Field Experience with High-Impedance Fault Detection Technologies in Distribution Systems

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***Abstract*—A downed conductor event, may lead to high-impedance faults (HIFs) that pose utility personnel and public safety concerns when left energized and unaddressed on distribution systems. Energized lines with HIF conditions can also result in wildfires, equipment damage and prolonged outages. Traditional protective relaying may be unable to detect and isolate for these types of events.**

In this paper, we present insight into Southern California Edison (SCE) efforts regarding implementation, testing, and improvement of HIF detection technologies in distribution system. This includes SCE's drivers in adding HIF detection and SCE's pilot to implement and evaluate the HIF detection algorithms embedded in field recloser devices (AR). The paper presents the high impedance fault field experimental stage testing results at Southern California Edison (SCE) Equipment Demonstration & Evaluation Facility (EDEF) for 12kV distribution circuit with covered conductor.

Lastly, the paper presents an analysis of HIFs algorithm performance under different system operating conditions, such as an actual HIFs faults and failed power system equipment that resulted in electrical arcing.

I. Introduction

HIFs are a public, employee safety hazard and wildfire risk that has always challenged the electric utility industry. A hardware failure on a distribution circuit may result with downed conductors [1-3]. An energized overhead distribution circuit may experience a hardware failure that may result in a conductor separation/break, causing a wire down event. These types of failures may occur for various reasons such as severe weather conditions, natural disasters, conductor splice failures, vandalism, tree fall and/or car hit pole. In certain downed conductor scenarios, the fault impedance is high enough, the fault may not be detectable by typical overcurrent relays. This type of faults is known as High-impedance faults (HIFs). HIFS can caused by object contacting distribution circuit conductors.

HIFs often draw low magnitudes of current and may be masked by typical system loading behaviors. The low magnitude current of HIFs makes it difficult for traditional overcurrent protective relays to detect HIFs. Traditional overcurrent settings may not be able to be set sensitive enough to avoid operating for system transients and be able to serve load without mis-operating for high system loading conditions. This can result in protection gaps that may result in hazardous and dangerous conditions to the system, personnel, and the public.

SCE serves approximately 15.6 million customers in parts of central, coastal and Southern California and maintains approximately 42000 miles of overhead distribution line which includes densely populated urban settings and remote rural areas. SCE's HIF detection pilot embedded HIF algorithms in field recloser controllers that protect SCE's Fire Climate Zones (FCZ) on their 16kV and 12kV distribution feeders. Approximately 600 circuit miles are covered by field reclosers that have HIF detection algorithm embedded within the recloser controller. Historically, Southern California Edison (SCE) has followed the standard utility practice of using bare overhead wire. SCE as part of its wildfire mitigation efforts started replacing bare overhead power lines with covered conductor (also known as coated wire) significantly reduces the chance that a power line could arc or spark if it comes in to contact with an object like a tree branch or metallic balloon. As of end of June 2024 SCE deployed 5,900 miles of cover conductor in the field. The presence of covered conductor will increase the complexity of detection of HIFs since the exposed area of the down cover conductor will be smaller than a down bare conductor.

This paper discusses SCE's experience with the implementation of HIFs detection algorithm on bare and covered conductor and discusses SCE's practical experience with HIF technologies and their performance in the field.

Section II describes how the HIFs detection algorithm utilize analog and digital quantities to detect potential HIFs conditions.

Section III describes the deployment of HIF detection algorithms on SCE distribution system, including the initial settings, and discusses the SCE investigation into false alarms during the pilot.

Section IV provides a summary of downed covered conductor (CC) stage testing for HIF algorithm conducted by SCE.

Section V provides event analysis and findings from real events encountered on SCE distribution system during the pilot.

II. HIF Detection Algorithm

HIFs may be challenging to detect with traditional overcurrent relays because of low magnitude current and the randomness of current during associated HIF arcing. A recloser controller that embeds the HIF algorithm within the controller is utilized to detect HIF conditions. The detection algorithm utilizes the harmonic or arcing signatures present in the current waveforms to detect HIFs. The commercially available recloser controller uses two nested algorithms for HIF detection. HIF Algorithm 1 (HIF1) uses the non-harmonic content of the phase currents, a stable pre-fault reference, an adaptive tuning

function, and decision logic to detect HIFs [1]. A second independent HIF Algorithm 2 (HIF2) measures and counts low magnitude ground current spikes to determine if there is a potential HIF arcing condition [5].

