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Experimental Investigation of High Impedance Faults in MV Overhead Distribution Networks due to Mango Tree Branches

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***Abstract*—The high impedance fault (HIF) has as one of its main characteristics the low magnitude of the current produced, causing its detection and location to be impaired for the equipment currently used to protect electrical power systems, which favors the driver remain energized, increasing the likelihood of fires and the risk of death for living beings. Records of HIF characteristics in trees are a gap in the literature, making it difficult to develop new algorithms and identification methods. This study presents details of the voltage and current characteristics of HIF shunt in Mango tree branches, the result of experimental tests carried out in a laboratory designed and assembled for simulation of HIF in aerial distribution networks, aiming to obtain data for future modeling HIF shunts on trees. These oscillographs were captured using a commercial protection relay.**

***Index Terms*—High impedance Fault, Electrical Power Systems, Overhead distribution networks, Tests on Tree Branches**

I. INTRODUCTION

The high impedance fault (HIF) when it occurs in electrical power systems, mainly in medium voltage distribution systems, has the reduced magnitude of current as one of its main characteristics, which makes it almost imperceptible to current protection equipment [1]. When there is contact between tree branches with one or more energized conductors, which is also considered as HIF, this is established without necessarily breaking the conductor, considerably reducing the magnitude of the fault current, although it is still capable of cause the branch to burn. Despite this fact, the current protection systems do not detect the HIF, leaving the driver energized, which can cause the occurrence of fires with high financial losses, the loss of the lives of people and animals. When a HIF occurs in rural aerial distribution networks, due to the radial topology with feeders of great extension and great afforestation, which normally cover long uninhabited stretches, the location presents even greater difficulty [2].

In the state of the art of HIF, oscillographs of the specific characteristics of HIF shunt currents in tree branches were not found, even more of events that occurred in aerial distribution networks and registered by their protection relays, which is also rare for other surfaces [3].Records of characteristics of the HIF series chains, when the conductor is broken, on surfaces such as sand, pebble, asphalt, concrete, grass and earth, were obtained in experimental tests using oscilloscopes and digital disturbance recorders [1] - [2] - [4] - [5].

This study presents specific characteristics of HIF currents in Mango tree branches, the result of experimental tests carried out in a laboratory designed and assembled for carrying out HIF experiments, simulating the occurrence in aerial distribution networks. These characteristics will compose an HIF database for future modeling of HIFs shunts in trees [6].

II. HIGH IMPEDANCE FAULT

The HIF in electricity distribution networks is not a recent failure, but it persists without a full solution and happens when an energized primary conductor, broken or not, encounters a surface of high electrical resistance such as trees, sand, grass, asphalt, etc. Its occurrence in distribution systems with voltages from 4 kV to 34.5 kV is significant, but due to the high resistivity, the fault electric current has a reduced amplitude, ranging from 0 A to values normally less than 100 A [7] - [8] - [9]. However, [3] records show real oscillographs of a HIF occurring in a medium voltage network where the current reached 190.5 A. Table I presents typical values of fault current in a 12.5 kV system for different materials, but there are no values for tree branches. [10] performed HIF tree tests, but did not present the oscillographs obtained, while [11] states that he considered carrying out tests with trees but gave up due to operational difficulties.

The variation in the system current due to HIF is usually inexpressive, being like oscillatory transients in the network, which is insufficient to trigger over current protection systems, such as fuses and relays, the fault remaining indefinitely [8] - [11] - [12]. For a HIF to occur in tree branches, it is only necessary that a branch is very close to an

TABLE I
CURRENT VALUES OF HIF

Surfaces	Currents (A)
Dry asphalt or dry sand	0
Wet sand	15
Dry grass	25
Wet grass	50
Reinforced concrete	75

energized conductor [2], with three possibilities: the contact of the branch with an energized primary conductor (single phase), with two conductors (biphasic) or with the three conductors (three-phase), as shown in Fig.1. The greatest occurrence of this type of fault is single-phase, and in the two-phase the time for the branch to catch fire is considerably reduced [1].

