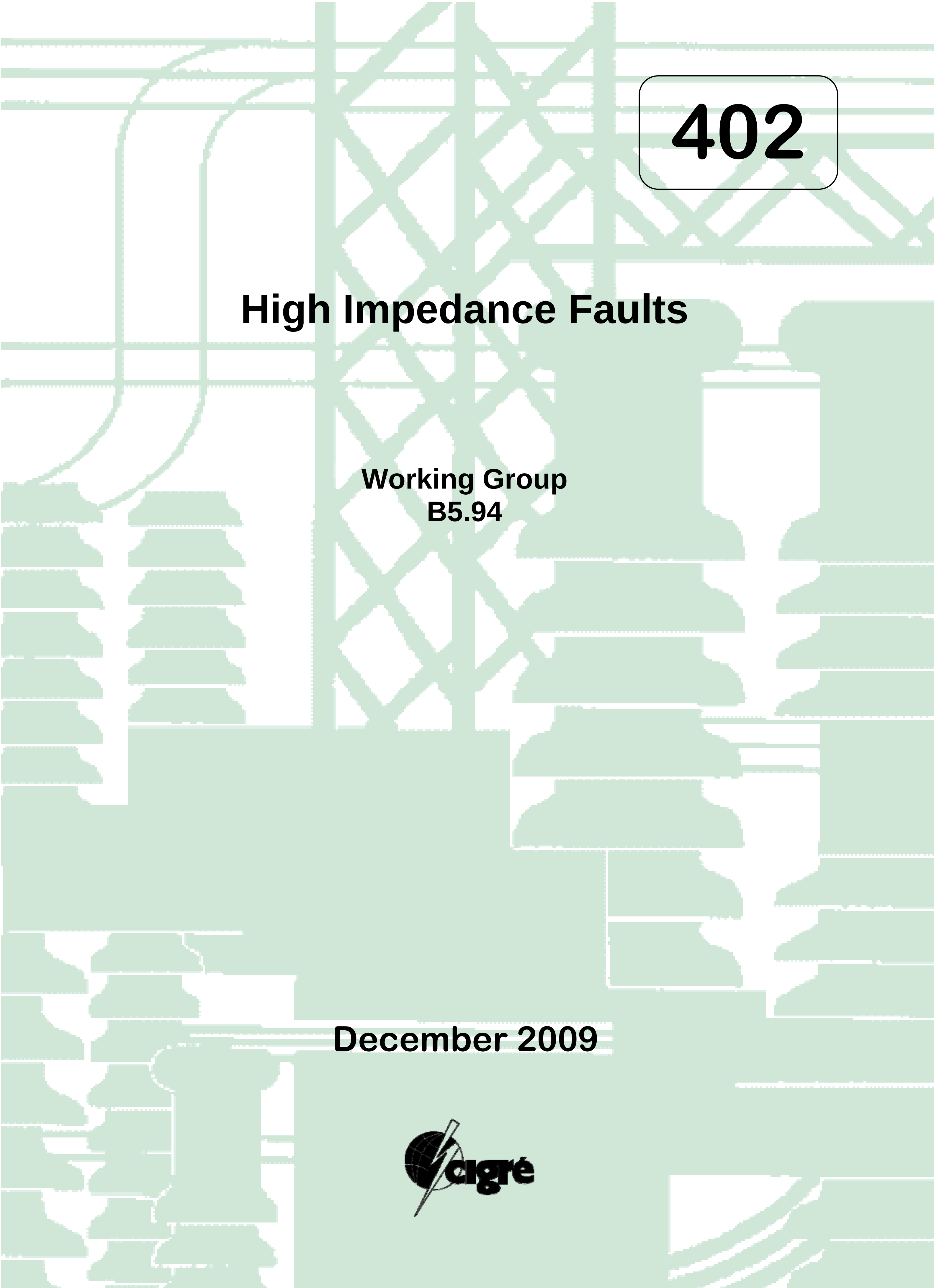

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High Impedance Faults

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High Impedance Faults

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1 Introduction

High Impedance Faults (HIFs) generally result when an energized primary conductor makes electrical contact with a quasi-insulated object, for instance, a tree, pole with very high impedance grounding, or the ground in the case of conductor breaking and falling – depending on the type of soil. In all these cases, the current flowing to ground is so low that it cannot be detected by conventional relays.

High Impedance Faults can also be multiphase faults, if for example a tree limb makes contact with two phase conductors. The majority of HIFs do actually involve a ground path, which may imply risks for life.

HIFs have been a challenge for protection engineers for a long time. HIFs that pose a danger to persons or animal life are not very common, however these faults do exist. How often? It is difficult to determine HIF frequency indexes because utilities' record-keeping practices do not normally track this statistic. Conventional wisdom of protection engineers is that the majority of downed conductors are detected by protection relays. However the perception of line crews is that a more significant percentage of downed conductors still remain energized when they arrive on the scene.

The protection world is normally very close to a world of YES or NO, that is, if there is a fault, the relay must detect it and trip the circuit breaker, otherwise the relay is not working properly. However, HIF detection is a quite different situation.

First of all, it is impossible to detect all HIFs, using only protection relays located at the line end or ends. In order to detect any type of fault there must be a difference in the measurements before and after the fault. But, depending on the type of fault, there may be no change in such magnitudes.

Reliability issues also need to be considered. Reliability is based on dependability and security. Dependability applied to HIF detection is the ability of the detection method or relay to detect all HIFs. Security is the ability of that relay/method to not confuse a normal situation with a HIF. Particularly in HIF detection, both characteristics tend to counteract each other. A high dependability forces a lower security, and vice versa.

Dependability is a target, but security is also very important, because outages that affect traffic control, hospitals, equipment in tunnels, critical loads, etc. create themselves a public hazard.

The design of the network, lines, line-poles, type of grounding, length of the lines, type of soil, vegetation and other parameters greatly influence the number of HIFs in a particular utility. Statistics may even be different in diverse areas. The result is that the concern about this problem is quite different in utilities around the world, and from that, the forces for research and innovation also.

Each utility has to evaluate the necessity to use HIF specific protections for each network, and each area, the most suitable detection method, and the way of applying the protection. In taking this decision the following factors should be considered: the experience of HIFs in the past, type of circuit construction, utility's experience with soil conditions, feeder lay-out, nature of load, type of grounding and performance of existing protection scheme.

Protection engineers have faced the challenge of HIF protection for a long time. In the nineties, a working group under PSRC (USA) produced a report about "High Impedance Fault Detection Technology" [B.3].

Since then, extensive research has been carried for distribution systems and still HIF detection in a very reliable way is under field testing. A lot of knowledge has been acquired about HIF characteristics, and several commercially available products have turned up since then, but utilities with enough HIF records and willing to improve the protection scheme for HIFs however don't yet use them in a general manner, due to lack of a sufficient percentage of HIF detection in a reliable (secure) way.

1.1 HIFs in Transmission and Subtransmission

In transmission or subtransmission networks, the situation is more controlled. On one hand, due to line design, the probability of downed conductors, or tree limb contacts is much lower, On the other, short-circuit power is higher and the current to ground may be detected. As a consequence, the number of undetected HIFs at these voltage levels is very low.

Modern technology, most notably digital relays, has also added substantial sensitivity, for instance, distance relays based on quadrilateral characteristics with load encroachment function, and in particular differential relays present significantly more sensitivity.

Generally speaking, it is possible to obtain high sensitivity with current differential protection, but it can be difficult to maintain that sensitivity for high impedance faults under very severe load conditions. A solution to this problem is to use residual current for differential protection. In this way, an increase of approximately 100 Ω in sensitivity can be achieved [B.1]. In other applications, current differential protection units with a very sensitive slope and a time delay (0,3 sec.) to avoid unwanted trips during transient phenomena are used together with the instantaneous differential stage, in order to amplify sensitivity.

In addition, utilities have been aware of this problem since the beginning of the widespread of distribution/transport of electricity, and generally use back-up relays such as directional/non-directional ground over-current relays with time-coordinated functions.

While HIFs in transmission or subtransmission networks impose challenges in the protection system such as those set out below [B.2], these faults very rarely remain undetected:

- Long tripping times.
- Unselective trips.
- Power swing blocking relays operation due to slowly changing arc resistance during the fault.
- Incorrect triggering of the weak infeed logic due to high resistance.
- Presence of fault resistance also affects shapes of relay characteristics (tilting) particularly on non-homogeneous systems and heavy loaded lines. Adaptive abilities of modern relays may introduce automatic compensation of these effects.

1.2 Scope of this document

Review the different methods to detect HIFs that have been published or/and proposed, or are being used, detailing the degree of advance of each one, e.g. academic study, real tests, commercially available product, etc.

Present world-wide practices, experiences and limitations of electrical utilities in MV, HV and EHV networks in relation with HIF protection.

1.3 Definitions

There is not a world-wide accepted definition for HIFs.

The report by PSRC Working Group D15, already mentioned, uses the following definition for distribution systems:

“A high impedance ground fault results when a primary conductor makes unwanted electrical contact with a road surface, sidewalk, sod, tree limb, or with other surface, or object which restricts the flow of fault current to a level below that reliably detectable by conventional over-current devices.”