A. Detecting HIFs Using Non-harmonic Content (HIF1)

The first detection algorithm (HIF1) must tune itself to the typical circuit load harmonic behaviors before providing protection functionality. Therefore, when a distribution line is energized for the first time or has been below minimal load conditions for a long period of time, the recloser controller requires a 24-hour tuning period. The 24-hour tuning period is utilized to monitor the line while the algorithm learns and adapts to the typical load behaviors. The recloser controller requires a continuous minimum phase current loading of 5% of nominal current through the recloser to start the tuning process. If load current goes below the minimum required threshold during the initial tuning period, the recloser controller will restart the initial tuning process when the load current is above the minimum load requirement. Loss of load or even a fault that is isolated can make the load current drop below the minimum threshold causing a restart of the initial turning process. Following the initial tuning, the recloser controller changes to normal adaptive tuning based on variations in ambient load conditions.

The HIF1 algorithm employs three-phase event restraining logic, which disables HIF detection outputs during conditions occurring on all three phases simultaneously like switching events or inrush events or three phase faults. HIF events are typically associated with one or two phases. This event decision logic did not operate as expected during some HIFs events encountered on SCE system associated with a falling conductor. The falling conductor contacted other two phases while falling to ground and initiated a three-phase to ground fault that resulted in the circuit tripping when the circuit reclosed the conductor landed already on the high impedance surface and the high impedance fault that was not detected due to this addon detection algorithm feature.

When a downed conductor event occurs, the downed conductor electrical phase may experience a reduction of load current due to a separation of the conductor. The amount of load current reduced is associated with the separation of the conductor and is dependent on the connected load beyond the break point that may not be detectable. The recloser controller employs load reduction logic to monitor for this scenario.

B. Ground Overcurrent High-impedance Method (HIF2)

The ground overcurrent detection algorithm counts the number of times an instantaneous ground overcurrent element asserts and de-asserts at a low threshold within a certain period of time. The activity may indicate the presence of low magnitude arcing fault on the system. This algorithm may not be effective for surfaces that produced zero currents like dry sand or dry asphalt.

III. HIF DETECTION PILOT

Detection of high impedance conditions is an industry-wide challenge. SCE elected to explore HIF detection technology on SCE's distribution system to evaluate its effectiveness for bare or covered conductors. SCE's feeder protection is traditionally based on overcurrent elements, meaning the protection elements rely on high fault magnitude events, and therefore may not detect HIF events. HIFs can be caused by tree branches touching a phase conductor, failing or dirty insulators, or downed conductors that have fallen on poorly conductive surfaces. The installation of covered conductors for wildfire mitigation may also have the unintended consequence of producing more HIFs. In an HIF event, the fault magnitude is relatively small to non-existent. Protection schemes utilized for the detection of HIF conditions may reduce the propagation of low magnitude fault conditions and therefore mitigate ignition risk. In 2020, SCE upgraded 2 existing recloser controllers with HIF algorithm. In 2021, SCE upgraded 15 existing recloser controllers with HIF algorithm. In 2022, SCE upgraded 20 existing recloser controllers with HIF algorithm. The pilot deployed HIF algorithms programmed in recloser controllers based on following criteria:

- The circuit is on an effectively grounded distribution system.
- The circuit traverses high fire risk area (HFRA) downstream of the recloser controller as shown in Fig. 1.
- Continuous load of 25 amps or greater down stream of recloser based on utilizing 500:1 Current Transformers (CTs)
- Existing reclosers equipped with three phase voltage sensors.

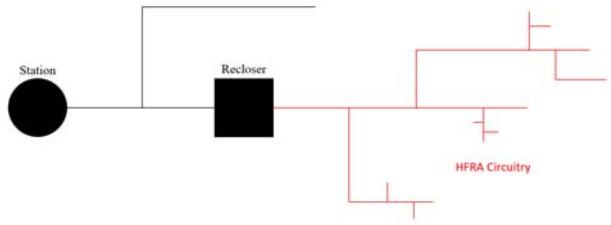

Fig. 1. Simplified circuit diagram showing recloser with HIF algorithm programmed upstream of HFRA circuitry.