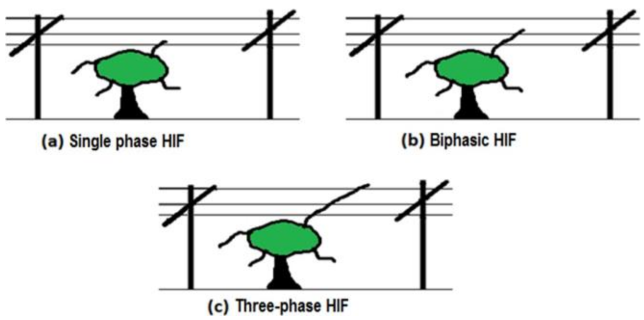


Fig. 1. HIF possibilities by contact with drivers.

The presence of an electric arc in the occurrence of HIF shunt is a very present characteristic, resulting from the air spaces due to the unstable contact between the energized conductor and the high resistivity surface or gaps in the surface [9]. Air is considered a good insulator if the potential difference is small, but if the voltages are higher, the electrical resistance of the air decreases and, after a certain threshold, its dielectric breaks, making it conductive by accelerating the free electrons caused by the electric field, which provides them with sufficient kinetic energy. These electrons will allow the release of others by colliding and ionizing air molecules, repeating the process and creating an avalanche phenomenon, with the electric arc conducting current continuously. This process, however, does not occur immediately, requiring that there be a rapid series of momentary disruptions of the dielectric, called sparking [8].

The HIF current has some known characteristics that distinguish it from other faults due to the electric arc and its reducedamplitude [8] - [13] - [14]:

- Non-linearity: The characteristic curve of the voltage as a function of the current is non-linear, and causes harmonics of the 3rd to the 10th order, approximately;
- Asymmetry: The fault current has different peak values for the positive and negative semi cycle, and promotes the appearance of harmonics of an even order from the fundamental;
- Intermittence: momentary discontinuity of the current, and causes the appearance of a spectrum of high frequency harmonics;
- Buildup: Progressive variation of the current at each semi cycle, causing interchanged harmonics;
- Shoulder: Constancy instants between the buildup.

These characteristics are illustrated in Fig.2, it should be noted that they depend on the environmental, spatial, geometric and electrical conditions of the system, which justifies that the electrical quantities involved in this fault show random behavior [15].

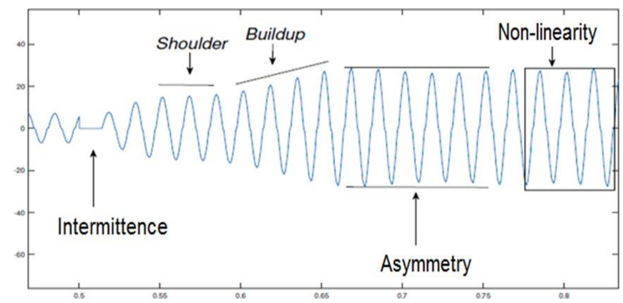


Fig. 2. Main known characteristics of a HIF.

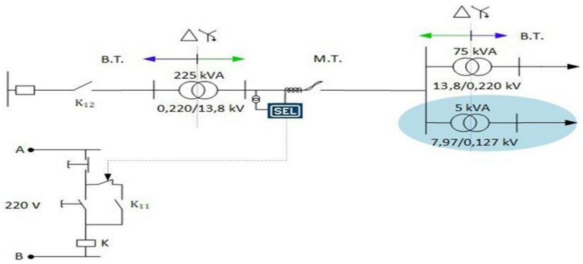
III. LABORATORY FOR EXPERIMENTAL TESTS OF HIF IN OVERHEAD DISTRIBUTION NETWORKS

For the realization of experimental HIF tests, the design and assembly of the Laboratory for experimental tests of HIF in Overhead Distribution Networks (LABFAI) in the High and Extra High Voltage Laboratory (LEAT) of the Federal University of Para´ (UFPA), this laboratory having been foreseen in the P&D ANEEL FAI (Research and Development Project approved by the National Electric Energy Agency of Brazil with a focus on HIF), which aims to develop a High Impedance Fault Locator in Overhead Distribution Networks. The LABFAI is constantly being updated for the continuity of this project entitled "Cabeça de Série FAI". The design and current structure of LABFAI can be seen in Fig.3 (a) and (b).

