CHARACTERIZATION OF HIGH IMPEDANCE FAULTS IN SOLIDLY GROUNDED DISTRIBUTION NETWORKS

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Abstract – High Impedance Fault (HIF) detection is increasingly present in the concerns of distribution network protection. Practical methods to deal with HIFs are in great demand in the USA, where HIFs are not detected by conventional protection devices. The lack of a globally accepted description of HIF is a drawback for HIF detection. In the effort to understand and explain HIFs we have performed a theoretical study, simulations, laboratory tests, and studied field recordings. The influence of certain factors has been studied by developing a ATP/EMTP simulation model and by defining laboratory tests. The drawn conclusions have been validated using HIF field recordings provided by Iberdrola Distribución Eléctrica S.A.U. In this paper, we present a complete HIF description and an explanation of HIF detection. This accurate characterization of HIF allowed the development of a pattern recognition method to detect HIFs.

Keywords: High Impedance Fault, solidly grounded networks, ATP/EMTP, High Impedance Fault laboratory tests, pattern recognition, analysis techniques.

1 INTRODUCTION

Power system protection must cope with new requirements of clients. Nowadays, methods to deal with faults that are not detectable by conventional devices are in great demand. The High Impedance Faults (HIFs) are one of these complex faults. Although important improvements have been done in the last two decades [2], [6], [7], the HIF detection is still a challenge for protection engineers. This paper presents a procedure to characterize and detect HIFs.

A HIF occurs when an energized conductor makes an undesired contact with a quasi-insulating object, such as a tree or the ground. This contact restricts the flow of the fault current to a very low level, from a few mA to 70A. The HIF current may be undetectable by conventional overcurrent devices. A practical and effective solution for the HIF detection is required as HIFs involve public security hazard and risk of fire.

The difficulties for HIF detection depend on some network aspects, such as the neutral grounding system and the load connectivity. The typical network configuration in the USA illustrates the worst potential situation: multiple solidly grounded systems supplying loads by single-phase transformers [8]. The ground protection installed in this type of networks is not very sensitive, for reasons that are explained further on in this paper. As a result, the low neutral current produced by HIFs is not detected by conventional protection devices. The ultimate aim of our research is developing a HIF detection method as a response to the demand in the USA. Therefore, this study focuses on solidly grounded networks supplying the loads by single-phase transformers.

General lack of knowledge concerning HIFs is the first handicap for the investigation. Consequently, the initial stage of this study consists of understanding and explaining the problem of the HIF detection. Since HIFs are seldom documented, we obtained the required data by performing simulation and laboratory tests. An ATP (Alternative Transients Program) model of HIF has been developed and simulated to understand the effect of the arc in the fault. However, simulation is not the adequate tool if a complete study is required. In consequence, laboratory tests have been defined and performed in order to accurately reproduce HIFs.

The HIF database consists of the results of the laboratory tests and fault recordings obtained from MV networks. This paper provides a precise procedure to describe HIFs, accomplishing the main task of practical and efficient HIF detection.

2 INFLUENCING FACTORS ON THE HIGH IMPEDANCE FAULT DETECTION

There are two aspects of the power distribution systems that determine the difficulty in detecting HIFs: the neutral grounding system and the load connectivity. The configuration of the distribution networks in the USA and in Europe presents important differences regarding these aspects [1]. This is the reason why the HIF detection problem is substantially more significant in the USA than in Europe.

2.1 Neutral Grounding System

Network grounding is the practice of connecting one point of the network (usually the neutral of the transformer or the generator) to the electrical ground. The most common grounding systems are:

- Solidly grounded (single-grounding or multi-grounding)
- Grounded by resistance
- Grounded by reactor
- Grounded by a Petersen coil (compensated system)
- Ungrounded or isolated

In the presence of HIF and, in general, of ground faults, the grounding systems have different behaviors. Although the objective of the ground protection devices is to identify those behaviors, under certain circumstances they are far from achieving this.

Compensated systems, isolated systems and systems grounded by a high resistance or a high reactance have a similar behavior concerning HIFs. When the fault occurs, the electrical neutral point of the system is displaced, and zero-sequence voltage (V_0) is produced. The main criterion for detecting faults to ground is the presence of zero-sequence voltage in the system. Selective detection methods developed for these grounding systems have a satisfactory detection rate regarding HIFs.