Due to the lack of practical experience with this reclosers HIFs detection functionality SCE elected to deploy the algorithm in alarm mode. In the future, after sufficient field evaluation, the algorithms may be enabled for tripping.

HIF alarm notification starts at the recloser controller. When the recloser controller's HIF algorithms detect a HIF condition, an output contact is programmed to change state of the output contact from open to closed. When that output contact changes the state to closed, the Distribution Management System (DMS) captures the alarm time and date of occurrence from the recloser controller. Data is gathered from the DMS and sent via e-mail the following calendar day as a notification of a potential HIF event.

Upon receiving the HIF alarm notification, protection engineering gathers any pertinent data from available tools to validate the HIF alarm. If the HIF alarm is suspected to be a HIF event, records from the recloser controller are retrieved for an in-depth analysis of the event. Once all the pertinent information is gathered, a thorough analysis of a suspected HIF

event is performed to find out if the event was truly an HIF event.

The initial data source of event validation are interruption reports and repair documentation. The repair documentation contains information such as replaced equipment, location, date, and time of the repair and assist in determining if repair involves a HIF condition and aligns with the HIF alarm. The interruption log contains record of substation circuit breaker and recloser operation and system restoration process. The documentation assists in determining if an event occurred such as wire down or failed equipment to help verify the accuracy of HIF alarms.

Every event with notifications has been analyzed and all suspected HIF events that have indications of being an HIF have been analyzed in-depth.

IV. Covered Conductor HIFs Testing

As part of SCE's wildfire mitigation efforts, the utility is actively replacing bare overhead conductor with covered conductor (CC). This effort potentially increases the likelihood of a down conductor event to be of high impedance because the exposed area of the conductor will be very small compared to a down bare conductor. Therefore, a method to detect HIF conditions is necessary. Testing of the HIF detection algorithms with downed CC was performed on a 12 kV phase-phase circuit at SCE's EDEF test facility connected to SCE's 12 kV distribution system. The test circuit was configured as shown in Fig. 2. The test circuit layout is shown in Fig. 3.

Covered conductor test scenarios included contact from external objects such as simulated animal and human contact using resistors, metallic balloon, green tree branch, palm frond, and dry tree branch as shown in Fig. and Fig. 5. The HIF algorithm was put into test mode which does not require prior tuning or minimum load. Due to the nature of covered conductor, there was no appreciable flow of fault current therefore both HIF1 and HIF2 algorithms did not assert for these cases nor records triggered by the relay.

Downed covered conductor on different ground surfaces were tested. The ground surfaces included asphalt, grass, sand, and crushed rock. These test cases yielded no response from HIF1 and HIF2 algorithms.

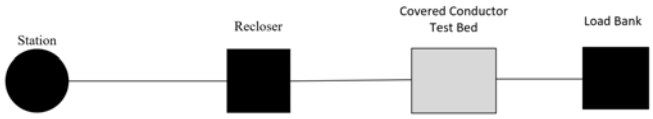

Fig. 2. Simplified test configuration diagram. Recloser with HIF detection algorithm embedded.

Fig. 3. SCE Braves 12kV Distribution test circuit.

Fig. 4. Green Tree Branch Test (Left). Dry Tree Branch Test (Right)

Fig. 5. Palm Frond Test (Left). Metallic Balloon Test (Right)

Fig. 6 shows the phase currents of non-fault base case condition collected by energizing 1.5MW load bank without any object contact to any of the phases of covered conductor. The sinusoidal waveforms shows between 67 and 71A peak phase currents (47 and 50A RMS) and 900mA peak ground current. Small amounts of harmonic reveal themselves at the current peaks that may be from the devices deployed on the test circuit and from the different power supplies used to energize different devices (relays, recloser controller, load bank cooling fans and control equipment, etc…)

