

High Impedance Fault Detection Technology

Report of PSRC Working Group D15

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Abstract

High impedance faults (HIFs) on distribution systems create unique challenges for the protection engineer. HIFs that occur do not produce enough fault current to be detectable by conventional overcurrent relays or fuses. This report presents a brief synopsis of what has transpired to date. It is based heavily on the history and application of today's technology, and discusses the results seen to date. It also presents some of the implementation strategies that are being used when applying this technology.

Introduction

This is a status report to the Line Protection Sub-Committee of the PSRC on the applications of high impedance fault detection technology. Not all unsafe conditions involve a HIF, i.e. a sagging conductor. This paper does not address the detection of those abnormal conditions where a conductor breaks and does not contact either another conductor or a grounded element.

A high impedance fault (HIF) does not have to involve a path to ground and, in fact, whether a ground is involved does not matter to the HIF detector. A high impedance fault can exist between two phase conductors (a tree limb lying across two phase conductors). The majority of HIFs do involve ground. In this discussion, high impedance faults will be referred to as HIFs whether or not ground is involved.

A high impedance ground fault results when a primary conductor makes unwanted electrical contact with a road surface, sidewalk, sod, tree limb, or with some other surface, or object which restricts the flow of fault current to a level below that reliably detectable by conventional overcurrent devices. Often this leaves a conductor energized on the ground surface posing a danger to the public. The nature of HIFs has been studied since the early 1970's with the hope of finding some characteristic in the current or voltage waveform that would make detection possible and practical.

History

A fault on a distribution feeder is an abnormal circuit condition which results in energy being dissipated in a manner other than the serving of the intended load. Also known as a "short circuit", a fault may result in damage to the electrical system, loss of power to customers, and/or possible unsafe conditions. The traditional method of detecting and isolating such abnormal conditions is overcurrent protection. The primary purpose of overcurrent protection is to protect the electrical system, and is based on the electrical properties of the circuit. Excessive current for too long will damage or interfere with normal operation of the system. The parameters (current and time) are easy to measure. Devices to detect an overcurrent event are well established, with decades of field experience. In practice, the removal of safety hazards caused by the fault is an additional motivation for overcurrent protection. See References 15 & 16 for further data on distribution feeder faults.

Most of the faults on power systems result in a substantial increase in current flow towards the fault point. Over the years, conventional overcurrent based protection schemes have been successfully used to detect and protect against these "low impedance" faults. However, for HIFs on distribution systems, the high impedance of the fault does not result in a substantial increase in current. Thus they can not be reliably detected using conventional methods. This is often the case with downed conductors on distribution systems. These downed conductors are a major concern for electric utilities as a public safety hazard. For this reason, The IEEE Power Engineering Society published a Public Affairs Document "Downed Power Lines: Why They Can't Always Be Detected" to address and educate the public about downed conductors and the difficulties in detecting such faults [16].

For many years, protection engineers and researchers have looked for solutions to this long standing problem. This search has resulted in the development of several techniques to detect HIFs. This group of faults, in addition to being characterized as low current faults, tend to exhibit random behavior with unstable and wide fluctuations in current levels. They are also characterized by the presence of harmonics and high frequency components. Most of the research on HIFs has focused on the development of sensitive detectors to reliably detect such faults. Some of the techniques used standard substation relaying inputs; a few others required special equipment. Details of the research and progress have been well documented [15].

Commercial Products

There are now two commercial products which detect HIFs. One is based in part on the research done at Texas A&M University. The General Electric Digital Feeder Monitor (DFM) analyses harmonic and non-harmonic components of the feeder currents between 30 and 780 Hz through the use of pattern recognition and artificial intelligence. An expert system with nine different algorithms is employed to detect and classify HIFs. Distinctions are made between downed conductors, persistent arcing, and intermittent arcing. Downed conductors are differentiated from arcing conductors by looking for a loss of load or a high current fault prior to the HIF event.