The situation is different for the solidly grounded systems and for the systems grounded by a low resistance or a low reactance. In these systems the neutral grounding prevents the variation of the phase to ground voltage, thus the ground fault detection is based on the monitoring of the current. Today overcurrent technology deals with HIFs in neutral grounded systems. HIFs are detected if the sensitivity of the overcurrent protection is high enough to measure the low current level produced by the HIF, and if the HIF current is higher than the operational residual current ($3I_0$). In certain distribution networks, the presence of substantial operational residual current is a critical drawback for the HIF detection.

2.2 *Load Connectivity*

Power distribution system design differs throughout the world. The typical USA configuration presents disadvantages regarding the HIF detection. The explanation is based on the fact that the neutral is multiple solidly grounded and on the method of connecting the loads. The USA general practice for load connection is to feed customers by single phase transformers. If the single phase loads connected to the transformers are equal in the three phases then the load is balanced and no current flows in the neutral conductor. Nevertheless, due to the load switching activities, an unbalance situation occurs under normal operation. A result of this unbalance is a residual current. The pickup setting of ground fault protections is set above the neutral current caused by the unbalance. Neutral current produced by HIFs are usually lower than the sensitive setting of the protection devices, therefore, at the present, HIFs are not detected.

The situation in Europe is different since loads are connected to the primary distribution system by three phase transformers. This practice protects the primary distribution system from eventual unbalances. In consequence, there is no appreciable residual current in normal operation, allowing the neutral protection to be highly sensitive. Most HIFs in Europe are detected by the sensitive overcurrent neutral protection. Therefore the improvement of the HIF detection in Europe is not a key issue in Europe.

3 LEARNING ABOUT HIGH IMPEDANCE FAULTS

The procedure we have followed to characterize the HIFs consists of four steps (figure 1): 1) description of the HIF situation, 2) study of the HIF behavior while preparing a database, 3) analysis of the HIF data and 4) application of an adequate data processing.

In this section of the paper we explain how HIF data are obtained by simulation and laboratory tests. The database is validated and completed by recordings obtained from European distribution networks.

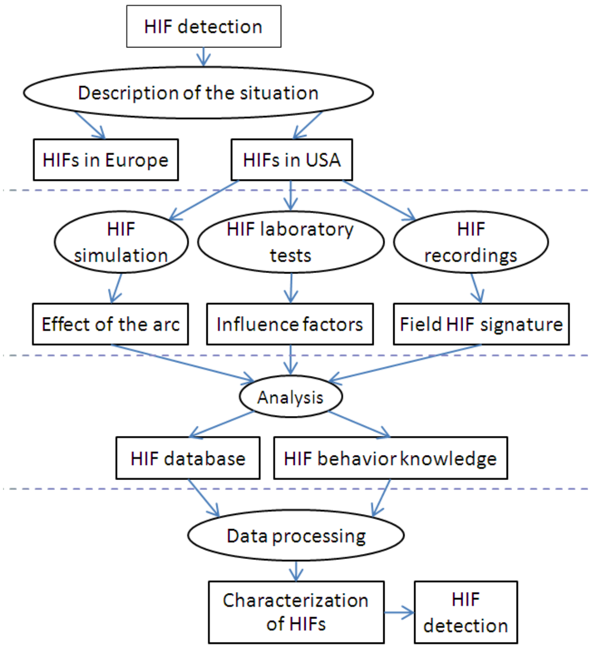

Figure 1: Procedure for the HIF characterization**.**

3.1 *High Impedance Fault Simulation*

The first stage for understanding any phenomena is to develop a model. We have developed a HIF model using ATP/EMTP (Alternative Transients Program / ElectroMagnetic Transients Program) [4], [9]. This simulation program is capable of accurately modeling lines and cables and non-linear elements as saturable transformers and electric arcs. HIF simulation has some limitations, since the randomness involved in HIFs cannot be modeled. Therefore, the results of the simulation are not adequate for HIF pattern recognition. Nevertheless, a robust and flexible simulation model enables the study of HIF factors.