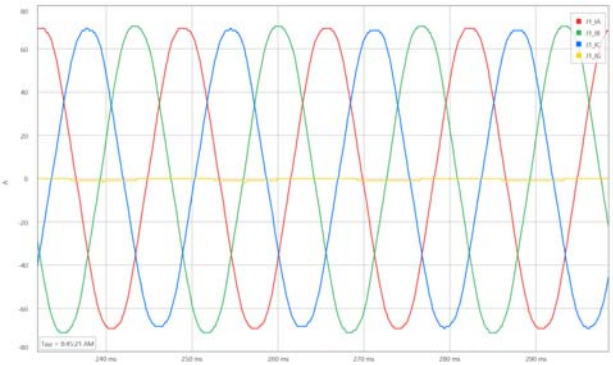

Fig. 6. Non-fault base case condition with energized 1.5MW load bank.

Fig. 7 shows the waveform capture of the green tree branch placed across all three phases with 1.5MW load bank energized. No significant change in currents compared to non-fault base case observed. The tests performed involving contact from metallic balloon, dry tree branch and palm frond waveform capture were all similar.

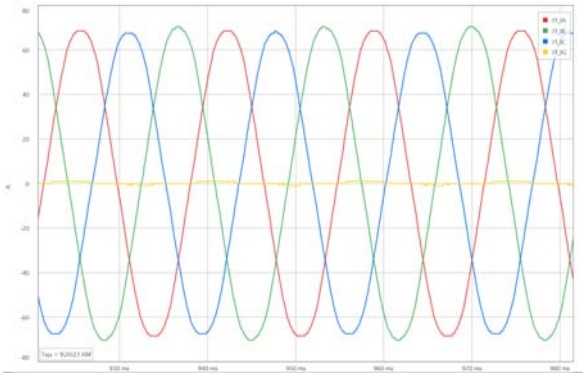

Fig. 7. Green branch placed across ABC phases covered conductor with energized 1.5MW load bank.

Simulated human contact to covered conductor was performed on A phase by clamping a 1024-ohm resistor clamped to the intact covered conductor with opposite end resting on grassy surface. In Fig. 8 the sinusoidal current captured in the system is purely positive sequence component (i.e., pure load) with negligible negative sequence component. The recloser controller and protective relays on the circuit did not sense the simulated contact.

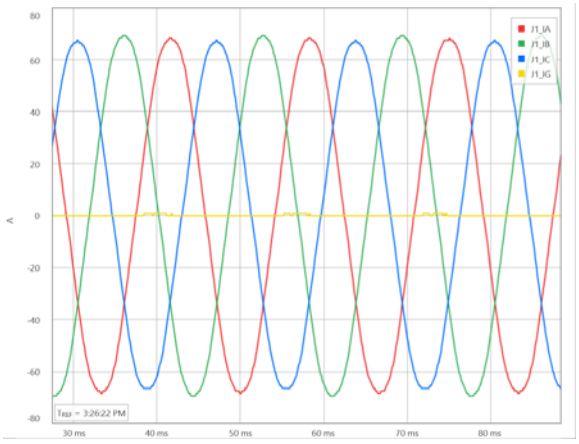

Fig. 8 Simulated human contact on A-phase.

The contact from object tests show that with intact CC the HIF1 and HIF2 algorithms in the recloser controller and other traditional protective devices on the test circuit may not be able to detect these conditions.

Additional testing was performed on compromised covering of the CC. The A phase of the CC was punctured by drilling through the conductor to simulate a gunshot. The simulated gunshot conductor rested on a dry grassy surface as shown on Fig. 9.

Fig. 9. Simulated bullet hole compromised CC resting on grass.

It was observed that when the system was energized, the simulated gunshot conductor immediately started to arc. The arcing persisted for approximately 20 seconds before evolving into a low-impedance (high current) fault in which was cleared by a fuse in the test circuit. Fig.10 shows the sinusoidal wave form captured during the testing. The arcing ground fault current level at inception was approximately 5.8A which then increased to 28.3A and evolved to a low-impedance 6.8kA high current fault.

The recloser controller records indicated HIF2 algorithm was processing however the high impedance portion of the fault was not long enough for the algorithm to alarm.

