

CHARACTERIZATION OF HIGH IMPEDANCE FAULTS IN SOLIDLY GROUNDED DISTRIBUTION NETWORKS

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Abstract – High Impedance Fault (HIF) detection is increasingly a concern of distribution network protection engineers. 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 HIFs is a difficulty for HIF detection. In the effort to understand and explain HIFs, we have carried out a theoretical study, simulations, laboratory tests, and studied field recordings. To study the influence of factors affecting HIFs, we have developed an Alternative Transients Program (ATP) simulation model and designed laboratory tests. HIF field recordings provided by Iberdrola Distribución Eléctrica S.A.U. validate the findings. In this paper, we present a HIF characterization to improve HIF detection. This accurate characterization of HIFs allows us to develop 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. High Impedance Faults (HIFs) are one of those faults. Although important improvements have been made in the last two decades [2] [6] [7], 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 up to 75A [3]. The HIF current may be undetectable by conventional overcurrent devices. A practical and effective solution for HIF detection is required, as HIFs represent a public security hazard and risk of fire.

The difficulty of detecting HIFs depends 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]. In these networks the neutral current under normal conditions may be higher than the current caused by HIFs, so overcurrent protection relays are not suitable for detecting HIFs.

The ultimate aim of our research is to develop a HIF detection method that responds to the difficulty of the HIF detection in solidly grounded networks supplying loads by single-phase transformers.

The final goal of our research is to develop a HIF detection method for solidly grounded networks that supply the loads by single-phase transformers. The first difficulty to achieve this goal is the general lack of knowledge concerning HIFs. Consequently, the initial stage of this study consists in understanding and explaining the problem. Since HIFs are seldom documented, we performed simulations and laboratory tests to obtain the required data. We developed and simulated an Alternative Transients Program (ATP) model of HIF to understand the effect of the arc in the fault. However, not all characteristics of HIFs can be studied by simulation. In consequence, we designed and performed HIF laboratory tests so we obtained realistic HIF recordings.

Our HIF database consists of the results of the laboratory tests and fault recordings obtained from medium voltage networks. We provide a precise procedure to characterize HIFs. This characterization will allow our researching group to develop a practical and efficient HIF detection method.

2 INFLUENCING FACTORS ON THE HIGH IMPEDANCE FAULT DETECTION

The difficulty of detecting HIFs is determined by two aspects of power distribution systems: the neutral grounding system and the load connectivity. Focusing on those aspects we find important differences between the network in USA and the network in Europe [1]. The distribution system configuration in USA is the most unfavorable one for HIF detection, thus detection problem in USA is substantially more worrying 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 through a resistance
- Grounded through a reactor
- Grounded through a Petersen coil (compensated system)
- Ungrounded or isolated

In the presence of HIF, and in general, of ground faults, the grounding systems have different behaviours. Although the objective of the ground protection devices is to identify these faults, 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 behaviour concerning HIFs. When a fault occurs, the electrical neutral point of the system is displaced, zero-sequence voltage (V_0) is produced, and limited neutral current appears. The residual current under normal operation in these systems is normally small, so sensitive current measurement can recognize HIFs. When sensitivity is low, ground fault protection is based on the presence of zero-sequence. Selective detection methods developed for these grounding systems have a satisfactory detection rate regarding HIFs.

The situation is different for solidly grounded systems and for systems grounded by low resistance or 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 current monitoring. 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 HIFs and if the HIF current is higher than the operational residual current ($3I_0$) [1] [3]. In certain distribution networks, the presence of substantial operational residual current is a critical drawback for HIF detection.

2.2 Load Connectivity

Power distribution system design differs throughout the world. The typical USA configuration presents disadvantage regarding HIF detection. The disadvantage is a consequence of the system used for neutral grounding, which is multiple solidly, and of the method used for connecting the loads. A general practice in USA 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, unbalance situations occur under normal operation. A result of this unbalance is residual current. The pickup setting of ground fault protection is set above the common level of the neutral current caused by unbalance. Neutral current produced by HIFs are usually lower than the sensitive setting of the protection devices. Therefore, at 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,

improvement of HIF detection in Europe is not a priority nowadays.

3 LEARNING ABOUT HIGH IMPEDANCE FAULTS

In this section we explain how HIF data are obtained by simulation and laboratory tests. After obtaining the database, it is validated and completed by HIF recordings obtained from Iberdrola Distribución Eléctrica SAU, distributor system operator in Spain.