This Working Group has carried out a survey on HIFs around the world, and as it may be seen in the conclusions set out in the following chapters, several different definitions are used by utilities. Most of them consider HIFs as ground faults with a fault resistance so high that they are not detected by line main protections. Therefore, these faults may or may not be detected by auxiliary protections such as ground over-current relays.

For the purpose of being used in this document, a **HIF is a fault with an impedance so high that it cannot be detected by fundamental-frequency current and voltage measurement based conventional relays, such as distance, differential, over-current, etc.**

The following classification is considered in this document:

MV: 11-34 kV
HV: 35-200 kV
EHV: > 200 kV

1.4 Detection Methods Classification

- Mechanical systems that produce a low impedance fault when the conductor falls, which triggers the operation of the conventional over-current protection
- MV feeder current and voltage monitoring, using high frequency sampling, low frequency current components, harmonics analysis, neural networks, etc.
- Under-voltage or voltage unbalance detection in secondary substations on high or low transformer side, in order to detect the open conductor condition. Due to the anticipated future spread of communications in the MV/LV networks of the companies, this alternative may become a good solution for open MV conductor detection.
- In HV and EHV, enhanced conventional protection functions of modern IEDs, for instance, “open conductor” detection based on negative current sequence, or negative voltage sequence polarized ground over-current relays, will step up the sensitivity of the protection system for HIFs.

2 World-wide practices, experiences and limitations of electrical utilities in MV, HV and EHV networks taking into account the different grounding methods.

2.1 Conclusions of Survey

The questionnaire was intended to be responded by utilities. It has been answered by 11 utilities from 9 countries, mainly from Europe: Netherlands, Norway, Sweden, France, Slovak Republic, Australia, Spain, South Korea and USA.

50% of the responding utilities operate MV networks, and 90% operate HV and/or EHV networks.

The minimum, maximum, and mean values for the overhead and underground length of the networks are shown in the following table:

Table 2-1: Minimum, Maximum and Mean Values of the Overhead and Underground Network Length (km) in the survey

Length (km)	MV			HV			*EHV*		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	*Max.*
Overhead	67.000	7.253	11.4540	13.000	1.500	48.835	16.000	4.408	46.422
Underground	1.900	1.015	50.000	750	35	2.315	800	90	2.543

The most typical type of grounding is exposed in the table below:

Table 2-2: Type of grounding in the survey

MV	HV	EHV
Low Impedance – 25% Solid – 30% Compensated – 25% Isolated – 10% High impedance – 10%	Solid - 88% Compensated - 12%	Solid - 100%

The questionnaire focuses mainly on definitions and classification of HIFs, records of HIFs, general protection requirements for these faults, conventional protection for ground faults and its sensitivity, special protections for HIFs in standard use in utilities, and R&D in this area by utilities.

The first conclusion that has to be highlighted is that there is no common definition for HIF across the utilities that have answered the survey. Some utilities don't even have a stated definition.

Most utilities consider HIFs as ground faults with a fault resistance so high that are not detected by line main distance protection, this means around 10÷30 Ω of fault resistance (primary). Therefore, these faults may be detected by auxiliary protections such as ground over-current relays. Definition 1.

The fact that this survey has been distributed to utilities participating in CIGRE and therefore that it has been answered mainly by utilities operating HV and EHV networks must be taken into account.

Other definitions that have been gathered:

- Ground faults with a sufficient fault resistance that are not detected by line main protections, such as distance or differential. The coverage thus depends on the type of protection being used, if differential line relay is used, the limit is raised to 100-250 Ω, compared to the 10-30 Ω mentioned above, and the coverage is highly improved. Definition 2.
- Ground faults that are not detected by differential line protection. Definition 3.
- Ground faults with an impedance so high that they are not detected by conventional over-current protection and can therefore pose a danger to the public. This definition is similar to the definition included in the chapter 1 “Purpose of this document” of the survey questionnaire, and is also the definition used by the PSRC Working Group D15 HIF Detection Technology. Definition 4. The focus of this definition is more for MV networks.

In conclusion, the concerns transmission utilities have about HIFs are that these faults are not detected by the main protections and therefore impose some difficulties in the protection system such as unselective trips or slow tripping time.

No utility uses a classification of HIFs, only Svenska Kraftnät (Sweden) suggests possible classification considering the limits of the four different steps of the over-current relay being used in Sweden.

Most of the HIFs are caused by trees or vegetation contact, broken conductor, vehicles and implements touching line parts, and high resistance pole grounding, according to the survey.

As each utility has used its own definition, the HIF record figures gathered are not homogeneous. Some utilities don’t even provide any numbers or qualitative estimation because they don’t keep HIF records. The following table is the summary of the figures given for each definition, including total overhead network length:

Table 2-3: HIF Records per total Length of overhead networks per year

For the first two definitions, Definition 1 and 2:

km	MV	km	HV	km	EHV
-	-	1.500	2	-	-
7.253	Very few	2.010	Never	-	-
-	-	11.000	Medium	8.200	17
-	-	-	-	26.324	< 10%
-	-	48.835	145	46.422	14

For the third definition, Definition 3:

km	MV	km	HV	km	EHV
-	-	-	-	15.013	90

For the fourth definition, Definition 4:

km	MV	km	HV	km	EHV
77.000	Several faults per 10.000 km	22.000	Figure not available	60.000	No fault registered

As can be seen, the figures cannot be easily compared, because of the different definitions used and probably also because utilities don't track HIF statistics and therefore these figures have been calculated for this survey in a more or less approximated way.

As a conclusion of the research of this WG and of the survey, HIFs not detected are extremely rare in HV and EHV. This is not the case for MV, especially in solid or Low/High impedance grounding, in this voltage level HIFs are not uncommon.

According to the survey, the real consequences of these faults are generally forest fire, damaged or broken primary and secondary equipment and animal death, as well as slow fault clearing and relay miscoordination.

Generally there are not clear established requirements for these faults in terms of ohms coverage or tripping time inside the utilities or for the whole country.

Some utilities use setting criteria for ground over-current, distance and other relays such as “the pick-up of the ground time over-current relay will be typically set to 0,5 amps secondary”.

One special case that has to be mentioned is Sweden, where:

- For HV and EHV networks, all faults leading to a fault current higher than 120 A must be detected and tripped. This means a coverage limit of 1.000 Ω in 220 kV and 1.900 Ω in 400 kV.
- In MV, ground fault protection for a network, in which there is overhead-line in reinforced design (overhead line with plastic covered conductors or hanging spiral cable conductor) shall:
  - have the highest possible sensitivity for detection of ground fault and,
  - be made so that relay function for disconnection is ensured up to 5.000 Ω or higher if this is possible, with respect to the risk of unselective operation due to, for instance, measuring errors in current transformers or induction.
- For other types of overhead lines, the requirement is 3.000 Ω or higher if this is possible, with respect to the risk of unselective operation.
- Faults up to 20 kΩ need to be alarmed (but only non-selective).

The case of Sweden is by far the most demanding one between the responses to the questionnaire and the research of this WG.

In relation to the risk of accidental human contact and the specific requirements for this type of situation, it should be noted that a few utilities do not use automatic reclosing for delayed trips or sensitive earth fault protection trips. Other utilities limit the number of reclosing attempts to minimize impact to public.

Among the conventional ground fault protection that utilities are using, the following can be mentioned, as well as the sensitivity and tripping time:

Table 2-4: Conventional Ground Fault protection, Sensitivity and Clearing Time in the survey

Type of grounding	Voltage level	Type of relay	Sensitivity	Clearing time
Solid or High/Low Impedance	HV & EHV	21G	5-30 Ω	**0,1 -1 s**
		87L	100-250 Ω	**0,1 s (or 0,3 s)**
		67N	100-600 A (<250 Ω)	**1-10 s**
		67N with teleprotection scheme	100-600 A	**0,1 s**
		K*Vo *Io, inverse time (zero sequence power relay)	100-600 A (100-300 Ω)	**< 10 s**
		51N	75-120 A (1.000-2.000 Ω)	**1-10 s**
	MV	51N	15-400 A (< 500 Ω)	**< 10 s**
Compensated	MV & HV	Transient Earth Fault	Transient high frequency current measurement	**Directional alarm**
		Earth Current	Watt metric earth current: 5 – 50 mA secondary	**Directional alarm (non-typical applications: trip and ARC)**
Isolated	MV	59N		

It should be highlighted that the settings and therefore the sensitivity of ground over-current relays (51N) in MV is very different between different utilities, in the range of 15 - 400 A, the reason is that in some network configurations the ground unbalance due to MV single phase to ground connected loads can be very high and the ground over-current relay must be set above this unbalance. In other networks the secondary loads consist of three phase transformers and as a consequence, this type of unbalance doesn't exist.

The utilities that have answered the survey do not use special protection for HIFs in MV, such as those based on harmonics analysis.

Some utilities use ground/earth sensitive over-current relays as particular protection against HIFs in MV, although they can be considered as conventional protection. These relays have a more sensitive setting in the range of 5-10 A, and a definite tripping time of around 5 s. Utilities try to improve the sensitivity even more, for instance by using metering instead of protection secondary cores of current transformers, or by using core balance current transformers.