Our HIF model considers the hypothesis of arc ignition at the fault point, given that the contact between the conductor and the quasi-isolating surface (such as a tree or the ground) is never perfect. Accordingly, the HIF model consists of the sum of a constant resistance (Rgp), representing the path to ground through the contact surface, and a non-linear dynamic resistance (r (t)), representing the arc.

The model describing the arc is derived from the generalized arc description of Hochrainer:

$$\frac{dg(t)}{dt} = \frac{1}{\tau}\{G(t) - g(t)\} \qquad (1)$$

Where g (t) is the time varying arc conductance, G (t) is the stationary arc conductance and τ s the time constant.

The stationary arc conductance is defined as [5]:

$$G(t) = \frac{|\, i_{arc} \,|}{u_{arc}} \qquad (2)$$

$$u_{arc} = (u_0 + r_0 \,|\, i_{arc} \,|\,) l_{arc} \qquad (3)$$

Where i_{arc} is the instantaneous arc current, u_{arc} is the stationary arc voltage, u_0 is the characteristic voltage per arc length, r_0 is the characteristic resistance per arc length and l_{arc} the arc length.

And the time constant is defined as:

$$\tau = \tau_0 \left(\frac{l_{arc}}{l_0}\right)^{\alpha} \qquad (4)$$

Where τ_0 is the initial time constant, l_0 is the initial arc length and α is a negative value coefficient.

As it can be seen in (3) and (4), the stationary arc voltage and the time constant are subject to the arc length. Since arc length variation is highly dependent on external factors, it is difficult to consider the effects in the arc model. Therefore, in this study we contemplate three parameters: the characteristic voltage, $u_0 l_{arc}$, the characteristic resistance, $r_0 l_{arc}$ and the time constant, τ.

Using the ATP/EMTP module TACS (Transient Analysis of Control Systems), the resulting non linear equation can be solved. The value of the arc resistance r (t) is estimated as the inverse of g (t). Besides the HIF, the elements considered in the network model are the following:

- Generator
- 110kV/15kV saturable transformer
- Distribution lines with frequency dependent parameters (J.Marti model)
- Underground conductors
- Saturable current transformers (CTs)
- Loads.

The load connection model has been simplified since it has no influence on the HIF signature. Figure 2 is the representation of the complete model using ATPDraw.

Results obtained by simulation show that the developed model is capable of describing and explaining the arcing component of the fault. By adjusting the characteristic voltage, the characteristic resistance, and the time constant, the model is adapted to a given arcing signature.

Figure 3 shows the simulated fault current during a HIF modeled with the parameter values of $u_0 l_{arc} = 348\,\text{V}$, $r_0 l_{arc} = 0.038\ \Omega$, τ =15 μs. Considering the values of the characteristic voltage and resistance as $u_0 = 12\ \text{V/cm}$ and $r_0 = 13\text{m}\Omega/\text{cm}$ [5], then the simulated arc length is 29 cm. We observe the transient at the beginning of the fault, the extinction and the reignition of the arc at the current zero crossing, the nonlinearity and the asymmetry of the current waveform. These characteristics are typical for HIFs.

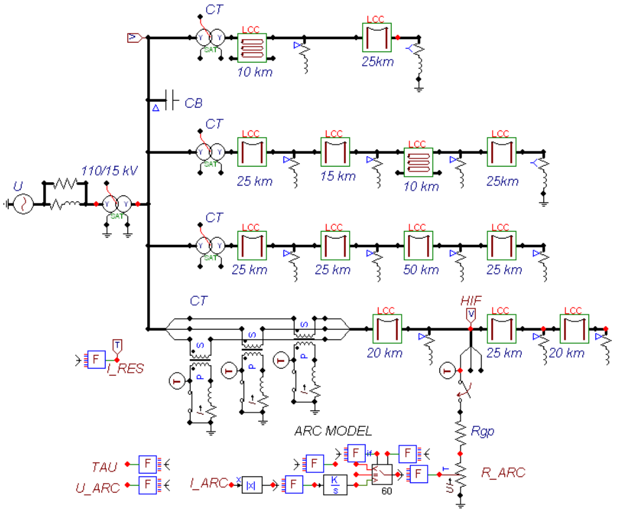

Figure 2: ATP/EMTP network model for HIF simulation**.**

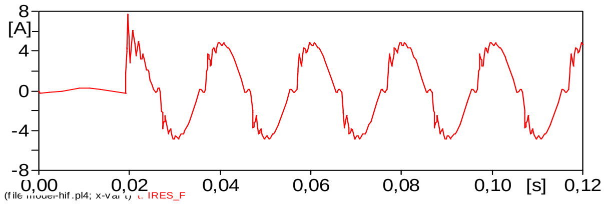

Figure 3: The simulated HIF current ($u_0 l_{arc}$ = 348V, $r_0 l_{arc}$= 0.038Ω, τ =15μs) illustrates the transient at the beginning of the fault, the ignition and extinction of the arc and the asymmetry of the waveform.