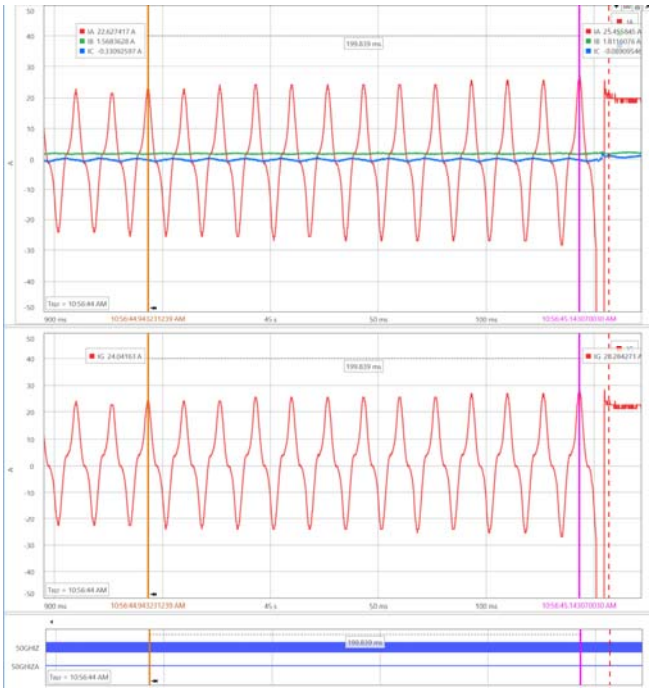

Fig. 10. Waveform of simulated bullet hole compromised CC resting on grass.

V. HIFs Pilot Alarms Event Analysis

During the pilot period, the HIFs detection algorithms produced a high volume of alarms. SCE's normal system operational practice and noisy loads contributed to these alarms. The alarms were consolidated into 113 triggered events. Through the process of evaluating the effectiveness of HIF, there was one HIF alarm event that was identified to be an actual HIF. Additionally, there was one HIF alarm event that was triggered by power system equipment failure.

A. Downed Conductor HIF Event

SCE Protection Engineering received an HIF event alarm. Interruption logs and repair documentation were reviewed and found to correlate to the date and time of the HIF event alarm. The provided data indicated there was a fault on the circuit in which the substation circuit breaker tripped and reclosed. A downed conductor was found downstream of a recloser controller programmed with HIF detection algorithm. Event records were retrieved from the recloser controller and analyzed by Protection Engineering department with support of the HIF detection algorithm vendor.

Fig. 11 shows the sinusoidal waveform captured by the recloser controller with A and ground currents in phase. In this figure, the station breaker has already reclosed.

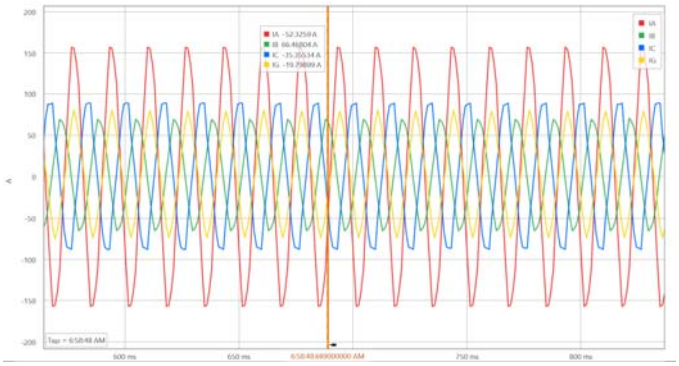

Fig. 11 Sinusoidal waveform of downed conductor HIF event.

In Fig. 12, the event records show the HIF1 algorithm counted the number of times the A phase difference current departed the reference difference current value and alarmed after 11 seconds. The difference current as seen by the recloser controller was 107.2A to 537.4A as compared to the reference value of 16.9A to 28.3A. Fig. 13 shows the time from when the station breaker recloses to the when HIF1 algorithm asserts, 71 seconds.

Fig. 14 is showing the sequence components of the open phase and subsequent energized wire on ground. The ratio I2/I1 is greater than 1 and there is existence of negative sequence voltage, V2. V0 and V1 magnitudes are significantly lower than V2.

