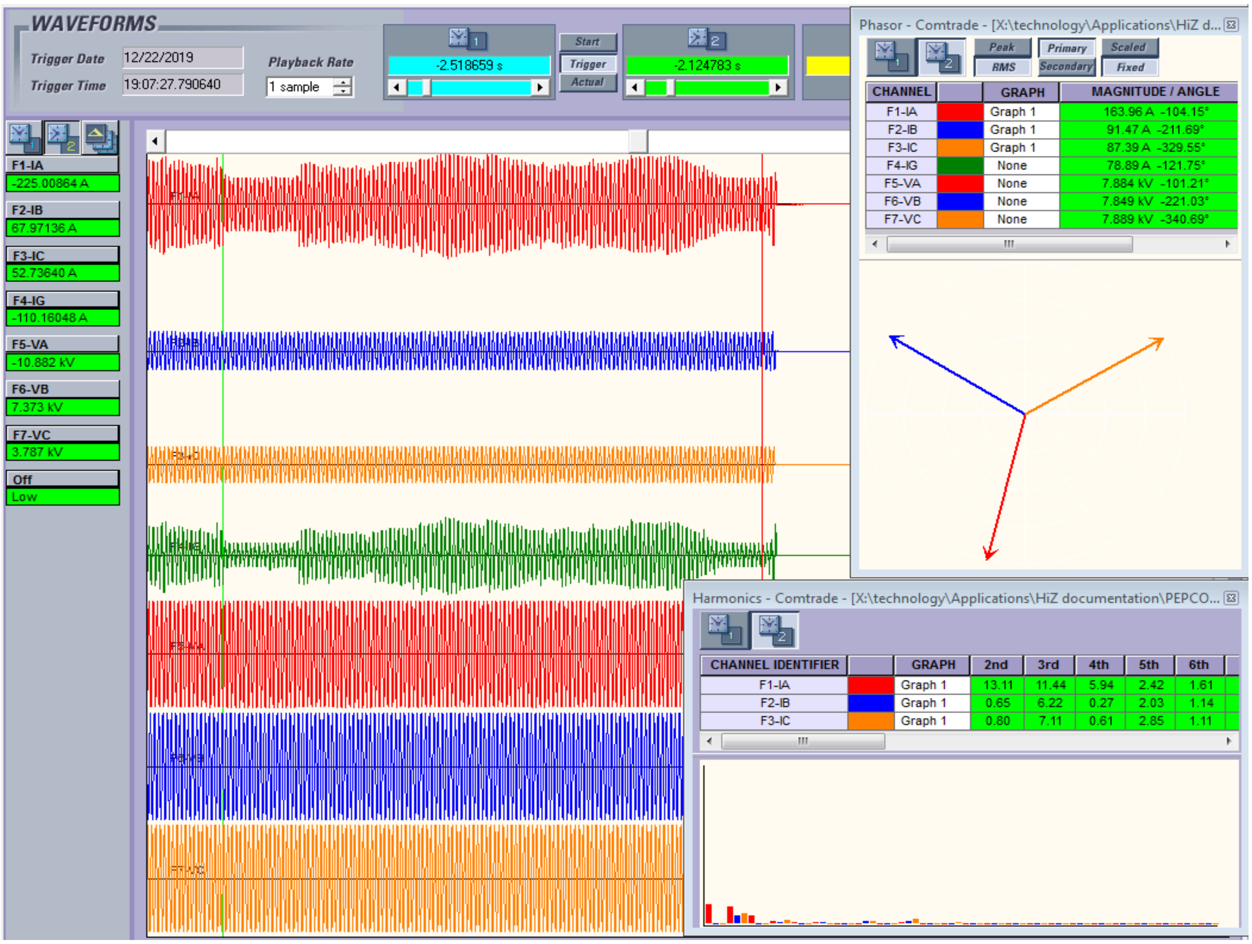
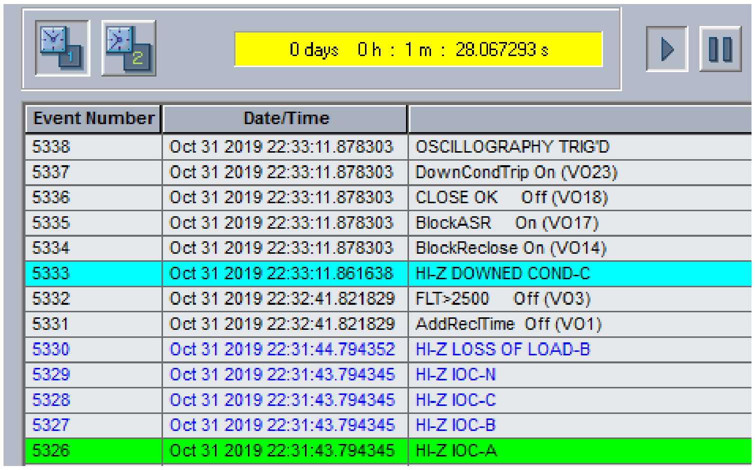