The Nordon Technologies High Impedance Fault Analysis System (HIFAS) measures the third harmonic current phase angle with respect to the fundamental voltage. The operating premise is

that the current associated with a HIF produces a third harmonic current with a unique phase relationship to the faulted phase voltage. At the fault location, they will be in phase. The ambient 3rd harmonic phasor is averaged over time and stored for comparison. When a fault occurs, the new 3rd harmonic phasor is vectorially subtracted from the stored value. If the resulting magnitude is above a preset threshold and the angle matches the preset value for a downed conductor, a HIF is declared.

Ongoing Research and Development Efforts to High Impedance Detection

Neural networks are being explored as another approach to HIF detection. A solution involving a neural network has been investigated by Sonja Ebron while a student at North Carolina University. It has been demonstrated that HIFs can be detected in faults simulated on a computer using a neural network, but no field tests have been reported. In 1992 Peter Snow of Kaman Science under contract to New York State Electric and Gas designed a neural network that reliably distinguished HIFs from other abnormal system conditions. There is no commercial neural network HIF detector available at this time.

Alternate Solutions to Broken or Downed Conductors

The Kearny Manufacturing Company Open Conductor Detection (OCD) system (under development) uses simple loss of voltage to detect a broken conductor. The system senses voltage at the end of a single phase lateral and signals the first upstream disconnect device to open if there is voltage present at that device. The OCD system has been under test at six utilities since 1992.

The Falgard device (invented by Irving Reedy in the mid 80's and now marketed by Alcoa Conductor Accessories) is a pendulum-mounted aluminum rod with hooked ends that is suspended from the underbuilt neutral conductor. The device catches and grounds a falling phase wire causing the conventional relaying to operate.

The Safety Yoke built by Electric Safety Products, Inc. is mounted to a cross arm or pole. It provides a solid ground fault by intercepting a falling conductor with a grounded spring-loaded bus bar. The force of the descending conductor pushes a release which triggers the internal spring and ejects the bus bar to make contact with the fallen wire.

Limitations on Detection

No matter what method is used, not all HIFs are detectable. Consider, for example, the case where a conductor near the end of a feeder breaks and falls to the ground. Since very little current flows for the detection, and very little load is lost, it is difficult for any HIF detector to sense the event.

This example points out an aspect of HIF detection that may not meet the expectations of some utility people. The ideal is to detect all HIFs and at the same time be immune to all non-HIF events. Practically, it is impossible to detect 100% of HIFs AND achieve a high degree of security against false outputs. This is true because of the probabilistic nature of HIF detection.

To install even a "near perfect" system would not be cost effective. It would require numerous monitoring points on every feeder, with all their attendant maintenance costs.

When a conductor is left energized on the ground, it represents an increased hazard to the public in the immediate vicinity of the downed wire. Therefore, the solution appears to be obvious - employ HIF detection and clear the circuit immediately for such conditions. Unfortunately, the decision is not that simple. No device, overcurrent or otherwise, can protect from initial electrical contact. The type of HIF detection currently available is relatively slow. Therefore, its ability to prevent and protect against an injury resulting when the downed conductor event and the occurrence of electrical contact close together is limited.

Frequency of HIF Events

There is no agreement within the utility industry on how often HIFs occur. Many relay engineers perceive that the number of HIFs are a small percent of all faults. Line crews generally state that a much larger percentage are not cleared by conventional overcurrent protection. Relay engineers typically make their judgements based on trouble reports, which tend not to include all downed conductor events. The field observations by line crews are probably closer to fact, but little data has been kept on HIFs. Utilities typically don't record an event unless it results in a breaker or fuse operation. Over an eleven year period, researchers at Texas A&M University staged over 200 high impedance faults at five utilities and on ten distribution feeders. Of these 200, only 35 were cleared by conventional protection. Clearly, for the type of fault that falls into the HIF category, the operation of conventional protection (and hence our ability to count the event) is not a good indicator of the number of HIF events. For example, re-energizing a line with a broken conductor may create a high impedance fault. The need for better data is evident for utilities considering the use of HIF detection. Some of the factors affecting the number of HIFs that occur are: voltage level, type of construction, and age of the circuit.