The LABFAI is powered by a low voltage (220 V) LEAT circuit and 400 A current, with the maximum high voltage current being limited to 6 A, due to the transformation ratio of the 225 kVA Trafo. To avoid undue activation of the supply circuit protection circuit breaker, the relay was parameterized with limit currents for phases in 5 A and 4.5 A for neutral. Despite this limitation, due to the high impedance of the tested surfaces, many experiments could be carried out without major difficulties, using the SEL 751 commercial relay to protect the network and record oscillographs. This equipment records up to 32 samples per cycle and 65 cycles in each event, having been assigned to the project by Equatorial Pará.

IV. CHARACTERISTICS OF HIF CHAINS AND TENSIONS IN MANGO BRANCHES

Considering the great diversity of tree species in the Amazon Region, where UFPA is located, and due to the little literature dealing with the characteristics of HIF voltages



(a) LABFAI Project

(b) Current LABFAI structure

Fig. 3. LABFAI

and currents in them [1] - [2] - [16],], it was decided to perform experiments with this surface, which was favored by the relative simplicity of simulation of this type of HIF in the assembled laboratory. It is emphasized that the knowledge of these characteristics is essential information in the great majority of methods used for modeling, detection and localizationof HIF [1] - [2] - [4] - [5] - [13] - [17].

Mango is a tree present in several regions of Brazil and abundant in the City of Belém do Pará, which is known as the “City of Mangos”, being in many of its streets, squares and parks, reaching heights well above 8 to 10 meters of medium voltage distribution networks [8], height used in most of the overhead distribution networks of the local concessionaire Equatorial Pará, financier of the P&D ANEEL HIF which aims at the “Localization of High Impedance Faults in Overhead Distribution Networks”. It is common to see energized cables passing between their branches, which makes the possibility of HIF on this surface a real and constant one, and these reasons motivated their choice for the study.

A. Conditions and Criteria for HIF Tests in Mango

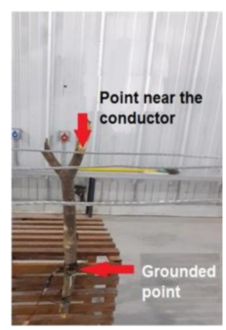
The temperature in LEAT, when the tests were carried out, was 29.2 ºC and the relative humidity was 75.9%. These data are cited for registration purposes, since it is not possible to control these parameters in that environment, which is why these parameters were considered as randomness for the tests performed. To ensure that the usual conditions of the branches were intact for HIF simulation, mango branches cut on the same date that the tests took place were used.

The tests were carried out on dates with different conditions, but which did not influence the characteristics of the HIF current. On November 1, 2019, the balanced and unloaded network was used, with the conductor of the contact phase “C” intact, that is, there was no “simulation” of breaking this cable. On March 9, 2020, the unbalanced network was used with a single-phase 5 kVA transformer connected in parallel in Phase A of the 75 kVA transformer, a load in Phase B of the same, but no load in Phase C, which remained intact, being it used in experiments. The need to perform new tests was due to inconsistencies found in the oscillographs of Tests 1 to 3 performed on the first day, which were redone on the second date.

In these conditions, two basic possibilities were considered: I - Branch (1) close to the conductor, but not touching; II - Branches (1,2 and 3) leaning against the conductor. For the second condition, the influences of the time of occurrence of the HIF and the variation of the linear distance between the point of contact with the energized conductor and the point of the branch connected to earth were also verified. For all conditions, since the cable is intact, the HIF current is the one that passes through the branch and goes to the earth, which was measured by Relay 751 SEL through the earth current (IG). To identify if there would be an increase in amount of data obtained from the currents, the relay was parameterized to record, among the 65 cycles available, 30 cycles as pre-fault, which enabled the capture of the initial and final information of the HIF currents.

1) Branch 1 close to the conductor, but not leaning: In Test 1, the linear distance between the point close to the energized conductor and the branch connected to earth was set at 0.5 meters, with a time limit of 15 seconds being established for the test. Fig.4(a) and (b) can be seen the positioning of the hose branch next to the “C” conductor, who was energized for HIF simulation, and the linear distance between the point near the energized conductor and the point of the branch connected to earth, respectively.

(a) Mango branch



(b) Close to the conductor

Fig. 4. Grounded point-Test 1

The current and voltage of the HIF recorded when the LABFAI was energized are shown in Fig.5, observing that only in the final moments of the test was the imposed voltage able to overcome the air and surface resistance, producing an HIF, about 30 event cycles were recorded. The Phase C voltage, however, did not vary due to the occurrence of HIF, confirming the resistive behavior of the fault.