The procedure we have followed to characterize the HIFs (figure 1) consists of four steps:

- 1) Description of the HIF situation,
- 2) study of the HIF behaviour while preparing a database,
- 3) analysis of the HIF data and
- 4) application of adequate data processing.

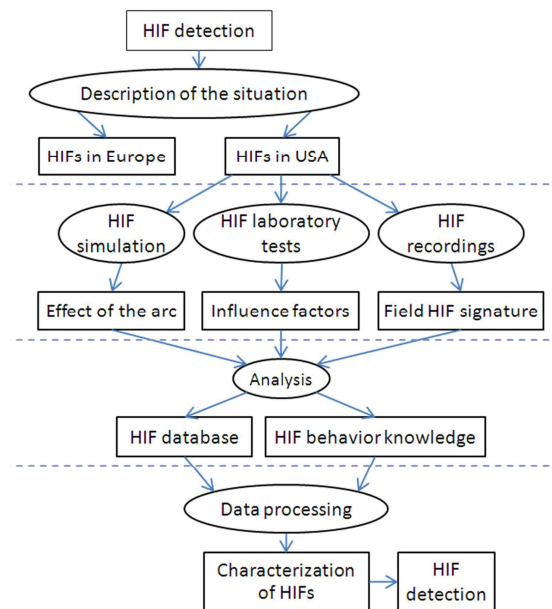


Figure 1: Procedure for the HIF characterization.

3.1 High Impedance Fault Simulation

We have developed a HIF model using Alternative Transients Program / ElectroMagnetic Transients Program (ATP/EMTP) [4] [9]. This simulation program is capable of accurately modeling lines and cables and non-linear elements such 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 R_{gp} , 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 [5]:

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

where $g(t)$ is the time varying arc conductance, $G(t)$ is the stationary arc conductance and τ is a time constant related to the energy loss during the arcing process. The stationary arc conductance is defined as [5]:

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

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

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} is the arc length.

And the time constant is defined as:

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

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 Transient Analysis of Control Systems (TACS), 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.

The 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 $u_0 l_{arc} = 348 \text{ V}$, $r_0 l_{arc} = 0.038 \Omega$ and $\tau = 15 \mu\text{s}$. 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], 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.

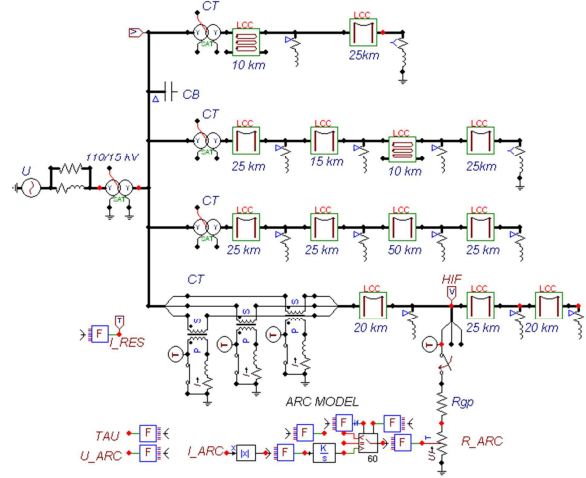


Figure 2: ATP/EMTP network model for HIF simulation.

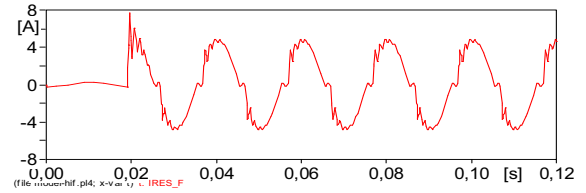


Figure 3: The simulated HIF current ($u_0 l_{arc} = 348\text{V}$, $r_0 l_{arc} = 0.038\Omega$, $\tau = 15\mu\text{s}$) illustrates the transient at the beginning of the fault, the ignition and extinction of the arc and the asymmetry of the waveform.

In our opinion, however, simulating a mostly periodical arc is not enough to reproduce HIF signatures. HIFs are expected to have random and dynamic performance [3]. Randomness and dynamism are consequence of the variability of the arc length, and the change of properties of the contacting point between the contacting surface and the arc. It is highly unlikely that any model is able to describe these facts. For that reason, although the simulation model allows us to advance the study, the creation of HIF data using simulation 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 was adapted for our tests.

As there is no standardization for HIF laboratory tests, we propose and validate a procedure. The test consists in producing contact between a medium voltage 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.

Table 1: Summary of the tests

<i>Surface Material</i>	<i>Test Conditions</i>		
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

Results of the tests show the dynamic behaviour 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 variability 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 with static conductor. The current decreases at 1.5 sec, 2 sec 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.