Figure 4. Waveforms of currents and voltages for the Downed Conductor Event along with estimated phasors and harmonics.

The most important observation here is with the envelope of the phase-A and neutral currents after the loss of load. We can see that current goes up and down, satisfying energy randomness algorithm and leading to the growing confidence that this is a true phase-A downed conductor event.

B. Non-Downed Conductor DNC Operation

The case under consideration is a non-downed conductor HiZ Event. All three phases were carrying approximately 80A current, but the voltages were not supplied to the relay because Voltage Transformer was out of service. Due to the stormy weather, the system was experiencing heavy switching and disturbances.



0 days 0 h : 1 m : 28.067293 s

Event Number	Date/Time	
5338	Oct 31 2019 22:33:11.878303	OSCILLOGRAPHY TRIG'D
5337	Oct 31 2019 22:33:11.878303	DownCondTrip On (VO23)
5336	Oct 31 2019 22:33:11.878303	CLOSE OK Off (VO18)
5335	Oct 31 2019 22:33:11.878303	BlockASR On (VO17)
5334	Oct 31 2019 22:33:11.878303	BlockReclose On (VO14)
5333	Oct 31 2019 22:33:11.861638	HI-Z DOWNED COND-C
5332	Oct 31 2019 22:32:41.821829	FLT>2500 Off (VO3)
5331	Oct 31 2019 22:32:41.821829	AddReclTime Off (VO1)
5330	Oct 31 2019 22:31:44.794352	HI-Z LOSS OF LOAD-B
5329	Oct 31 2019 22:31:43.794345	HI-Z IOC-N
5328	Oct 31 2019 22:31:43.794345	HI-Z IOC-C
5327	Oct 31 2019 22:31:43.794345	HI-Z IOC-B
5326	Oct 31 2019 22:31:43.794345	HI-Z IOC-A

Figure 5. event log showing 3-ph IOC event and subsequent DNC operation in phase-C.

From the sequence of events log shown in Figure 5, it is evident that at time 22:31:43.794345, a 3-phase IOC event occurred, which armed the DNC logic in all the phases. It can be seen from the Figure 6 that for 70 seconds after IOC event, Hi-Z algorithm did not detect any signature of Hi-Z fault. Thereafter, Hi-Z element started detecting the signature of Hi-Z fault and built-up enough confidence within next 18 seconds window to declare a DNC in phase C. PEPCO service crew inspected the line and did not find any downed conductor and the case was initially classified as False Downed Conductor Event.