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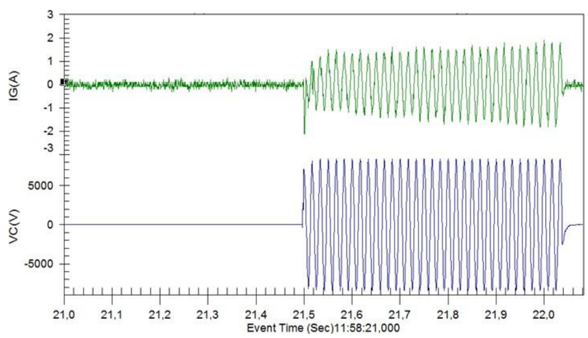

Fig. 5. HIF Current and Voltage of the branch near the cable - Test 1.

In the current details, seen in Fig.6, moments of current constancy (shoulder), growth (buildup), nonlinearities (distortions) and asymmetries, relevant characteristics of HIF, are recorded.

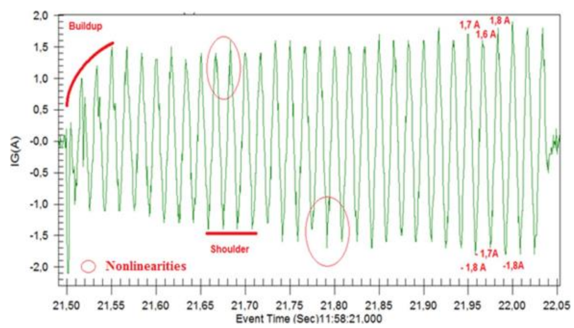

Fig. 6. Details of the HIF chain in Test 1 - Buildup, Shoulder, Nonlinearities and Asymmetries.

2) Branches in contact with the conductor: Branches 2, 3 and 4 were used to carry out these tests, which were in the conditions previously established, with varying test duration times and the linear distance between the contact point with the energized conductor and the branch point connected to earth. It was defined that the total testing time for each of these branches would be 8 seconds, divided according to Table II.

In Test 2, the linear distance between the point of contact to the energized conductor and the point of the branch connected to earth was established at 0.5 meters, with the conductor being energized for 5 seconds. The HIF voltage and current of the test are seen in Fig.7, with (a) the initial record and (b) the end.

It was found that the current started immediately after energizing the network, which was facilitated by the firm contact established between the cable and the branch. The path established for the current, even with a high impedance, allowed the passage of a current that started at 0.8 A, reaching 2.7 A, in the final moments recorded in the test. The current level reached in the test was not sufficient to activate the protection of the relay, as the test ended after the established

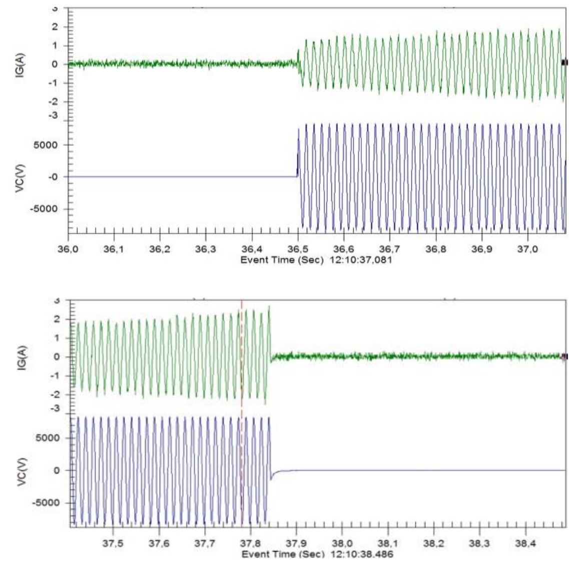

Fig. 7. Current and voltage of HIF of the branch leaning against the cable - Test 2

time had elapsed. The oscillographs also revealed that the effects on the voltage of phase C are negligible despite the branch having been touched by the conductor. Fig.8 shows the characteristic curve obtained for a final cycle of this record, considering its permanent regime.