However, in our opinion, the arc is not the dominant component of the signature of HIFs. Once an arc is established, its behavior is generally constant. On the contrary, HIFs are expected to have a random and dynamic performance. If the arcing component of HIFs is mostly periodical and regular then we conclude that the cause of the dynamic performance of HIFs is the varying path to ground resistance. Finding an accurate and unique model for the path to ground resistance is not possible. For that reason, although the simulation model allows us to advance in the study, the creation of HIF data is limited.

3.2 High Impedance Fault Laboratory Test

The characteristics of HIFs depend on many factors that can only be studied experimentally: the type of contact surface, the arc length or the moisture level. To consider all the influencing factors and to get a realistic fault signature, we defined and performed laboratory tests. The Medium Voltage Testing Laboratory of Siemens AG in Berlin had been adapted for our tests.

As there is no standardization for HIF laboratory tests, we propose and validate a procedure. The test consists of producing contact between a Medium Voltage (MV) conductor and a quasi-isolated surface, as for example paving stone or a tree. The conductor is placed on the test surface using an insulating stick, starting a fault. Voltage and current are measured starting a few milliseconds before the fault is produced, in order to record the first transient. Given that some factors, as the wind or inertia of the conductor when falling, make the downed conductor move, the tests have been done not only with the conductor laying on a fixed point but also moving the conductor over the surface. In this manner we performed realistic faults including intermittent arcs, variable length arcs and faults with multiple contact points.

We used eleven test surfaces in different conditions of moisture level. Several typical distribution voltage levels were used in the tests. A summary of the tests is shown in table 1.

Surface Material	***Test Conditions***		
Sand	Dry/wet	20 kV	Static/moving
Stone	Dry/wet	20 kV	Static/moving
Paving stone and sand	Dry/wet	20 kV	Static/moving
Asphalt	Dry/wet	12/20 kV	Static
Earth	Dry	12/20 kV	Static/moving
Concrete paving stone and sand	Dry	20 kV	Static/moving
Concrete paving stone	Dry/wet	12/20 kV	Static/moving
Tree branches	Outdoor humidity /wet	12/20/36kV	Static
Tree bole	Outdoor humidity /wet	12 kV	Static
Brick and concrete sidewalk	Outdoor humidity	12/20 kV	Static/moving
Reinforced concrete	Outdoor humidity	12 kV	Static/moving

Table 1: Summery of the tests

Results show the dynamic behavior of the fault when observing the current during enough time. The continuous variation of the HIF current is mainly caused by the change of the contact surface properties, and the instability of the arc. Heat emitted by the fault is especially involved in the variation of the contact surface resistance. Heat decreases the humidity of materials, therefore, in general, the electrical resistance of the surface increases and the current decreases.

Figure 4 presents the current of a HIF test on earth. The current decreases at 1.5 sec, 2sec and 2.4 sec, as a consequence of the heat emitted by the fault. In fact, evaporation of water was easily perceived during this test.

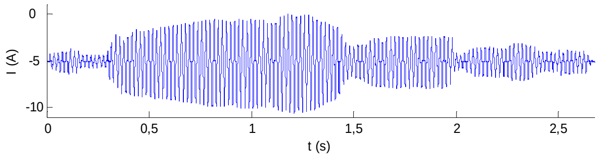

Figure 4: The current of a HIF test on earth decreases as water of the surface is evaporated because of the heat.

The energy released by the fault can lead to physic-chemical reactions, which change the properties of the contact point of the surface. Melting and re-solidification of material was noted during the tests on sand, concrete, and sidewalk surface. The resistance of the melted surface is modified, therefore the current changes.