HIF Characteristics: Two characteristics of HIFs are the low fault currents and arcing. By definition, HIFs produce little or no fault current. Typical fault currents range from 10 to 50 amps, with a very erratic waveform. Here are typical results of staged faults at two different test sites for a typical 12.5 kV feeder [3]:

TYPICAL FAULT CURRENTS ON VARIOUS SURFACES

Typical 12.5 kV Distribution Feeder

Surface Current (A) @ 7200 V L-G

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Dry asphalt 0

Concrete (non-reinforced) 0

Dry sand 0

Wet sand 15

Dry sod 20

Dry grass 25

Wet sod 40

Wet grass 50

Concrete (reinforced) 75

Voltage Level: The majority of high impedance faults occur at distribution voltages of 15kV and below, with the problem becoming worse at the lower voltages. The problem is less severe at 25kV and above, but HIFs can occur at these voltages as well. Generally, the prospective user can limit the application of HIF detectors to 15kV and below distribution circuits. There may be some user-specific cases where these detectors may be useful at a higher voltage.

Type of Construction: Underground feeder circuits will not need HIF detectors, since they pose few public safety concerns. Newer overhead circuits with large conductors and large neutrals will be less susceptible to HIFs due to wire breakage. Older circuits are more likely to have small conductors or a non-existent neutral and are more susceptible to HIFs. Ungrounded systems are likewise good candidates for HIF detectors.

Age of Circuit: Circuits with conductors in poor condition, or those that have experienced severe storms or overloads, significant tree contact, or with histories of excessive broken conductors may benefit from HIF detectors. Older circuits may also have been constructed with practices which tended to favor the occurrence of a HIF.

Arcing: A characteristic of HIFs with some current is the presence of arcing. Arcing is the result of air gaps due to the poor contact made with the ground or a grounded object. Also, there may be air gaps in the ground (soil) or grounded object (concrete, tree, etc.). These air gaps create a high potential over a short distance, and arcing is produced when the air gap breaks down.

The sustainable current level in the arc is not sufficient to be reliably detected by conventional means. Part of this is due to the constantly changing condition of the surface supporting the arc and while maintaining a high impedance.

Application of HIF Detectors

As the industry begins to apply HIF detectors to its distribution systems, there are a number of issues to be addressed: trip or alarm, location of the fault, economics, and liability. Before addressing these specifics, a comparison of the HIF problem on a grounded power system to other design and operating practices may be in order to appreciate the impact of this technology.

Similarity of HIF Alarms to Operation of Ungrounded Delta Systems

In the early days of electrical distribution in the U.S., most utilities operated three-wire ungrounded delta 2300 volt distribution systems. After 1925, many of these systems were converted to 2300/4000 V four-wire wye circuits, some were left at 2300 volts, and other were converted to 4800 volt delta. Some of these ungrounded systems are still in operation. Other higher voltage ungrounded distribution systems were also used. Three-wire distribution systems are still the norm in Europe, Japan, and other parts of the world.

A distinguishing feature of such systems is the ability to continue to operate the system with a ground on one phase. Since the system neutral is not grounded, there is little current flow in the fault-to-ground connection, and operation of the system in this state does not involve abnormal current levels.

Because of the very limited ground fault current, it is frequently considered impractical to try to provide ground-fault relaying on such systems. Typically, the only relaying provided is an alarm actuated by zero-sequence overvoltage on the bus (with no indication of which feeder is faulted). The alarm only indicates that a ground fault exists somewhere on the system. Typical operating practice is to manually run tests to determine the faulted feeder, then initiate a patrol of the feeder to determine the location of the ground fault. Once the fault has been found, the necessary portion is de-energized to facilitate removal of the fault.