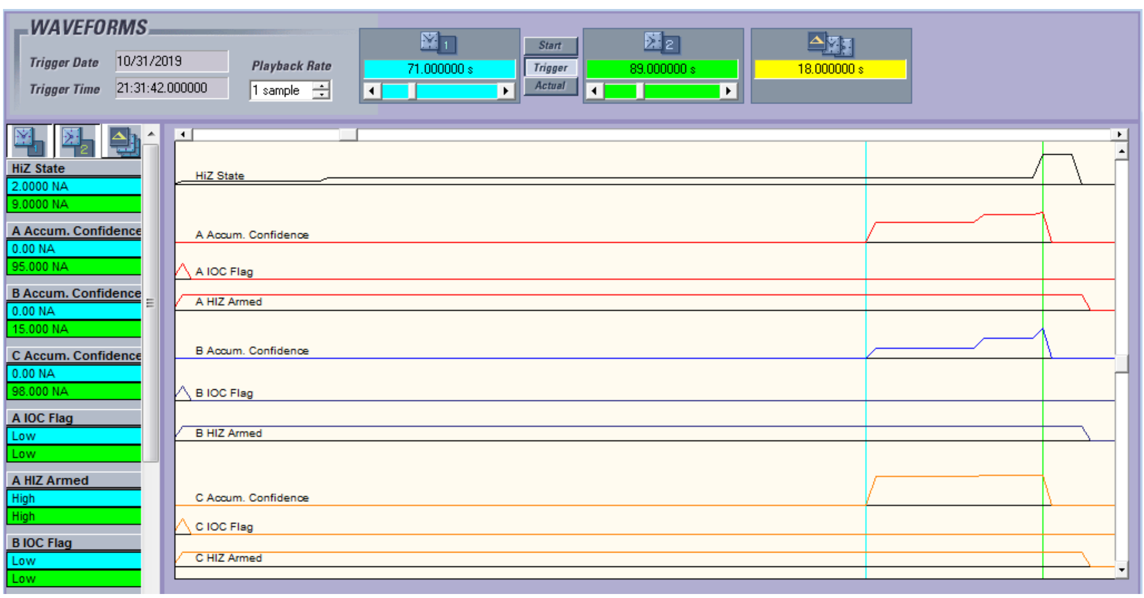


Figure 6. Hi-Z oscillography captured from F60 showing the arming and operation of DNC.

When the waveforms captured during this event shown in Figure 7 were analyzed, it was observed that all phases had high content of harmonics especially in phase C. Another peculiar observation was that phase C showed a repeated high amount of non-linearity in each fundamental cycle, which was propagating to other 2 phases at the same time instant. Interestingly, about half an hour after the DNC operation, it was found that a tree limb was hanging on the phase C of the tie.