Figure 5 illustrates a HIF test produced by the contact between the conductor and a concrete and brick sidewalk. The randomness of the current is explained by several reasons. The first one is the evaporation of water of the surface due to the heat emitted by the fault. Consequently the current decreases progressively during the first 2.2 sec. The second factor is the melting and re-solidification of concrete, which produces a solid of high resistance at the contact point. At 2.5 sec the resistance of the contact point is so high that the current changes the path to ground. A sudden increase is observed at 2.6 sec because the current flows through a different path to the ground. The properties of the new contact point are more constant thus the current is more stable.

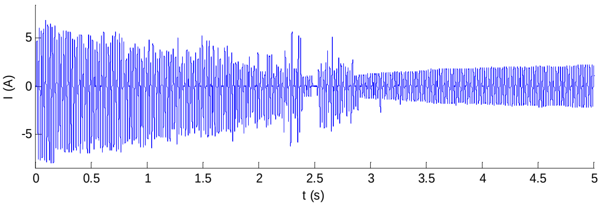

Figure 5: The signature of the current of a HIF test on a sidewalk is explained by the effect of the emitted heat, the effect of concrete melting and the change of path to ground.

Although the characteristics of the HIF current on a determined surface can be described, they cannot be generalized for all HIF. We have recognized several different behaviors, depending mostly on the material of the test surface. Figure 4 presents the usual fault current signature of a HIF on earth surface. The logarithmic enveloping curve of the current represents the establishment of the arc. At 0.36 sec the process of fault establishment begins, but it is not until 1 sec that the fault is established, showing a constant current value for some msec.

A different behavior is shown in figure 6: a HIF caused by the contact between a conductor and a tree. In this case, the arcing fault produced requires longer time to become stable. There are no remarkable sudden changes in the current, which increases gradually until reaching a constant value.

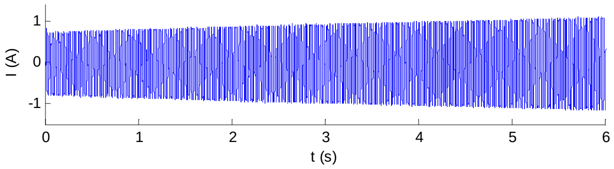

Figure 6: Gradual establishment of the HIF in a test produced by the contact between a conductor and a tree.

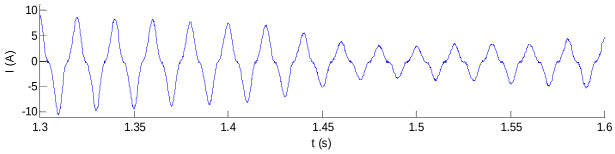

Figure 7: Randomness, non-linearity and asymmetry of the current waveform of a HIF test on earth.

Regarding the waveform of the current, the test results are similar to those obtained by simulation. In most of the current recordings the arc is measured even if during the performance of the fault we perceived only a little sparkling at the contact point between the conductor and the surface. However, as expected, the arc is not the dominant property of the HIF current signature. Figure 7 shows the current waveform of the HIF test on earth presented in figure 5. We can observe the change in the amplitude cycle by cycle, the consequent asymmetry of the waveform and the effect of the arc. These properties give HIF the characteristic of randomness.

3.3 *High Impedance Fault Recordings*

Field HIF recordings validate and complete the HIF data base. Iberdrola Distribución Eléctrica S.A.U., one of the main DSO in Spain, collaborates on our research providing us with information about their experience facing HIFs.

Apparently, the most common cause of the registered HIFs is the contact between power conductors and tree branches, situation that is perfectly possible in the case of storms or strong wind.

Figure 8 shows the sensitive measured current of a ground fault produced by the contact of a pine tree at a windy and rainy day. In this case, the effect of the electric arc is significant, and also the asymmetry of the waveform and the randomness. These characteristics have been constantly observed in the HIF study.

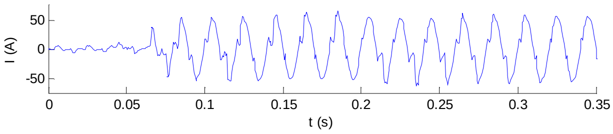

Figure 8: Current of a real HIF caused by a pine, illustrating the representative HIF characteristics.