The situation with downed-conductor is similar to the operation of ungrounded systems. The amount of current flowing in the HIF is not a hazard to the system (if it were, the conventional ground overcurrent relaying would trip). Service continuity to loads can be improved by using the HIF detector to only alarm for a downed-conductor. The affected feeder can be patrolled without affecting service to other feeders on the bus, and the problem repaired once found. This approach maximizes service to customers while still responding to the need to detect and repair downed conductors.

Risk Analysis

When determining how to apply HIF detection for downed conductors, one must consider all of the trade-offs involved. Unlike most forms of relay protection, downed conductor protection is primarily employed for safety reasons since high impedance faults rarely cause secondary equipment damage. As discussed in previous sections, HIFs exist because of an energized conductor contacting a poor conducting surface such as the earth or pavement. An HIF usually will not be detected using conventional protection such as overcurrent relays, reclosers, or fuses. While reported instances of HIF may be significantly less than those resulting in the proper operation of the conventional protection, IEEE surveys indicate that these cases do exist. Therefore, step one in determining whether to employ this detection involves reviewing the circuit in question to see if conventional protection is adequate. A utility's experience with the soil conditions, type of circuit construction, past experience with energized downed conductors, and the nature of the load on the circuit give an indication of the priority for the application of HIF detectors.

It may not be practical or advisable to trip the circuit immediately. The consequences of power loss on a circuit need to be considered. Power outages, by their very nature, represent an increased hazard to the public in areas that are remote from the actual downed conductor. The consequences of traffic lights not functioning at busy intersections, elevators without power, lack of heating, life support equipment, etc. must be considered.

Unfortunately, at this time the associated risk can not be accurately quantified. There is a scarcity of data on the number of electrical contacts resulting from downed conductors or from injuries or damages resulting from power outages. The apparent low frequency of such occurrences, poor record keeping, and legal issues all contribute to this scarcity of data.

Instead of tripping the circuit, a utility may elect to alarm. In this case, the utility could begin a public address advising of the danger, and also dispatch service personnel to search for the downed conductor.

The root issue is an assessment of the consequences of falsely tripping when there is no HIF or not tripping when there is a HIF. If a feeder is not tripped or patrol action started for a downed conductor, then possible loss of life, legal liability, or property damage may result. If a feeder is tripped unnecessarily, then possible traffic hazards (due to inoperative traffic signals), medical emergencies, reduced reliability, and loss of load may result. Each utility must evaluate their use of HIF detectors (including trip vs. Alarm) based on their own situation.

Trip versus Alarm Issues - Issues for consideration of tripping versus alarm include:

- 1 - The tradeoff of percent of faults detected vs. level of security, accepting that both criteria cannot be maximized. The goal should be to make a meaningful improvement in HIF detection.
- 2 - The negative effects of outages must be considered. What types of outages can be endured? Which are completely unacceptable on the distribution system?
- 3 - What types of hazards are likely and what are their effects on the particular feeder? How should the operating personnel react to the information provided by the HIF detector?
- 4 - What is the most cost effective device for a particular distribution feeder? The answer may vary with different locations. How will HIF detectors merge with existing and future protection systems? How might they complement or add value to those systems?
- 5 - What will be the effect of HIF detectors on those that operate the system?

Reliability

Reliable performance is traditionally measured by dependability and security. A high level of dependability occurs when the HIF detector correctly recognizes every downed conductor event that happens on its feeder. A high level of security occurs when the HIF detector does not falsely indicate a downed conductor when there is no conductor on the ground. There is a trade-off between these criteria. A high dependability forces a lower security level and a high security

reduces the level of dependability. The dilemma is to determine the best dependability vs. security level for the situation. How a HIF detector does this trade-off is determined by the design and operating characteristics of the HIF detector and by its settings. Dependability to detect certain types of faults may be tested by a series of staged fault tests. Security can only be tested by leaving the HIF detector in service for long periods of time to ensure it is not sensitive to non-HIF events.