Nevertheless the threshold of these relays cannot be set below the network inherent unbalance (for instance single phase to ground connected secondary transformers, underground cable capacitance current during single phase switching or fuse operation, etc.) or current transformer or induction errors.

These relays although significantly improving the sensitivity of conventional electromechanical ground relays, still lack enough coverage and some HIFs even now remain undetected in MV.

One of the utilities in the survey has tested and evaluated new special HIF relays from different manufacturers over several years, but the results are not clearly satisfactory, as the faults they are specifically trying to identify (downed conductor on asphalt, tree faults, etc.) are those much harder to detect, and the repeatability of correct identification of HIF faults must be improved. Currently, this utility does not intend to test or evaluate new relays until further improvements are made.

The functionality of HIF detection is included in line relay with or without additional cost, depending on the manufacturer.

As a conclusion of the survey, there is a clear and challenging need for better detection of HIFs in solid or High/Low impedance grounded MV networks especially with single phase loads, but the utilities in the survey are not currently testing or developing new non-conventional HIF detection functions.

3 HIF detection methods.

3.1 *Introduction*

This chapter will present an overview of measurement and detection methods of high impedance faults. By definition, the HIF cannot be detected by simple over-current or under-impedance protection. Looking at fundamental components, the HIF is nothing like a short circuit as the HIF fault current is only a fraction of normal load current. HIFs can only be detected with non-conventional measuring techniques.

In Continental Europe many medium and high voltage systems (≤ 110 kV) are operated with compensated or isolated neutral grounding. A brief explanation of the simple ground fault detection for these systems is provided.

Methods for the detection of open pole (broken conductor) are briefly mentioned as the HIF is often caused by conductors breaking and making contact with non-conducting surface.

Different CT connections for measuring the residual current are illustrated.

3.2 *Summary of available detection methods*

The measurement types presented here are all based on direct measurement of online available current and voltage signals. Other methods for localizing the high impedance fault such as monitoring zero sequence voltage variation when switching individual feeders are not included (Lamberty & Schallus 1981 [B.6])

3.2.1 *Residual Current Measurement*

As stated above, the residual current measurement in its classic form, fundamental or RMS over-current, is not relevant to HIF as the fault current level is not detectable in this manner. Special current measuring techniques with delta measurement or compensation of CT errors can increase sensitivity. A residual current measurement purely based on the fundamental frequency is however not suitable for HIFs.

In systems that are not solidly grounded, core balance CTs are often applied (Figure 3-2). With this type of current measurement the sensitivity and security against CT errors is significantly greater than with a Holmgreen connection (Figure 3-1) as the CT ratio for the core balance CT may be significantly smaller than that of the main CTs.

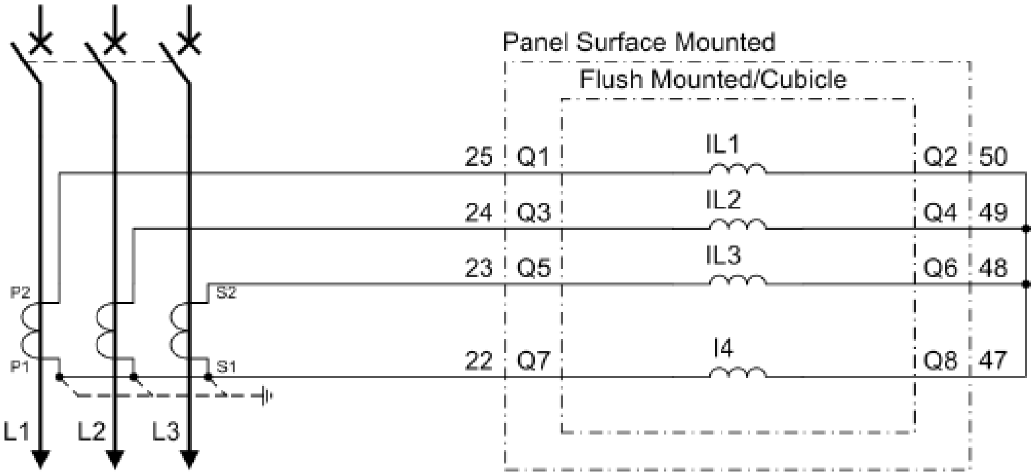


Figure 3-1: Residual current measurement with Holmgreen connection

The most common CT connection for measurement of the residual current is the Holmgreen connection shown above (Figure 1). No additional CT is required as the phase CTs are applied for this purpose. Care must be taken to avoid false measurement due to errors in the phase CT measurement (saturation) as this “error” current appears as residual (zero sequence) current.

If a core balance CT is available, the connection shown below (Figure 2) can be applied:

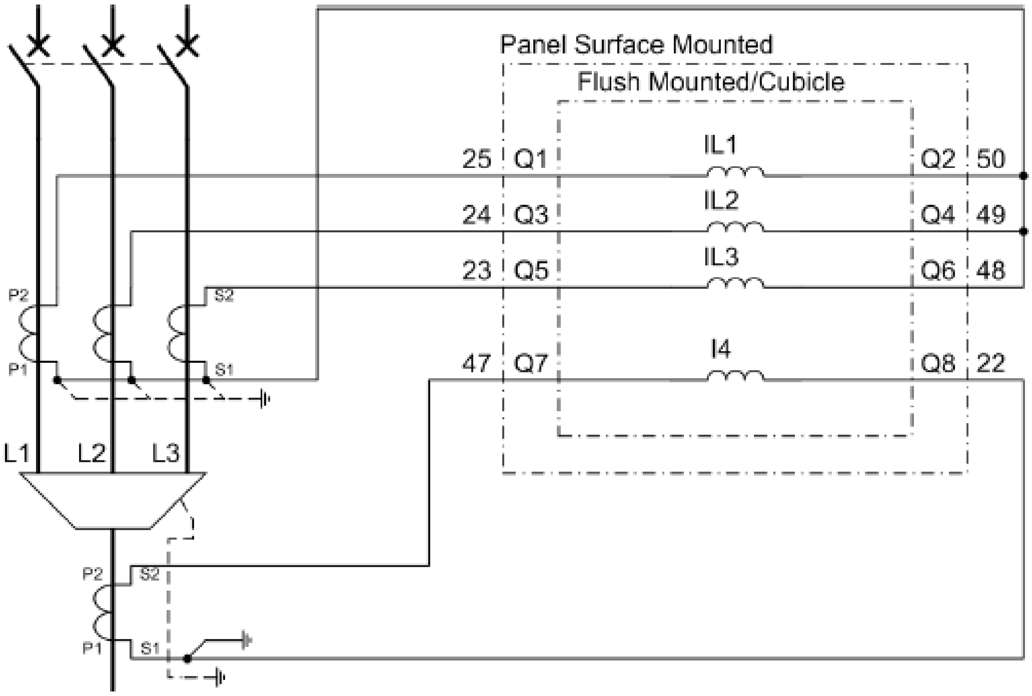


Figure 3-2: Residual current measurement with core balance CT.

The separate measurement of residual current with a core balance CT allows for higher sensitivity as it is not disturbed by errors of the phase CTs. Note the connection of the cable screen, which must be fed back through the CT to cancel the screen current from the measurement.

3.2.2 Neutral voltage and residual current analysis

This method determines the resistance in the neutral path by analysis of the zero and positive sequence voltage and the change in residual current. Whereby the change (delta) in the zero sequence voltage is superior for the achievement of immunity against system unbalance. (Lehtonen 1999 [B.7])

3.2.3 Harmonic Component Evaluation

The analysis of harmonic frequency components for the detection of HIFs is widely investigated. Particularly in the USA, where the downed conductor and consequential threat to human injury is a critical issue, this type of measurement is common in literature. One example of a harmonic measurement is the evaluation of the 3rd harmonic current and comparison of its phase angle with the fundamental current. The assumption is that the HIF has a particular relationship in this regard. (Yu & Khan 1994 [B.8])

3.2.4 Spectral Power measurement (Randomness)

An energy algorithm monitoring the variation of spectral power in the three phases was introduced by Shiping & Russel (1991 [B.9]). It looked at a particular frequency or frequency band in the 2-10 kHz range. This detection method uses the non-system frequency power dissipated in the fault (arc). Further distinction is the randomness – continuous changing of the power spectrum resulting from the HIF.

3.2.5 Loss of Potential (open conductor detection)

As HIFs are in part of the cases associated with a broken conductor, this method is based on the loss of potential at the load end, e.g. the 120 VAC. A signal is transmitted to the upstream station when loss of potential is detected. The system proposed by the Kearny Manufacturing Company was already tested in 1992 [B.10]. Several voltage unbalance prototype sensors have been installed and tested in some feeders of Brazilian utility companies [B.11].

3.3 Primary detection devices (physical /mechanical)

By installation of additional primary equipment, further methods for the detection or avoiding of HIFs can be found. For example grounded brackets below the phase conductors can be applied to ensure that broken isolators result in solid ground faults.