TABLE II
BRANCHES AND TESTS

Branch	Test	Estimated Time	Linear Distance(m)
2	2	5	0.5
2	3	3	0.5
2	4	1	0.5
3	5	5	1
3	6	3	1
3	7	1	1
4	8	5	1.5
4	9	3	1.5
4	10	1	1.5

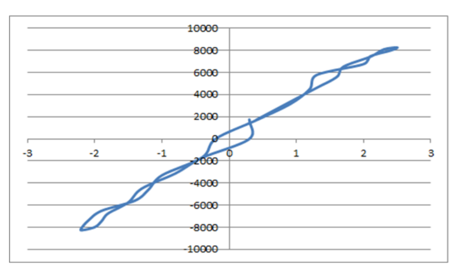

Fig. 8. HIF characteristic curve VxI - Test 2.

In the chain details, seen in Fig.9, moments of chain growth (buildup), constancy (shoulder), nonlinearities (distortions) and asymmetries are highlighted, but the tension is practically not influenced by HIF, characteristics that are relevant to the event.

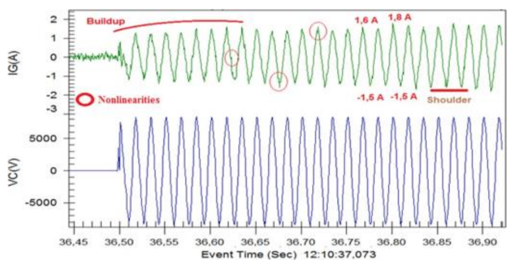

Fig. 9. Details of the HIF chain in Test 2 - Buildup, Shoulder, Nonlinearities and asymmetries.

Tests 3 and 4 used the same branch as Test 2, remaining on for 3 and 1 seconds, respectively. Current and voltage oscillographs showed wave forms very similar to those of Test 2, with changes mainly in the amplitudes that the current reached, which can be justified due to the reduction in the test times.

The current and voltage oscillographs of Test 3, seen in Fig.10, present waveforms very similar to those of the previous test. The current in this test started at 1.6 A, reaching 2.6 A, which demonstrates that despite the relative increase in the initial current value when compared to that recorded in Test 2 (0.8 A), the remaining resistance on the branch prevented high current growth during the test application time. Fig.11 records the details of the current - growth (buildup), constancy (shoulder), nonlinearities (distortions) and asymmetries.

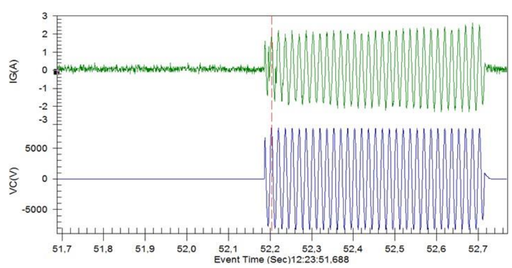

Fig. 10. Current and voltage of HIF of the branch leaning against the cable - Test 3.

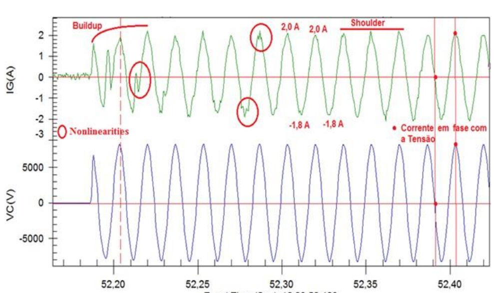

Fig. 11. Details of the HIF chain in Test 3 - Buildup, Shoulder, Nonlinearities and asymmetries.

In Test 4 the conductor remained connected for only 1 second, with current and voltage oscillographs seen in Fig.12. It is noteworthy that from this test, the relay was parameterized to record, among the 65 cycles available, only 5 cycles as a pre-fault, which made it possible to capture the initial and final information of the FAI currents of this experiment in a single record, different from what happened in Test 2. The start of the current occurs in the energization of the network, which is favored by the firm contact between the cable and the branch, being verified that the voltage of the missing phase does not suffer significant variations due to the occurrence of HIF. It is also confirmed that there is a resistive behavior of the fault, as the current remains in phase with the voltage.

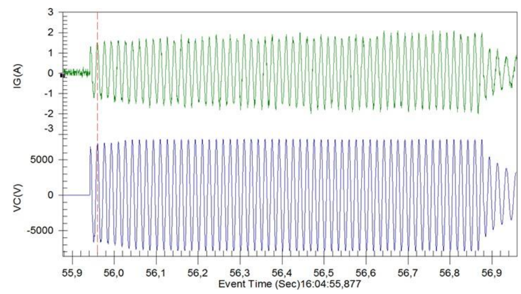

Fig. 12. Current and voltage of HIF of the branch leaning against the cable - Test 4.