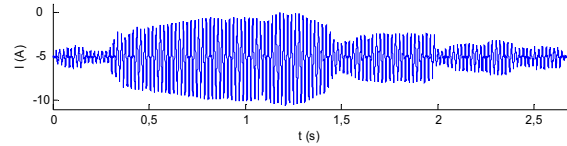


Figure 4: The current of a HIF test on earth decreases as water of the surface is evaporated because of the heat.

The energy released by the fault can lead to physical-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 factors. 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.

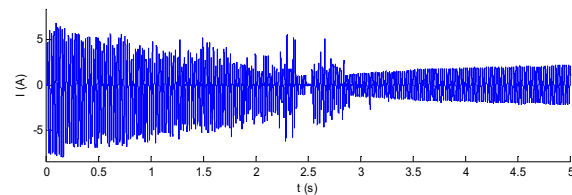


Figure 5: The signature of the current of a HIF test on a sidewalk is explained by the effect of the emitted heat, the effect of concrete melting and the change of path to ground.

Although the characteristics of the HIF current on a surface can be described, they cannot be generalized for all surfaces. We have recognized several different behaviours, 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 behaviour is shown in figure 6. A HIF is 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.

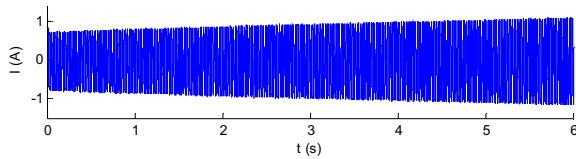


Figure 6: Gradual establishment of the HIF in a test produced by the contact between a conductor and a tree.

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 fault we perceived only a little spark at the contact point between the conductor and the surface. However, as expected, the arc is not the only distinguishing property of the HIF current. 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 to the HIF current the characteristic of randomness.

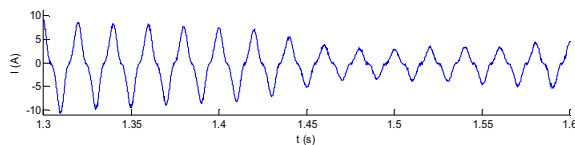


Figure 7: Randomness, non-linearity and asymmetry of the current waveform of a HIF test on earth.

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, collaborated 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, a situation that is plausible 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. The fault was detected by the sensitive neutral protection and the line was tripped. The substation where this recording is coming from is Riolanza, a 5 MVA substation consisting of a 45/15 kV transformer connected Yy0 and grounded at the 15 kV side.

The presented recording shows the characteristics that have been constantly observed in the HIF study, which are the effect of the electric arc, the asymmetry of the waveform and the randomness. The field recordings are a guarantee that our laboratory test results are reliable.

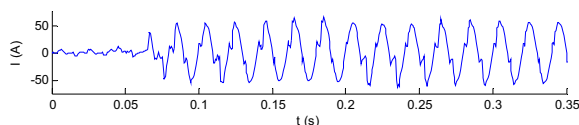


Figure 8: Current of a real HIF caused by a pine, illustrating the representative HIF characteristics.

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 15 A. 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 and 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 [2][3][6][7], and the analysis of the HIF database, we propose the following HIF characteristics:

- Current level between 1mA and 75 A, depending mostly on the contact surface. While HIFs on dry asphalt or dry sand produce negligible fault current, HIFs on wet grass or reinforced concrete produce a current up to 50 or 75 A.
- Arcing or spark at the contact point between the conductor and the quasi-isolating surface.
- Dynamic behaviour seen as unstable and wide current fluctuations occurring intermittently. The main reasons for the dynamic behaviour being 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-symmetrical 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 cycle by cycle variation of the energy, the amplitude of the harmonics, and the rms current value.
- Third harmonic current study. Description of the representative behaviour 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 loads 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

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

The difficulty of HIF detection depends on 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 such faults.

Understanding and characterizing HIFs is the first challenge. 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, recognizing HIFs is possible. At the present we are working in the search of indicators of HIFs. Those indicators are quantitative or qualitative variables

that reveal the present of distinguishing characteristics of HIF in the current, such as the dynamic behavior and the randomness.

Nevertheless, HIF detection involves not only identifying the fault but also distinguishing between HIFs and critical loads. For that reason, the HIF detection research will not be accomplished until obtaining and processing a critical load database and determining a differentiation criterion.

The faithful description of HIFs is the basis of our research towards a reliable HIF detection method.

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