3.4 Isolated and resonant grounded systems

For systems that are not solidly grounded the simple earth fault condition is considered an exceptional operating condition, which may, in some cases, be tolerated for several hours. In Germany and Austria 110 kV subtransmission systems are often operated with resonant grounded neutral. The simple ground fault detection is based on zero sequence voltage with directional supplement based on wattmetric zero sequence current [B.12]. For detection of a HIF in these systems the fault must unbalance the system capacitance sufficiently for zero sequence voltage detection. Fault direction can only be determined when the residual current (fundamental component) due to non-symmetrical phase-ground voltage is measurable.

3.5 Broken conductor protection (current unbalance)

Detection of broken conductors is possible with simple current balance measurement in the presence of load. On radial feeders the voltage at the load side can also be used to indicate a missing (broken) phase. Often the negative sequence (out of balance) current or the ratio of negative sequence current to positive current (I2/I1) is used for the detection of a broken conductor [B.27]. This will only work if load current flow is above the set negative sequence current threshold i.e. above the unbalance present when there is no fault.

3.6 Conclusion

There is far more interest in HIF protection in the USA compared with Europe and most other parts of the world. In most cases outside the USA the HIF is not distinguished from high resistance ground faults that are detected by conventional residual over-current protection. It can therefore be supposed that some aspects of the North American distribution and reticulation system, for this is where there is most interest in HIFs, are particularly at risk in this regard.

The research and tentatively applied HIF protection in most cases is concerned with the reliability and sensitivity in relation to the security against mal-operation due to certain load characteristics (e.g. fluorescent lighting). This environment is very interesting for research. For example, self-learning systems (neural networks) have been proposed; these would be “fed” with fault simulations to be “learned” and then applied in real systems to “learn” load conditions. Technology has made products of this nature viable, however practical proof of their viability is not yet evident.

The commercial products are limited to application in the USA and use measuring principles that were discovered during the earliest research in this area. The acceptance and proliferation of these products will steer future developments (R&D budgets).

4 New Protection Scheme and Field Experience of MV Compensated Networks

This Chapter deals with a new protection scheme adapted to Neutral Compensated MV French network and first field experience results concerning the very few HIFs (or very resistive faults) that are not eliminated by this protection scheme, as described in paper [B.13].

4.1 Introduction

Since 2001, the French MV network's neutral earthing policy has changed as described in paper [B.14] in Cired 2005. As more cables are installed in France and a new touch-and-step voltage standard came into place, a new compensated grounding for capacitive non-urban networks became justified. The installation of a tunable compensation coil with a high 600 Ohms resistance in parallel limiting the fault current to 40 Amps was adopted. Since then, a certain number of benefits were achieved thanks to compensated neutral grounding for the mixed overhead lines and cable networks:

- The step-and-touch voltage, and the over voltages on LV networks and Telecommunication system comply now with the standards,
- The protection scheme was consequently adapted: Wattmetric and Voltmetric relays adapted to mixed cable and overhead line feeders improved the sensitivity of the protections,
- The overall power quality was improved even if not equally on all feeders. The number of self-extinguishing faults increased, thus reducing the number of short fault elimination reclosing cycles.

In 2006, the EDF MV neutral grounding planning policy was re-written: the criteria determining which substation transformer should be equipped with a new neutral compensated grounding was put in place (the criteria is a capacitive current over 100 A per transformer). Moreover, the rhythm of deployment of the neutral-compensated grounding project was increased in the last two years.

This chapter gives:

- a description on the zero-sequence protection scheme of EDF neutral-compensated MV distribution grids,
- a feedback on the efficiency of the resistive zero-sequence faults elimination.

4.2 Description of EDF's MV zero-sequence protection scheme

Since 2001, EDF's protection scheme on neutral-compensated MV networks (in paper [B.15]) is based on the feeder zero-sequence wattmetric relay and the more sensitive transformer zero-sequence voltmetric relay (also mentioned in papers [B.16] and [B.17]).

4.2.1 Definitions

Most **zero-sequence faults** on neutral-compensated MV networks are generally detected and eliminated by the feeder zero-sequence wattmetric relay, which is a directional protection well adapted to the Compensated Neutral Networks (it replaces the zero-sequence maximum current relay that was no longer adequate).

- A **resistive fault** is usually eliminated by the transformer zero-sequence voltmetric relay and not detected by the feeder zero-sequence wattmetric relay.

- A **very resistive fault** is usually not detected by the transformer zero-sequence voltmetric relay, which is a non-selective protection (no identification of the faulty feeder).

The **resistive sensitivity** of a protection scheme is given in Ohms and corresponds to the highest fault resistance value that can be detected.

4.2.2 Description of the Zero-sequence Protection Scheme

The French MV zero-sequence protection scheme is based on zero-sequence voltmetric and wattmetric relays.

Wattmetric detection

On faulty feeders, the zero-sequence wattmetric relay detects negative zero-sequence active power. It detects restricting faults and remaining zero-sequence faults. With a low threshold, sensitivity is very good (typically 8 kW up per feeder). Tripping usually happens within 1 s. A delay is set typically at 700 ms in order to deal with self extinguishing faults.

Voltmetric Detection

The voltmetric relay detects high impedance faults. The detection threshold is set as low as possible, but should be set above the sum of:

- The existing zero-sequence substation voltage (it is due to the unbalanced feeders capacitive components: around 1% of nominal voltage),
- The existing zero-sequence voltage due to the precision of the compensation coil. Typically the threshold is set at 4%. This guarantees a detection up to 5 kΩ resistive fault for 35 Amps overtuned Neutral Compensated networks, as shown in Table 4-1 below.

Indeed, the theoretical protection scheme resistive sensitivity performances can be summarized as follows:

Table 4-1: Sensitivity levels of zero-sequence relays

	Tuned Neutral Compensated	**Overtuned Neutral Compensated**
Zero-Sequence Wattmetric Relay	5,3 kΩ	2,5 kΩ
Zero-Sequence Voltmetric Relay	10 kΩ	5 kΩ

4.3 EDF’s Field experience in MV neutral compensated network zero sequence protection scheme

A field experience on zero sequence protection scheme for MV neutral compensated network was launched in 2005 in 25 EDF distribution areas throughout France. The study covered 42 substations equipped with neutral-compensated transformers. The survey dealt with the recorded zero-sequence faults that occurred in year 2004.

The results can be summarized in the Table 4-2:

Table 4-2: Statistics of Detected Faults

Number of Zero-sequence faults detected per transformer and per year	Number of Resistive Zero-sequence faults detected per transformer and per year	Number of Very Resistive Zero-sequence faults detected per transformer and per year
38,3	0,43	0,03

The results can also be expressed in percentage of zero-sequence faults (see Table 4-3):

Table 4-3: Efficiency of the Relay Detection

Percentage of detected zero-sequence faults	Percentage of resistive zero-sequence faults	Percentage of very resistive zero-sequence faults
99,93 %	1,14%	0,07%

The origins of such resistive faults are generally MV/LV transformer faults, cable touching the ground or cable failures between tower anchor clamps.

This field experience improved the knowledge of the protection scheme used on neutral-compensated networks as follows:

- Around 0,07 % (less than 1 over 1000) of very resistive faults are not detected by the zero-sequence Wattmetric and Voltmetric relays. The protection scheme is therefore around 99,9 % satisfactory. This corresponds to about 1 non-detected fault in a neutral compensated substation every 21 years.
- Around 1,1 % of resistive faults are detected by the zero-sequence Voltmetric relays and not by the zero-sequence Wattmetric relays: faults which resistance is greater than a mean value of 4.000 Ω. This corresponds to 0,7 fault per year per neutral-compensated substation. This low figure can be explained not only by the improved sensitivity of the neutral-compensated protection scheme (compared to the neutral impedance protection scheme), but also by the growth of cables installation and network equipment reliability.

5 Latest developments for HIF detection

The electric utility must always have public safety as a top priority. The utilities need an economic solution and a system that can reliably detect high impedance faults, and is also secure against false detection of a high impedance fault, if they exist. High Impedance Fault (HIF) detection requires a different approach than that for conventional low impedance faults. Reliable detection of HIFs provides safety to humans and animals. HIF detection can also prevent fire and minimize property damage. Two examples of new commercially available products for HIF detection by two different manufacturers are described below.

5.1 First example of HIF detection

This equipment is based in the use of the harmonics content in the current waveforms for arcing fault detection.

The typical HIF is when a conductor physically breaks and falls to the ground. The break in the conductor will usually result in either a drop in load on the affected feeder or possibly a momentary over-current condition as the falling conductor briefly comes in contact with a solidly grounded object. Once on the ground, the resulting electrical signature is very much a function of the contacted surface. Surfaces such as concrete, grass, dirt, and wet surfaces in general will result in an arcing fault with RMS fault currents in the range of 10 to 50 Amps whereas surfaces such as dry sand and asphalt will result in a constant low level of current flow. Arcing faults result in a very definable and detectable pattern whereas the signatures presented by the latter surfaces present a challenge to secure and reliable detection.