As in the previous tests, in Fig.13 there are evident characteristics of HIF in the current of Test 4, with moments of growth (buildup), constancy (shoulder), nonlinearities (distortions) and asymmetries being highlighted.

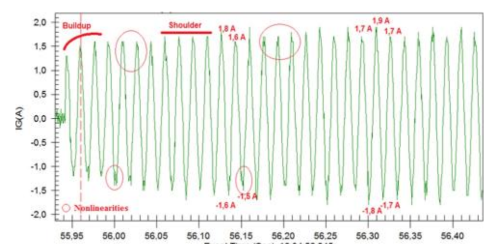

Fig. 13. Details of the HIF chain in Test 4 - Buildup, Shoulder, Nonlinearities and asymmetries.

In Tests 5, 6 and 7, the linear distance between the point of contact with the energized conductor and the point of the branch connected to earth was increased to 1.0 meters, with the recorded currents being reduced to values close to 0.5 A. The oscillographs of these tests, represented by Fig.14, demonstrate that the values reached by the currents were below the measurement capacity of the sensors used. This shows that the increase in the size of the branch under test resulted in a significant increase in the resistance imposed to the fault, making it impossible to have current or at least compromising its identification, due to the great presence of noise in the records.

In Tests 8, 9 and 10, the linear distance between the point of contact with the energized conductor and the point of the branch connected to earth was again increased to 1.5 meters, verifying the current behavior like the previous

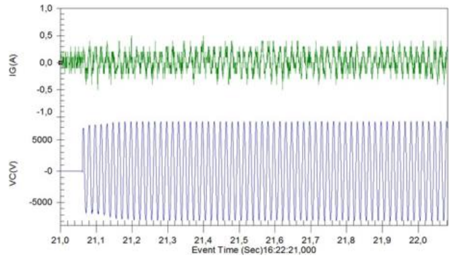

Fig. 14. Current and voltage of HIF of the branch leaning against the cable – representative oscillography of the Tests 5,6 e 7.

three tests, as shown in Fig.15, which confirms that the high impedance of the branch interrupted the current flow in it.

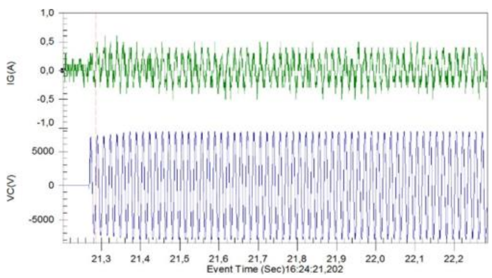

Fig. 15. Current and voltage of HIF of the branch leaning against the cable – representative oscillography of the Tests 8,9 e 10.

V. CONCLUSION

In none of the tests carried out with Mango branches, the occurrence of intermittency in the HIF current was verified, and this feature is ineffective for modeling or identifying this type of event. On the other hand, several characteristics of HIF were recorded in these experiments, and their intensity varied according to the resistance of the branch used.

In the first three tests there was an effective recording of the current flow, with the occurrence of HIF being proven by known characteristics such as buildup, shoulder, asymmetry and nonlinearity, in addition to the low current amplitude, also observing the non-sinking of the missing phase voltage, which reinforces the event that it is not a short circuit.

In the last six experiments, when the branches and the linear distances between the fault point and the ground were increased, with a consequent increase in the total resistance of the tests, the applied voltage was not enough to produce a HIF current whose registration has not been compromised network noise. Under these conditions, the attempt to detect HIF by current known characteristics would be affected, requiring the use of other methodologies or identification and measurement parameters.

The characteristics of HIF in Mango branches, obtained through experimental tests and registered through a commercial relay, are unprecedented in all the literature and will compose a database for the creation of more mathematical models specific for HIF shunt in trees, allowing its detection and localization. The application of this research can result both in the reduction of operational costs of the Distributor through the identification and location of HIF in its overhead distribution network, as well as by the predictive detection that makes it possible to carry out pruning, avoiding the occurrence of fires and mainly the loss of human lives.

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