Service Continuity

The detectors available for HIFs may be applied in a variety of ways. The central issue in devising application and response strategies is the trade off between protecting people from the hazards of a possible downed conductor, and maintaining continuity of service. The latter concern may also involve safety issues, considering that traffic signals or other critical equipment may be supplied from the feeder in question. The purpose of this section is to discuss the factors relevant to these strategies, recognizing that utilities will, at least initially, be biased on the side of maintaining service continuity.

An output from a HIF detector may be used for automatic breaker tripping. However, it is anticipated that at least in the early phases of applying this technology, utilities will elect to alarm rather than trip. This requires that the system operator be adequately educated so that he can make an informed decision to trip the feeder or not, as information from various sources (including the HIF detector) become available.

The following factors should be considered in devising response strategies, keeping in mind that there will often be no "right" or "wrong" approach, given the wide variety in circumstances from utility to utility, and from feeder to feeder:

1. HIF Detector Capabilities

An arcing condition in the absence of any other evidence of a possible downed conductor will generally not be sufficient reason to de-energize a feeder, since the conductors may well be intact and out of reach of the public. On the other hand, arcing in conjunction with evidence of a fault or broken conductor has far more serious implications.

2. Response Time

To the degree that a utility's service personnel can provide very fast response, there may be less need to de-energize a feeder with a suspected downed conductor. On the other hand, should the decision be made to trip, the fast response by service personnel to isolate the faulted section and restore the remainder of the feeder would minimize the effects of de-energizing. It must be recognized, however, that locating a HIF on a de-energized feeder is more difficult than when energized.

3. Feeder Layout and Number of Customers Served

The protected feeder may or may not have significant exposure in areas accessible to the public. Following a downed conductor indication, it may be prudent to de-energize a feeder having significant overhead exposure through a residential neighborhood or school zone. On the other hand, this action might be less appropriate if the feeder serves primarily a rural area or industrial park. The more customers affected, the more the utility must be sure of the validity of a problem before tripping a feeder.

4. Demographics of the Feeder Load

The decision to trip or alarm may be affected by the criticality of the load. Service to traffic lights, hospitals, equipment in tunnels, critical commercial or industrial process etc., may bias a decision in the direction of maintaining service. Likewise the time of day, or year, weather, and the activities that are time related (school or rush hour) may influence the decision.

5. Supplementary Information from the Power System

Additional information from the power system includes indications of faults on the feeder in question or on other feeders sharing the same poles, and the amount of feeder load suddenly lost. Information of this type might come into play if a pole were struck by a vehicle and broken in half. This could result in conductors down on the road, but not broken or faulted.

Prior history of feeder behavior and of the specific HIF detector may be of value. The HIF detector may be connected to a telephone line for remote interrogation for more detailed event data, including wave form information.

6. Supplementary Information from the Public

Information from the public includes reports of wires down, loss of service, poles struck, etc. Appropriate consideration of these factors should allow a utility to devise strategies for response to HIF detector outputs of 1) arcing, and 2) downed conductors. This will require input from both system protection personnel as well as distribution personnel intimately familiar with the nature and behavior of the distribution system.

Communications Issues

In the implementation of high impedance fault detection technology, there are a number of issues related to communications that need to be considered. These include the availability and capability of direct communications with an HIF detector, the implications on how the device is applied, and the consequential information which may be available regarding a HIF which may be useful in responding to that fault.

In applying a HIF detector, one of the fundamental considerations is how to use the output of the device - whether to trip a circuit breaker or to initiate an alarm. In arriving at that decision, one must know whether direct communications exists, capable of sending that alarm, between the

substation and the utility's dispatch center. If not, whether it is feasible to add that communications capability.