A second type of HIF occurs when the conductor does not break, but comes into contact with grounded objects either through a failure of the conductor mounting system, insulation failure, or inadvertent contact with some external element such as a tree limb. These faults will usually exhibit the same arcing signature as a broken conductor lying on the ground, however, the event will not be preceded by any change in fundamental current.

A third type of event is a sagging conductor. Although not technically a fault, it does present a considerable public safety hazard. In this circumstance, a conductor hangs low enough to enable human or other contact. Note that this type of event offers no electrical signature for detection.

5.1.1 SIGNATURE BASED HIF DETECTION

The signature based HiZ IED performs expert system pattern recognition on the harmonic energy levels on the currents in the arcing fault. This technique is based on the technology developed at Texas A&M University after more than two decades of research started in the seventies, funded in part by the Electric Power Research Institute. Early fault characterization efforts by Texas A&M and by other groups found that most high-impedance faults produce arcing, and that this arcing generally produces detectable changes in multiple electrical parameters. Every fault is different, and surface conditions have a significant influence on the behaviour of any given fault. However, in general, researchers found that many faults produce only subtle changes in fundamental frequency current, but marked changes in low order harmonic and non-harmonic frequencies and in higher frequency currents (e.g., in the kilohertz range). In other words, these efforts demonstrated that electrical parameters often contain significant information indicative of the presence of high-impedance faults. In the mid 1990's, the concerned manufacturer commercialised the algorithms in the first relay for detecting a large percentage of these faults, while maintaining security against false operations.

Figure 5-1: Arcing fault

The overall process in the HiZ IED incorporates nine algorithms, each performing a specific detection or classification function. High impedance fault detection requires inputs from the three phase and ground currents via relaying current transformers. Voltage inputs are used to enhance security and to provide supplemental phase identification and are not required for arcing detection.

The primary detection algorithms are the Energy and Randomness algorithms.

The Energy algorithm focuses on the fact that arcing causes bursts of energy that register throughout the frequency spectrum. The energy values computed as the square of the harmonic and non-harmonic spectral components (except the fundamental) are integrated into odd, even, and non-integer harmonics values. Sampling at 64 samples per cycle allows computation of frequency components up to the 25th harmonic. The Energy algorithm monitors these computed harmonics on all phase and ground currents. After establishing an average energy value for a given signal, the algorithm indicates arcing if it detects a sudden, sustained increase in the value of that component. Figure 5-2 shows normal energy levels as measured on an actual feeder. Indications of energy increase are reported to the Expert Arc Detector (EAD), which performs a probabilistic integration of the arcing inputs from all phases and all harmonic components.

The second detector in the algorithm suite is the Randomness algorithm. This algorithm keys on a second characteristic of an arcing fault, which is the fact that the energy magnitudes tend to vary significantly on a cycle-to-cycle basis. Figure 5-3 shows the energy values during an arcing fault. The high level of energy as well as the variance in the energy can clearly be seen. The Randomness algorithm measures these magnitude variations and reports detection of magnitude variation to the Expert Arc Detector.

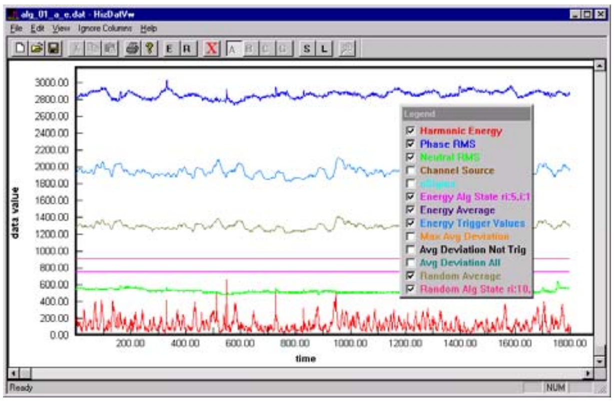


Figure 5-2: Steady State Harmonic Energy

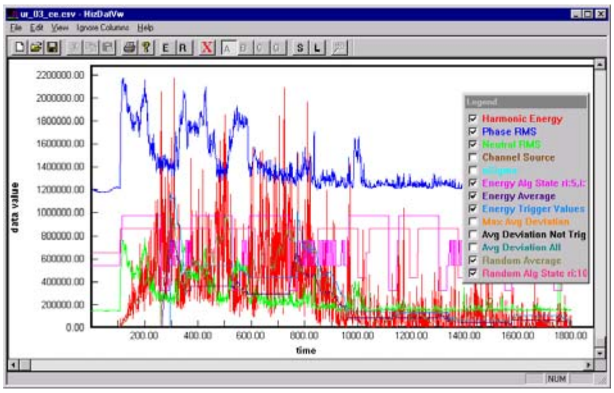


Figure 5-3: Arcing Fault Harmonic Energy

The purpose of the Expert Arc Detector algorithm is to assimilate the outputs of the basic arc detection algorithms into one cumulative arc confidence level per phase. There are actually 24 independent basic arc detection algorithms, since both the Energy and Randomness algorithms are run for the odd, even and non-integer harmonics for each phase current and for the neutral/ground current. An arc confidence level is determined for each phase and neutral/ground. The expert arc detector algorithm compares the cumulative arc confidence level values or high EAD counts to the user's arc sensitivity setting. Figure 5-4 shows the block diagram of how the Energy, Randomness, and Expert Arc Detector algorithms function together.

For the device to be secure and dependable, the Expert Arc Detector integrates the outputs from the Energy and Randomness algorithms. The number of times that the integration is performed depends on the arc sensitivity setting. The more sensitive the setting, the lower the integration level and the fewer integrations required.

An arcing detected output is issued once all the EAD requirements are satisfied. If either a loss of load or a momentary over-current condition is detected immediately before an arcing detected output is registered, the downed conductor output is set to indicate that there is actually a conductor on the ground.

Conductors that do not continuously arc, but have time periods between arcs can be detected by the arcing suspected identifier algorithm. For example, if arcing is caused by tree limb contact or insulator degradation, arcing will typically be present intermittently with relatively long periods of inactivity. In such cases, arcing may be affected by such factors as the motion of a tree limb or the moisture and contamination on an insulator. The purpose of the arcing suspected identifier algorithm is to detect multiple, sporadic arcing events. If taken individually, such events are not sufficient to warrant an arcing alarm. When taken cumulatively, however, these events do warrant an alarm to system operators, so that the cause of the arcing can be investigated. The user can select the maximum number of arcs and an acceptable period of time. Due to the possible long periods of arcing inactivity, a HIF decision could be reached in up to 5 minutes.

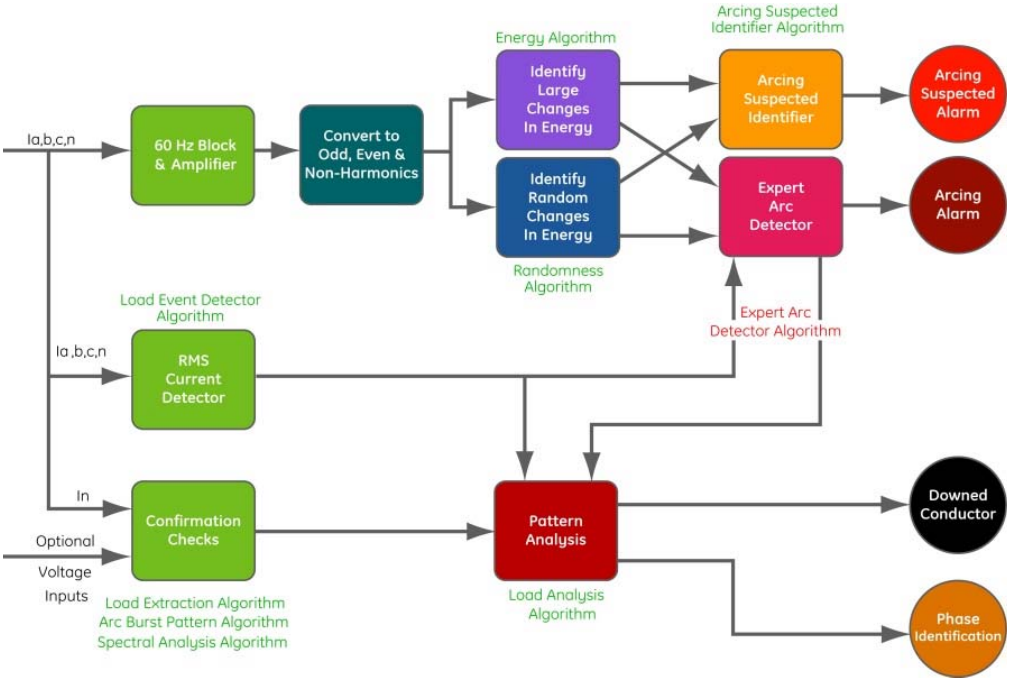


Figure 5-4: Blocking Diagram of the HIF Algorithms in the relays

5.1.2 FIELD EXPERIENCES. PEPCO'S SYSTEM AND EVALUATION

The Potomac Electric Power Company, or Pepco, provides electric service to the Washington, DC area and surrounding Maryland suburbs. Pepco's service area is 640 square miles, with a population of over two million. Pepco's distribution system consists of 1.295 13 kV feeders, 620 of which are overhead. They are of standard multi-grounded wye configuration.