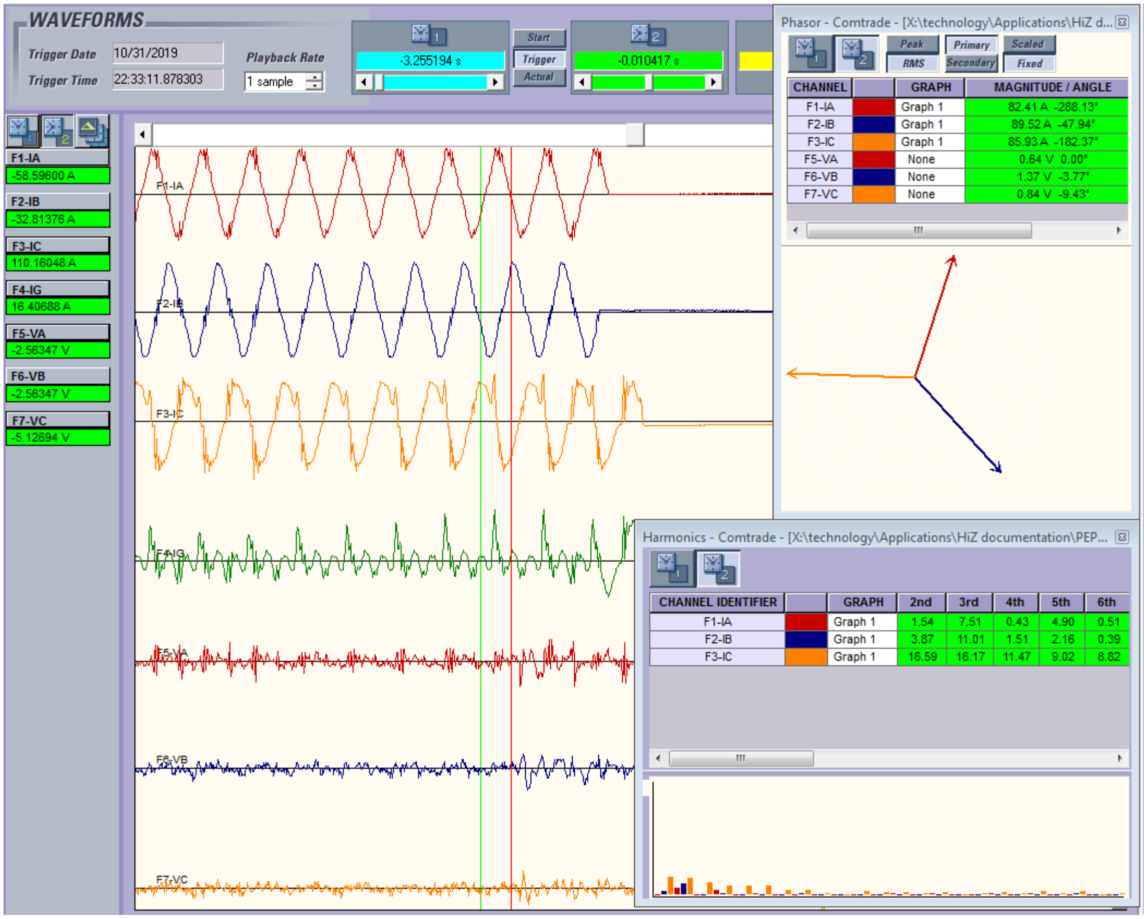


Figure 7. Current and voltage waveforms with estimated phasors and harmonics

Another observation that becomes significant in the light of finding is a hanging tree limb on phase C: 8 minutes prior to DNC operation of the Hi-Z element, it yielded the output of Hi-Z ARC DETECTED Phase C, 5 times within the window of approximately 3.5 minutes.

Most likely, the sequence of events that led to the DNC operation was that the tree limb hanging on phase C was creating arcing that Hi-Z element was correctly being detected as “Arc Detected in Phase C”, repeatedly. Unfortunately, at time 22:31:43.794345 a 3-phase switching event happened in the system which armed the Hi-Z DNC logic. The continued arcing produced by the hanging tree limb was picked up as a signature of a downed conductor by Hi-Z DNC logic. Ideally, the output for this case should also have been “Hi-Z Arc Detected C”, however, due to the system events the Hi-Z element yielded “Hi-Z Downed Conductor C”, in spite of there was no physical conductor touching the ground.

C. Unsuccessful DNC Operation

The case being reviewed is when a false Downed Conductor Event in phase-B happened due to extra-ordinary system conditions. Figure 8 shows recorded current and voltage waveforms for this case. The phase voltages were balanced, while, significant unbalance was observed in the phase currents. Also, a relatively high neutral current (~70A) was noted which is approximately 60% of the Phase B current.

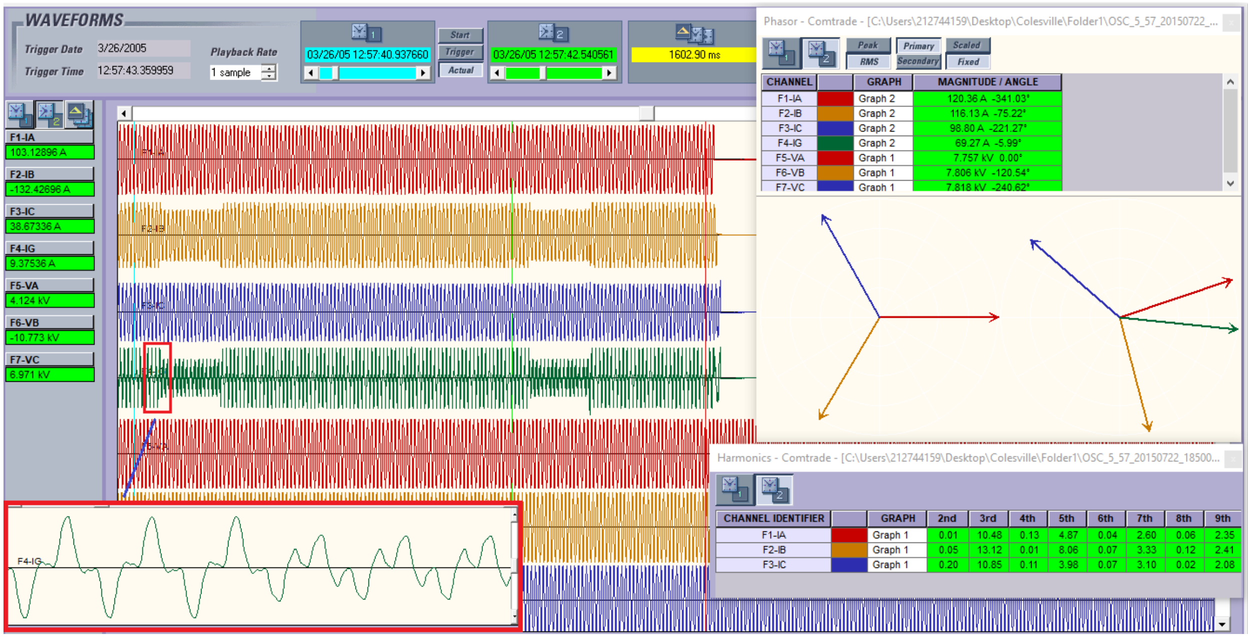


Figure 8: Current and voltage waveforms for the false downed conductor event along with estimated phasors and harmonics.