The alarm could be transmitted by a variety of methods, including a distribution SCADA system, a substation wide area network, or a simple auto-dialer alarm system. While some utilities have SCADA covering all distribution breakers, some have no permanent communications to any distribution substation. The extent of any existing alarm type communication, and the cost and feasibility of adding communications where none exists, will have a significant bearing on the decision to apply a HIF detector to trip or to alarm.

If the decision is to trip the circuit breaker (whether or not an alarm can be transmitted), then a second, less direct, method of alerting the dispatcher to the problem exists - the report of an outage by customers. A telephoned report of a wire down or of an outage (assuming the HIF is accompanied by loss of load) has long been the traditional and virtually the only means a utility had to detect a high impedance fault. It remains a very useful means of detecting and/or locating a downed conductor. While the technology for detecting HIF is becoming commercially available, locating them will still depend on traditional patrolling methods. In the past, a HIF would be found by a layman's report of a downed wire, or by a utility patrol initiated by an outage complaint. Even with HIF detectors, this will still be the case.

In the event the circuit breaker was tripped, the outage report would identify the circuit involved, if this were not already known, and the downed wire report would help to locate the fault. If the HIF detector were used only for alarm, then the outage report and the downed conductor alarm would both aid in locating the fault. One additional consideration is that layman reports of downed wires often turn out to be a case of a downed telephone or CATV cable. An alarm from a HIF detector accompanied by a layman's report of a downed wire would serve to confirm that the wire was in fact a power conductor.

Another means of communications which might be useful in locating a HIF is a customer billing meter which can be remotely interrogated. Following receipt of a HIF alarm, if the circuit is not tripped and no outage complaints have been received, it may be possible to locate the fault by selectively interrogating the meters along the circuit to determine which meters are energized. If the utility has a distribution automation system, the feeder sectionalizing points may be polled to determine if voltage is present.

If the HIF detector is microprocessor based, then there is a wide variety of information that may be communicated either to the dispatch center or to engineering. This could include the identification of the phase involved, and the amount of load prior to and subsequent to the HIF event. The load change could be used to aid in fault locating based on a known loading profile of the circuit.

The digital record of voltages and current during a fault episode (known as a Digital Fault Record, DFR) provides a picture of the event than can provide a wealth of information as to what happened. Oscillography such as this has been used for years by transmission system operators to locate and analyze faults. A microprocessor type relay can collect such data from multiple

events, thus providing a history of events. This type of analysis over time can identify trends and problems before they become an alarm or a breaker trip.

To be useful, the data (oscillography, demand, breaker duty, power quality, etc.) must be retrieved from the HIF detector in the field. With the current lack of standards for substation communications, this is no small problem. The utility must assess the technology available and choose the system that best fits its current and future needs. That system may range from a simple modem for communication with a single HIF detector, to a telephone controller directing calls to various modem connected devices including a HIF detector, or to a Local Area Network (LAN) within the substation tying various devices on different software platforms to a single outside communication port. The utility must acquire and train personnel capable of operating the system and analyzing the data.

Conclusion

The capability of these new detectors should provide the utility a new tool that can be used to help minimize the public's exposure to downed conductors. It is a tool that should be used with discretion. The issue of how to respond, once a downed conductor (HIF) is detected, is paramount. This will often determine whether or not the overall risk to the public has truly been minimized.

Future distribution feeder costs may be a bit higher as HIF detectors become standard in new installations. This incremental cost may be minimized to some degree as other useful functions are packaged with the device and are included in the operational evaluations. Such functions may include primary or backup protection, metering functions, fault analysis, cumulative breaker duty, and power quality measurement.

As experience with HIF detectors is accumulated, the confidence level of companies may reach a point that will allow them to defer certain aspects of line maintenance and to rely on HIF detector outputs as a standard form of protection. While HIF detectors are just becoming available, their use has not been formally established.

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