Potomac Electric Power Company (Pepco) recognized the need to address the perennial problem of downed-conductor faults several years ago. Because of their commitment to finding a solution to the high-impedance problem, they embarked on a widespread, long-term evaluation of high-impedance fault detection technology developed by Texas A&M University.

Pepco evaluated the HIF algorithms on 280 of their overhead feeders over a period of two years and gained significant operational experience with them. During this time, the relays detected arcing associated with 96 percent of the downed conductors that occurred, and produced Downed Conductor outputs 58% of the time. Perhaps more importantly, during the 560 relay-years represented by this evaluation period, the relays produced only two false Downed Conductor indications. Pepco is pleased with the performance they have seen and is currently deploying these relays on their remaining feeders.

The installation of these relays occurred over a period of four years. As the detectors were installed, Pepco began to monitor their performance and collect operational statistics. Having no historical or other basis for setting the relays' sensitivity to other than the "medium" setting that comes from the factory, Pepco left the sensitivity setting at this factory default setting, which was designed as a conservative setting with a bias toward security.

5.1.2.1 Pepco’s operating statistics

As stated previously, Pepco's evaluation involved approximately 280 relays for an average of two years. This represents an extensive evaluation period of 560 relay-years of operation. During that time period, Pepco had several hundred instances of downed conductors on the feeders instrumented with high-impedance fault relays. Of these, operator logs and target logs indicated 71 incidents for which crews found downed conductors that were not cleared by conventional protection and that remained energized when they arrived on the scene to make repairs. Pepco investigated all 71 incidents, but found that there were 23 of them for which the relays no longer had data for the period of interest, because of the passage of time between when the event occurred and when personnel retrieved data from the relay.

There were 48 incidents that met the criteria of 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. The relays armed the downed conductor algorithm for 46 of the 48 incidents (96%). As a part of the relay's bias toward secure operation, it does not indicate a downed conductor unless either a loss of load or an over-current immediately precedes the detection of arcing. Even with the bias toward security, the relay's algorithm requirements were met, resulting in "Downed Conductor" outputs, for 28 of the 48 faults (58%). This detection rate is quite good, considering the security bias and especially considering that none of these 48 faults were cleared by any conventional means!

Table 5-1: HIF Relay Evaluation Statistics

High Impedance Fault Relay Evaluation Statistics		
Feeder-years of experience	560	
Confirmed high-impedance faults evaluated	71	
False alarms	2	
Faults with relay data available	48	
- Faults that armed relay	46	(96%)
- Faults that were detected	28	(58%)

5.1.2.2 Needed enhancements

Pepco was pleased with the results they obtained from the current embodiment of the high-impedance fault detection technology. However, there are always areas for potential improvement. It is Pepco's view that one of the main areas in which the current embodiment could be improved is in data storage and retention in the relay.

5.1.3 FIELD EXPERIENCES. JACKSONVILLE ELECTRIC AUTHORITY EXPERIENCE

The experience of this company can be summarized as follows:

- The ratio of “detected” downed conductors to the total population of downed conductors was 80%.
- Investigation based on a periodic “arc detection” alarm lead to detect a motor failure at the customer site.
- Arcing due to loose transformer bushing was detected by HIF algorithms.
- A downed conductor on an asphalt surface found paths through cracks in the asphalt, which lead to “down conductor” detection by the HIF algorithms.

5.2 *Second example of HIF detection*

Recent development in high impedance fault detection came from another manufacturer in a commercial product. It is based on a multi-algorithm approach. Each algorithm uses various features of phase and/or ground currents to detect a high impedance fault. Suitable features of the currents include their waveform signatures, their sample values, etc. Harmonic and non-harmonic current signals are used in different algorithms to detect the presence of high impedance faults. Fig. 5-5 shows a schematic diagram of an electrical power system having a high impedance fault detection system HIF Detect^{TM}. Also shown in Fig. 5-5 are the potential transformer PT and the current transformer CT which provide the analogue inputs for the high impedance fault detection system. Same set of CTs and PTs are used for the protection of the feeder. As a matter of fact, HIF Detect^{TM} is included in a standard IED that is used for the protection of the feeder.

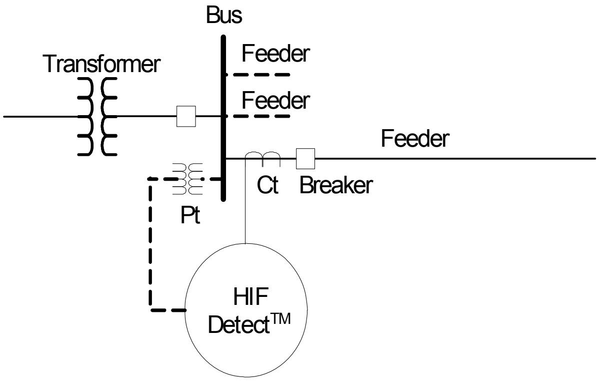


Fig. 5-5: Electrical power system having high impedance fault detection system.

The high impedance fault detection system, HIF Detect^{TM}, is based on some of the techniques discussed in references [B.18] - [B.21]. The individual high impedance fault detection techniques have different algorithms for detecting high impedance faults. The individual high impedance fault detection algorithms can each have a different confidence level. A fault is identified as a high impedance fault once it is detected independently by the algorithms and processed through decision logic.

As shown in Fig. 5-6, power system signals are acquired, filtered, and then processed by individual high impedance fault detection algorithm. The results of these individual algorithms are further processed by a detection logic to provide the detection decision. The detection logic can be modified depending on the application requirement.

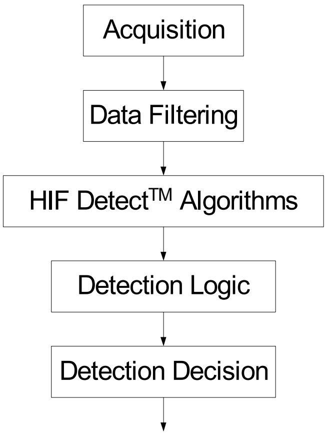


Fig. 5-6: High impedance fault detection system.

The high impedance fault detection system is based on algorithms that use current signatures in all of the 3-phases and/or ground which are considered non-stationary, temporally varying, and of various burst duration. All harmonic and non-harmonic components within the available data window can play a vital role in the high impedance fault detection. One challenge is to develop a data model that acknowledges that high impedance faults could take place at any time within the observation window of the signal and could be delayed randomly and attenuated substantially. The model is motivated by previous research, actual experimental observations in the laboratory, and what traditionally represents an accurate depiction of a non-stationary signal with a time dependent spectrum.

The high impedance fault detection problem addressed in the development is formulated as such:

Hypothesis $H_0 : s(t) = l(t) + n(t)$ (1)

Hypothesis $H_a : s(t) = l(t) + n(t) + f(t)$ (2)

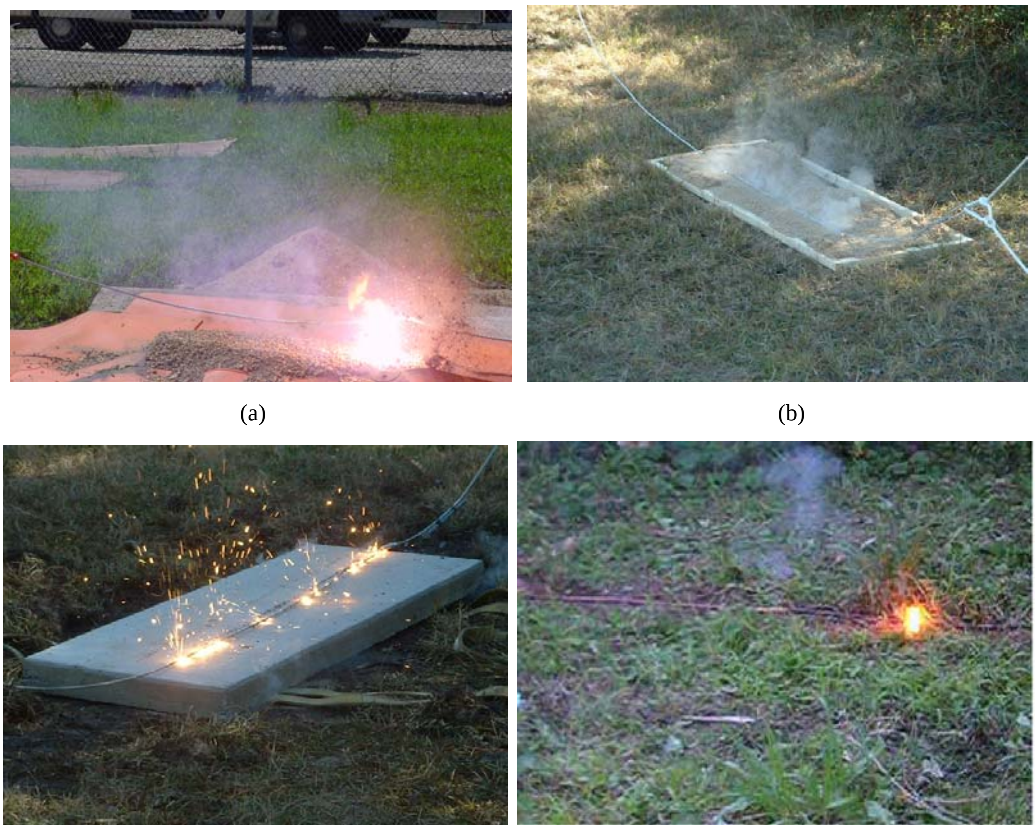
Where s(t) represents the monitored phase and/or ground currents. It is assumed that all measurements are corrupted with additive Gaussian noise n(t). The high impedance fault signature is denoted by f(t) and represents the instantaneous value of the fault current. Normal load signals are denoted by l(t). Hypothesis H0 represents a non-fault situation and Hypothesis Ha represents a high impedance fault situation.