Field HIF recordings cover a range between 10 A and 70 A. Currents lower than 10 A are, in general, not detected by the existing protection devices. Laboratory tests were performed in such a manner that the fault current was not higher than 15A. Therefore, the obtained HIF database comprises all the possible values.

4 TOWARDS A HIGH IMPEDANCE FAULT DETECTION ALGORITHM

4.1 *Characterization of High Impedance Faults*

HIF current signature depends on multiple factors: the properties of the contact surface, the voltage level, the humidity of the ambience or the presence of wind. Therefore, we observe a wide number of possible patterns for the HIF current signature. But we must be able to find some characteristics of the current that are common to most of the cases, so that we have an indicator of HIF.

According to the literature study and the analysis of the HIF database, we propose the following HIF characteristics:

- Current level between 1mA and 70 A, depending mostly on the contact surface.
- Arcing or sparkling at the contact point between the conductor and the quasi-isolating surface.
- Dynamic behavior seen as unstable and wide current fluctuations occurring intermittently. The main reasons for the dynamic behavior are the varying resistance of the contact surface, the relative movement between the conductor and the contact surface, and the non-linearity of the arc resistance.
- Distorted sinusoidal current waveform, due to the presence of a high number of harmonic and non harmonic components in the signal.
- Asymmetry of the current waveform, due to the non-asymmetrical arcing process.

The main restriction on developing a HIF characterization and detection method is that the amplitude of the current cannot be used. This restriction is imposed because the typical level of the operational residual current in USA is higher than the HIF current level therefore the amplitude is not useable. Considering this restriction, our proposal for the HIF characterization is to apply the following functions:

- Randomness study. Calculation of the variation cycle by cycle of the energy, the amplitude of the harmonics, and the rms current value.
- Third harmonic current study. Description of the representative behavior of the magnitude and phase of this current component [3].
- Down conductor recognition. Identification of loss of load and overcurrent condition, which may be an indicator of down conductor.
- Asymmetry study. Definition and calculation of a waveform asymmetry index, by calculating the energy of the harmonics in each quarter of cycle.

In future work we will study the optimal techniques for the application of these functions to the HIF database. This will offer the possibility to enlarge the amount of information available for the characterization of HIF, which will be used to develop a technical and more accurate HIF description.

4.2 Critical Loads for High Impedance Fault Detection

Designing fault detection algorithms involves not only recognizing the fault but also differentiating the fault from other events. We define “critical loads for HIF detection” as those loads and events that produce similar residual current to those produced by HIFs, as, for instance, resistance welding or inrush currents from transformer energization. An essential future work in our research is to analyze critical load in order to find a distinction method.

4.3 High Impedance Fault Detection Algorithm

When the objectives of HIF characterization and the distinction between HIF and critical loads are achieved, a reliable and effective HIF detection method will be developed. The detection algorithm will have to consider two essential requirements: the application of a learning process and the use of multi-pattern recognition. A learning process enables the extraction of the background load and the identification of randomness. Moreover, the multi-pattern recognition is necessary because of the existence of several typical HIF signatures. By classifying the HIF recordings in the database, we obtain multiple typical patterns. This practice is more accurate than the attempts to define a general HIF pattern.

5 CONCLUSION

High impedance fault detection is still a challenge for protection engineers. An effective solution is required due to the public and property security hazard involved in the HIFs.

The difficulty in the high impedance fault detection is highly influenced by the configuration of the power distribution network. The typical configuration in USA is especially unfavorable due to two practices: the use of multiple grounding and the installation of single-phase distribution transformers. These practices result in neutral protection devices with low sensitivity, which are inadequate to measure HIF currents. This paper presents a proposal to develop a functional HIF detection algorithm based on a comprehensive study of the characteristics of HIFs.

Understanding and characterizing HIFs is the first difficulty. A complete study, consisting of simulations, laboratory tests and analysis of field recordings, enables us to faithfully describe HIFs.

Once a reliable and accurate characterization is obtained, the recognition of HIFs is possible. It is pointed out the need of analysis techniques to extract information about the HIF dynamic behavior from the current. HIF detection involves not only identifying the fault but also distinguishing between the fault and the critical loads. The faithful description of the performance of HIFs is the key to continue the research towards a reliable HIF detection method.

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