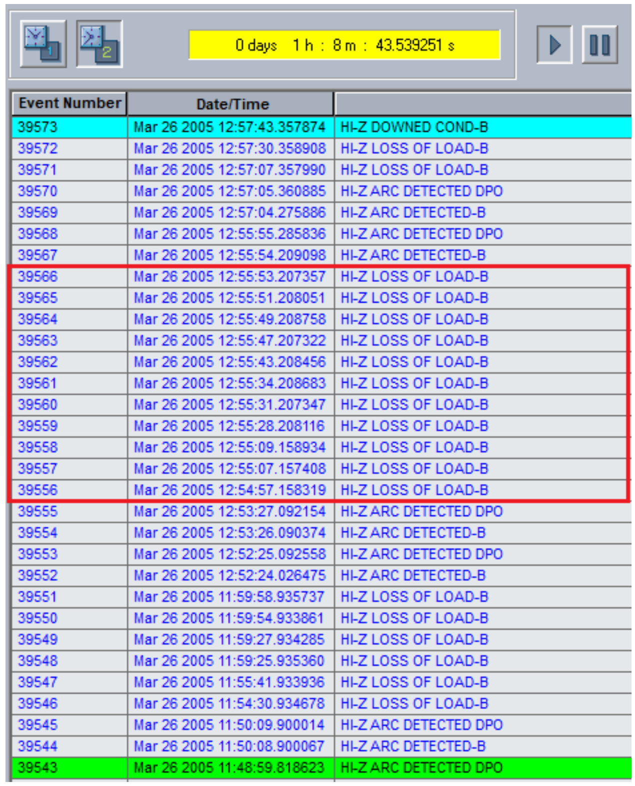
It can also be seen from Figure 8, that two 'dips' occurred in phase B and neutral currents, simultaneously. Following are the interesting facts observed about the 'dips':

- Both 'dips' involved identical change in the phase B and neutral fundamental currents (approximately 30A).
- Duration of both 'dips' was identical (250ms).
- The fundamental component of the neutral current was reduced significantly during the 'dips' as seen from the magnified waveform of the neutral current around one of the current 'dips' in Figure 8 (highlighted in red)

From facts above, it is highly likely that a relatively high power electronic device (such as a VFD or an inverter) was malfunctioning in Phase B. The HiZ algorithm picked the abrupt decrease in phase B as loss of load and got armed. The event log of the relay presented in Figure 9 shows that "HiZ- Loss of Load-B" was logged multiple time before HiZ algorithm declared the "HiZ-Downed Cond-B". As a matter of fact, during a window of 53 seconds, "HiZ- Loss of Load-B" was asserted 11 times as highlighted in Figure 9. The event log further showed that (not shown in Figure) that this unusual disturbance in phase-B lasted for about 3.5 hours, before the operation of "HiZ-Downed Cond-B".

This false DNC operation occurred due to extra-ordinary system operating conditions which involved repeated occurrence of loss of load events, high harmonic content in phase and neutral currents which varied with time. Thus, satisfying loss of load criteria and the randomness, and energy algorithms of the HiZ algorithm.

From the above discussed false DNC operation, it becomes evident that highly abnormal system conditions can cause HiZ algorithm to mis-operate. The proposed security enhancements to avoid operation for such conditions are discussed in next section.