High impedance fault detection system was developed with research and development effort conducted over seven years. HIF algorithms were first tested in the laboratory which was followed by field testing. High impedance fault detection algorithms have been extensively tested between 1998 and 2000 using data generated at the laboratory. Test results are very encouraging. Detection rates are around 80% while the false operation is close to 0%.

The laboratory results encouraged the manufacturer to implement the techniques in an embedded platform so that HIF detection can be integrated into IEDs (Intelligent Electronic Device) used for protection and control of feeders. Additional HIF field data was obtained in 2002 from a research laboratory that independently performed HIF testing in a distribution system. The implemented HIF detection system required adaptation and modification to perform satisfactorily both with laboratory data and acquired field data.

Once satisfied with the performance of the implemented HIF algorithms, with laboratory and acquired field data, the manufacturer approached several utilities to verify the performance of the HIF detection system and collect HIF data with staged-fault testing. Many utilities responded to the request positively and successfully conducted field testing.

In addition to the IEDs equipped with the HIF detection system HIF Detect^{TM}, a separate data acquisition system for the collection of field data from staged HIF testing was also developed. This has been done to collect data from the field testing that is independent of the HIF detection units for future use and replay of the fault events. Field testing of IEDs equipped with high impedance fault detection system HIF Detect^{TM} was done in the process of collecting data from staged HIF testing – these field tests took place six times between January and December 2004 at various locations. Photographs of some of the staged-fault testing on various surfaces are shown in Fig. 5-7.



(a) (b)

(c) (d)

Fig. 5-7: Validation of HIF Detect^{TM} on various surfaces: (a) Gravel, (b) Concrete, (c) Sand and (d) Soil.

Results of field tests were very encouraging. High impedance fault detection system, HIF Detect^{TM}, could successfully detect HIFs on gravel, sand, concrete, soil and grass. The HIF Detect^{TM} also proved to be very secure when presented with various load conditions that resemble HIF situations.

The manufacturer implemented the HIF Detect^{TM} as a standard feature in its state-of-the-art IED, released in January 2005. One of the hallmarks of the HIF detection system is its user-friendly design. There are only two settings. The user can select the level of security in the HIF detection system with a very intuitive setting called HIF level (Security Level), which can be set anywhere between 1 and 10 in steps of 1, 10 being more secure than 1. The default setting is 5. The other setting is related to the grounding system – the user can select between an ungrounded and grounded system and also has a choice to disable the feature. Field testing of the commercially available unit is continuing.

Future challenges will be to detect high impedance faults on trees (various types) and on asphalt. Both these surfaces produce very little (in some cases, none) change in current in the feeder due to the fault. Newer algorithms will be required to address these challenges.

6 Conclusion and perspectives

This working group's report is based on the survey answered by eleven utilities in nine countries, on research of the existing literature and commercially available products and on the operating experience of various utilities around the world.

The first conclusion drawn by this working group is that the scope and effect of the HIF problem differs greatly between MV and HV/EHV grids. The fault current and the percentage of non-detected faults by protection systems depend on the voltage level.

With HV/EHV, the number of high-impedance faults not detected by the protection devices reported to this work group is more or less zero. Only less than 1% of the total faults are not detected by the main protection systems (distance, differential ..), except in networks with high bushfire risk areas, in which this percentage can be higher.

These faults (<1%) are detected by ground directional/non-directional over-current back-up relays, so HIFs do not represent a risk to personal safety. However, non-selective trips occur due to the difficulties for proper coordination of ground over-current relays. Therefore there is an opportunity for improvement, by extending the sensitivity of the main protection systems to the level of the back-up ground over-current relays (maximum, 120 A for EHV in the case of Sweden).

Another area open to advance is right faulted phase selection for HIFs in order to attain correct single phase tripping and reclosing. Conventional current or impedance based phase selectors may not correctly select faulted phase and more sophisticated selectors based on voltage and current symmetrical components are being proposed and investigated.

Many of the electricity companies that took part in the general survey define high-impedance faults as faults that are not detected by the main protection devices, but rather by the back-up devices. In relation to this subject, it must be mentioned that there is no generally and globally accepted definition of HIF, so there is a lack of standardisation in this area.

The most suitable main protection schemes for HIF are the differential relay and the directional earth fault comparison protection. For back-up functions ground directional/non-directional over-current and zero sequence power relays are the possible solutions.

With MV, based on the survey, high-impedance faults are considered differently around the world: some companies consider the problem as virtually solved with very few high-impedance faults that are not detected, whereas other companies consider the problem as unresolved owing to the existence of a significant number of high-impedance faults that are not detected.

On compensated distribution grids, such as those found in most of continental Europe, operating experience shows that only very few high-impedance faults remain undetected, which shows the effectiveness of the protection technique based on the measurement of the zero-sequence busbar voltage (99,9% detection rate and up to 20 kΩ of sensitivity). These relays are non-selective and normally produce only an alarm. Selectivity is obtained for HIFs by using new techniques based on wattmetric principle that present a detection rate of 98.8 % (3-5 kΩ of sensitivity).

In solid or low impedance networks, conventional ground relays reach a sensitivity of 15 Amps, which has proven to be enough for networks with low soil resistivity. In networks with high soil resistivity, the sensitivity can be improved to 5-10 Amps using ground sensitive over-current relays with Holmgreen CT connection, and below 5 Amps, with core balanced CTs.

However, HIF related to trees and some type of soils such as asphalt still cannot be detected, due to the very low levels of zero current produced.

The "broken conductor" protection based on I2/I1 ratio is a good recommendation, because it complements the ground sensitive over-current protection for these faults produced by downed conductors with very little earth current, but only when there is substantial load on remaining healthy conductors. It can be used as an alarm with a sensitive setting or for tripping purposes with a less sensitive setting.

In other areas of the world, such as the USA and Australia, owing to the particular characteristics of the distribution system with single phase loads, the tripping level of the conventional ground over-current relays has to be adjusted to values that are above the neutral imbalance on the grid. Consequently, a significant percentage of ground faults cannot be detected.

As a result, these areas are more interested in the field of high-impedance fault protection. In the 1970s, research began in the USA on the characteristics of the waveforms of arcing faults. In the mid-1990s, the first relay based on the use of the harmonics content of the current waves for detecting arcing faults was developed. Another device has recently been placed on the market with multiple algorithms, similar to the basis of the detection method, harmonics and inter-harmonics of the current waveforms, although with different approach and algorithms. In both cases, the HIF protection functionality is included in multifunction feeder protection devices, which aims to allow an implementation that is economically viable for electricity companies.

These products have been tested in the field by various companies in the USA for several years. They are being implemented in the USA more slowly than previously scheduled for a variety of reasons. At the beginning, certain maloperations happened and utilities lost confidence in HIF detection techniques in general. In addition, the detection technology they use is very different from that of conventional protection devices and the companies have not had sufficient information about the product or the experience required for their appropriate use. As a result, at present, most of the companies are waiting to verify their effectiveness and behaviour before taking a decision on a larger scale, generally using the HIF functionality exclusively for alarm purposes at the present time.

The initial conclusions drawn from real operating experiences point out the fact that these devices are not yet reaching optimum values of HIF detection rates (60-80%), when they are used with parameters and configuration biased toward secure operation of the relay, i.e. to avoid false trips.

In the future, the working group expects that, after new developments and improvements and once more operating experience and knowledge of how to use these devices has been gained, this type of detection may be successfully applied to the grids and will represent a certain improvement to the current situation. However, their application to other types of distribution grids is not considered viable at the present time due to their different characteristics and behaviour with regard to high-impedance faults.

Are new developments in the field of HIF on MV networks necessary on grids with high detection indexes? As already mentioned, certain distribution grids have high HIF detection indexes (i.e. very few non-detected HIFs); however, the possibility of an undetectable ground fault exists and all the utilities have had and regularly continue to have undetected HIF records. In spite of the important progress that has taken place, it still can be asserted that HIF detection is even now an important technical challenge that has not received a complete and entirely satisfactory answer.

Each company needs to analyse the behaviour of the protection system on their grids with regard to high-impedance faults and make decisions that are technically and economically viable in order to minimise the risk as far as possible. Given the growing importance of personal safety all across the world, more efforts are anticipated in research, development and application within this difficult and complex field.