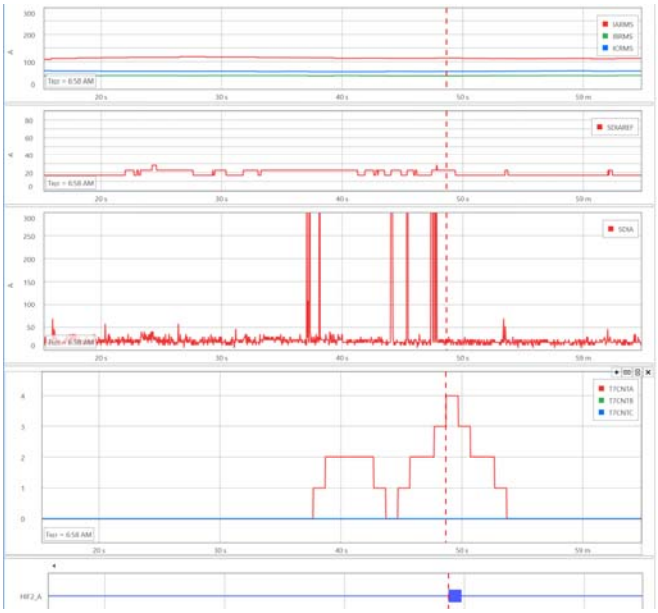

Fig. 12. HIF1 algorithm oscillography of downed conductor HIF event.

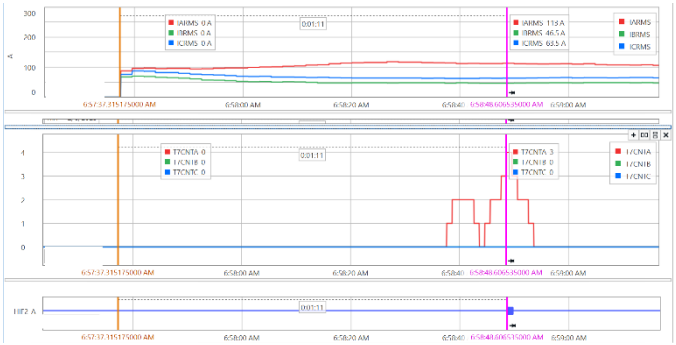

Fig. 13. Circuit recloses and approximately 71 seconds later HIF2_A is asserted.

Fig. 14 Sequence components of downed conductor HIF event.

The records from the recloser controller and event documentation correlated to determined that the HIF1 algorithm correctly detected the high impedance condition.

B. Power System Equipment Failure Detection

SCE Protection engineer received an HIF alarm indicating that there was a possible HIF event. Interruption logs and repair documentation correlate with to the HIF alarm and it was determined that there may have been an arcing condition. Event records from the recloser controller that had the HIF algorithms embedded in the controller were requested for further analysis.

After receiving recloser controller records, they were thoroughly analyzed by the SCE protection engineer to find evidence that there was possible arcing. It was found that HIF2

algorithms counter incremented and reached the threshold. The HIF2 counter reaching the threshold caused the recloser controller to alarm. A failed cabled was found on the following day. Fig. 15 shows the HIF2 algorithm counts sum prior to the complete failure of the cable. HIF1 did not operate for the failing cable.

Beginning Time	Ending Time	Counts
04:57:23.217	04:58:20.452	100
04:54:27.703	04:55:23.452	51

Fig. 15. HIF2 algorithm low magnitude ground current counts

VI. CONCLUSIONS

This paper presented the SCE experience with the initial deployment of HIF detection algorithms within the recloser relay (AR). Staged covered conductor testing showed for an intact covered conductor detection may be challenging while for compromised covered conductor there may be opportunity for the algorithm to detect an HIF event. During the field evaluation period the HIF detection algorithm performance was evaluated under real system operating condition by analysis of the generated HIF alarms. While the HIF algorithms were able to detect some events in the field correctly a large number of false alarms were generated from normal circuit behavior and normal system operations. SCE is currently investigating an improvement to the detection algorithm to improve the HIF algorithms performance to positively identify a high impedance fault while minimizing nuisance alarms including supervising the HIF detection using symmetrical voltages.

VII. REFERENCE

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