0 days 1 h : 8 m : 43.539251 s

Event Number	Date/Time	
39573	Mar 26 2005 12:57:43.357874	HI-Z DOWNED COND-B
39572	Mar 26 2005 12:57:30.358908	HI-Z LOSS OF LOAD-B
39571	Mar 26 2005 12:57:07.357990	HI-Z LOSS OF LOAD-B
39570	Mar 26 2005 12:57:05.360885	HI-Z ARC DETECTED DPO
39569	Mar 26 2005 12:57:04.275886	HI-Z ARC DETECTED-B
39568	Mar 26 2005 12:55:55.285836	HI-Z ARC DETECTED DPO
39567	Mar 26 2005 12:55:54.209098	HI-Z ARC DETECTED-B
39566	Mar 26 2005 12:55:53.207357	HI-Z LOSS OF LOAD-B
39565	Mar 26 2005 12:55:51.208051	HI-Z LOSS OF LOAD-B
39564	Mar 26 2005 12:55:49.208758	HI-Z LOSS OF LOAD-B
39563	Mar 26 2005 12:55:47.207322	HI-Z LOSS OF LOAD-B
39562	Mar 26 2005 12:55:43.208456	HI-Z LOSS OF LOAD-B
39561	Mar 26 2005 12:55:34.208683	HI-Z LOSS OF LOAD-B
39560	Mar 26 2005 12:55:31.207347	HI-Z LOSS OF LOAD-B
39559	Mar 26 2005 12:55:28.208116	HI-Z LOSS OF LOAD-B
39558	Mar 26 2005 12:55:09.158934	HI-Z LOSS OF LOAD-B
39557	Mar 26 2005 12:55:07.157408	HI-Z LOSS OF LOAD-B
39556	Mar 26 2005 12:54:57.158319	HI-Z LOSS OF LOAD-B
39555	Mar 26 2005 12:53:27.092154	HI-Z ARC DETECTED DPO
39554	Mar 26 2005 12:53:26.090374	HI-Z ARC DETECTED-B
39553	Mar 26 2005 12:52:25.092558	HI-Z ARC DETECTED DPO
39552	Mar 26 2005 12:52:24.026475	HI-Z ARC DETECTED-B
39551	Mar 26 2005 11:59:58.935737	HI-Z LOSS OF LOAD-B
39550	Mar 26 2005 11:59:54.933861	HI-Z LOSS OF LOAD-B
39549	Mar 26 2005 11:59:27.934285	HI-Z LOSS OF LOAD-B
39548	Mar 26 2005 11:59:25.935360	HI-Z LOSS OF LOAD-B
39547	Mar 26 2005 11:55:41.933936	HI-Z LOSS OF LOAD-B
39546	Mar 26 2005 11:54:30.934678	HI-Z LOSS OF LOAD-B
39545	Mar 26 2005 11:50:09.900014	HI-Z ARC DETECTED DPO
39544	Mar 26 2005 11:50:08.900067	HI-Z ARC DETECTED-B
39543	Mar 26 2005 11:48:59.818623	HI-Z ARC DETECTED DPO

Figure 9: Event log of F60 relay showing the unusual activity in phase B of the feeder.

V. HiZ Security Enhancements

From analysis of the false downed conductor and correct downed conductor operations number of improvements were identified and are in the process of implementation:

- Use voltage supervision to detect voltages are normal - HiZ faults don't cause voltage dips.
- IOC or LOL events cannot arm the downed conductor detection for too long – usually when conductor is on the ground, harmonics accumulation starts happening right away. In current HiZ implementation it is arming for 120 seconds without monitoring if harmonics accumulation is happening shortly after IOC or LOL event.
- IOC or LOL in any specific phase can arm DNC in this phase only. IOC or LOL detected simultaneously in more than one phase should not arm DNC and instead should inhibit algorithm for some time.
- Harmonics accumulation in the neutral/ground channel can be significantly higher than in phase channels due to harmonics in all phases are additive to the neutral/ground channel – therefore neutral/ground channel alone cannot be used to qualify DNC event.
- Monitoring breaker status in the trip-reclose cycle to prevent using false IOC or LOL events to arm HiZ.
- Some industrial processes are causing currents up/down repeated patterns which can satisfy energy randomness algorithm if currents are polluted with harmonics from industrial processes.

Summary

High-impedance faults will continue to be an electric utility issue going into the future, however, experience with the technology has identified enhancements that promise to add security and dependability to the technology. Detection of such faults becoming more important than ever due to hazard to the people and animals. Future high-bandwidth data and processing capabilities promise to improve the safety of the power grid in the future.

Unlike detection of the conventional faults, detection of the high-impedance faults is challenging due to very low fault current magnitude, variable and unpredictable nature of the fault arc, which is depending on the many factors, such as surface, system grounding, weather and others. Most common techniques to detect such faults rely on the detection of harmonics in currents, randomness of currents and harmonics and some other supervisory conditions to make detection more secure and dependable.

Field experience with the high-impedance faults detection at Potomac Electric Power Company indicates fairly high percentage of the successful operations: nearly 70% successful operation downed conductor detection rate and an 83% overall high-impedance faults detection rate. Analysis of all operations revealed that there is a room for improvement to make detection of such faults even more reliable. Future improvements identified are; enhancing supervisory conditions by using other elements available in the relay, reducing reliance on the currents harmonics in the ground channel, differentiating between harmonics from industrial processes and ones resulting from the true high-impedance faults,

VI. References

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