One of the areas in which there is a clear need for improvement is the detection of high impedance faults related to trees and on asphalt. Both these surfaces produce very little (in some cases, none) change in current in the feeder due to the fault. Another case is the detection of broken conductors on the load side. Under some circumstances (lightly loaded feeder…), it may be extremely difficult to detect this fault. Both of these situations represent a key challenge to the protection system.

As a general conclusion, although important progress has been made during the last years in this field, still there is a necessity for improved detection and hence further research and efforts are required in order to achieve more reliable and effective solutions for HIF protection.

A Definition of acronyms

Term	**Definition**
A	Amps
ARC	Automatic Reclosing Cycle
CT	Current Transformer
EAD	Expert Arc Detector
EDF	Electricitè De France
EHV	Extra High Voltage
HIF	High Impedance Fault
HV	High Voltage
IED	Intelligent Electronic Device
km	Kilometres
kΩ	Kiloohms
kV	Kilovolts
kW	Kilowatts
LV	Low Voltage
mA	Milliamps
ms	Milliseconds
MV	Medium Voltage
PSRC	Power System Relaying Committee
PT	Potential Transformer
R&D	Research and Development
RMS	Root Mean Square
USA	United States of America

VAC	Volts Alternating Current
WG	Working Group

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C Summary of survey

C.1 Purpose of the survey

The survey issued a questionnaire regarding high impedance faults.

A high impedance fault (HIF) is a fault characterised by having an impedance sufficiently high so that it is not detected by conventional phase or ground over-current protection.

The Cigre WG would like to pay attention to HIF and to gather information about utilities practices and experiences in order to assist users in the performance optimisation of HIF protection and identify new requirements of protection relays.

C.2 Utility

This document summarizes the survey's answers. Survey's inputs were received from Spain (Iberdrola), Norway (Stattnet), France (RTE), Korea (KEPCO), Slovakia (SEPS, VSE), Sweden (Svenska Kraftnät), Australia (ETSA), Netherlands (ESSENT), USA (BPA, TXU).

Lexicon:

abbreviation	Country
AU	Australia
FR	France
KR	Korea
NL	Netherlands
NO	Norway
SL	Slovakia
SP	Spain
SW	Sweden
US	United States of America

C.3 Description of the networks (MV, HV, EHV)

Assuming the following definitions:

MV: 11-34 kV.
HV: 35-200 kV.
EHV: > 200 kV.

The table below summarizes the answers:

Voltage level (kV)	MV	HV	EHV
System grounding	*Various: solid, low and high impedances, resonant*	*Solid or low impedance, except NO 145 kV: Petersen coil*	*Solid or low impedance*
Total length (km)	*264.513*	*109.974*	*130.667*
Overhead Line construction (Wood Pole, Earth Wire, etc, any data related)	*Mainly steel and concrete*	*Steel tower with earth wires, some wood poles (NO, SW)*	*Steel tower with earth wires*
Total length (km) - underground	*95.042*	*3.750*	*3.738*

C.4 Definition and classification of the HIF according to your company

Definition:

- There is no common definition for HIF, each utility answered in its own way. There was also no reference to any standard. Most of the utilities answered in relation to high resistance faults (ground faults), that are not detected by main lines protections such as distance relays, differential relays.

Classification of these faults, if it exists:

- No classification for HIFs or high resistance faults.
- Optional: Most common types of HIFs in your company:
- Trees, vegetation, broken conductor were the most common related faults.

C.5 Records of HIFs

How many HIFs occur per year?

Only a few figures from Stattnet, RTE, SEPS, Svenska Kraftnät, ESSENT and BPA.

Voltage level	MV	HV	EHV
Total length (km)	--	58.364	90.548
HIFs/year/100 km	--	0,267	0,144

Optional: real consequences of these faults, incidents, accident...

Received answers are summarized below:

Voltage level	MV	HV	EHV
Consequences	*Animal death, fire burning*	*Animal death, damaged or broken primary or control equipment*	*Some forest fire, damaged or broken primary or control equipment*

C.6 General protection issues

Are there any established sensitivity requirements in terms of Ohm (fault resistance) and time in your utility/country?

Most of the answers do not mention requirements in terms of fault resistance and tripping time, but mention general commitments with respect to regulation authorities. In Sweden, all primary faults giving a fault current higher than 120 A must be detected and tripped.

Is the risk of accidental direct human contact also considered in the HIF protection in your utility/country? What are the requirements of the protection system for this particular risk?

One utility mentions the trip time and the touch voltage, two utilities do not use automatic reclosing after delayed trips. The maximum tripping time in the protection scheme depends on the admissible touch voltage, sometimes indirectly imposed by the law.

C.7 Conventional protection for ground faults

Which types?

As expected, most of the utilities use relays such as 50N, 51N, 64 for medium voltage, 21G, 67N for high voltage and 21G, 87L, 67N for extra high voltage. Some particular relays or practices are shown below:

Voltage level		Type of grounding	Type of ground fault relay (ANSI Number, or Function)	Sensitivity		
				Unit	**Value**	**Tripping time**
MV	*AU*	*Solid* *11 kV*	*Sensitive Earth Fault*	*Amps*	*5 A*	*5 seconds*
HV	*FR*	*Solid* *63 & 90 kV*	*K*Vo*Io and inverse time*	*Amps*	*3*Io=100 A*	*< 10 s*
EHV	*FR*	*Solid or low impedance* *220 kV*	*K*Vo*Io and inverse time*	*Amps*	*3*Io=300 A*	*< 10 s*
	FR	*Solid or low impedance* *400 kV*	*K*Vo*Io and inverse time*	*Amps*	*3*Io=600 A*	*< 10 s*
	KR	*Solid grounding*	*87G*		*20%(1A)*	*0.3 s*
	SW	*Solidly grounding* *220 kV*	*Non- directional zero-sequence current measuring relay, time curve t=5,8-135(ln(I/80))*	*Amps*	*80 to 120 A logarithmic*	*Delayed min1,2 s max 5,8 s*
	SW	*Solidly grounding* *400 kV*	*Non-directional zero-sequence current measuring relay, time curve t=5,8-135(ln(I/80))*	*Amps*	*120 A logarithmic*	*Delayed min1,2 s max 5,8 s*

Comments:

AU: sensitive earth fault settings set above maximum expected CT error at full load, typically 5 A. Where single phase to ground connected transformers are installed on the feeder set above maximum expected ground current owing to unbalance loading, typically 60 A.

SW uses very sensitive relays.

FR uses a directional zero sequence power relay with regards to non-transposed double lines.

KR uses a delayed differential ground relay.

C.8 Special protections[1] for HIFs in standard use by your company

Which types?

Voltage level	**MV**	**HV**	**EHV**
HIF relay? (brief description) *SP*	*Ground sensitive over-current relay*	*Ground sensitive over-current relay*	
HIF relay (other)? (brief description) *AU*	*Sensitive Earth Fault protection (SEF)*		

Comments, long description :

The utilities use only conventional relays, even if some of them try to improve the sensitivity of these relays (for example, using measurement windings instead of protection secondary windings). Particular relays based on harmonics measurements are not used.

Do you know or evaluate the limits of these protections? in Ohm/Amp? in time?

SP expects 1.000-1.500 Ohms from ground sensitive over-current relay.

FR expects 300 Ohms from zero sequence power relay.

Need for better detection? which cases?

Needs for better detection exist: tree limb contact undetected by conventional relay, arcing fault for covered conductor in MV, high ground resistance area, downed conductor on asphalt, intermittent tree faults… were mentioned.

Evaluation of performance? any improvements necessary?

Very few answers.

SP: some false trippings from sensitive ground relays.

AU: SEF relays used in MV (11 kV) work well, but not enough sensitive on primary fault current less than 5 A

Are these protections included in conventional relays as an additional function? extra cost (%)?

Very few answer, extra cost negligible, or no extra cost with numerical relays.

What is your practice after detecting HIF? alarm? only trip? automatic reclosure?

Most of the utilities practice automatic 3 phases reclosure. SW does not use automatic reclosure for delayed tripped faults. AU does not use automatic reclosure for faults tripped by SEF (to confirm).

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[1] e.g. current harmonic based protections

C.9 Special protections for HIFs under test or R&D in the utility?

Is your company testing or developing any new protection for HIFs?, description?

TXU (US): Not at this time, we have done some evaluation testing for a few manufacturers in the last few years but we are not testing or evaluating any products at this time.

SP: some test on ring CT or core-balance CT in order to improve sensitivity.

Number of relays already installed or under test?, since?, voltage level?

None.

Results up till now?

None.

TXU (US): Currently we do not have any HIF detecting relays in service and the only relays that have been evaluated were connected at 12,5 kV.

Expected direction of investigation:

SP: Transformer level centralized network measurement and monitoring techniques, associated to changes of system grounding (resonant grounding).

Plans to use as standard substation equipment?

None.

Comments:

None.

C.10 Free comments or suggestions

VSE (SL):

The reasons why high impedance faults in our company are so unusual: Periodical logging under overhead lines on all voltage levels, solid grounding and earth wire in 110 kV network, foot tower resistance below 15 ohms, etc.