Adaptive Protection in Microgrids Using Machine Learning for High Impedance Fault Detection

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Abstract- ***High impedance faults (HIF) in microgrids exhibit lower fault current amplitudes, as well as inherent nonlinearity and erratic behavior. The fault current during HIF initiation is further decreased by the possibility of weather intermittency in PV-based microgrids, as well as the introduction of harmonics from nonlinear loads and power electronic devices. HIF detection by standard overcurrent relays is challenging due to the low fault current. To overcome this issue, a robust protection mechanism for fault detection and classification during HIF in microgrids was provided. It is built on a hybrid architecture of Discrete Wavelet Transform and Bagged Decision Tree. The suggested protective strategy is to extract real-time features from current signals. When tested for robustness during HIF, the suggested system outperformed Support.***

Keywords: ***Microgrid, Distributed energy resources (DER), Wavelet transform, High impedance fault (HIF), Photovoltaic (PV).***

I. INTRODUCTION

Due to a notable rise in energy consumption and awareness about the necessity of reducing carbon emissions, the paradigm of power generation has gradually shifted from central to distributed generation [1]. This generation technology, in combination with advances in power electronic technology, has made it possible to integrate smaller-scale Distributed Energy Resources (DERs) in Microgrids [2][3]. Because microgrids operate in both directions, they can switch between standalone and grid-connected modes in response to changes in the availability of grid electricity. DERs based on photovoltaic (PV) technology are extensively utilized because of their accessibility, affordability, and simplicity of use [4].

The intermittent nature of renewable-based DERs makes their implementation in microgrids a security risk. Different fault currents from different DER types and differences in current and voltage profiles by grid integrated versus isolated modes further complicate safety techniques [5]. The issues of protection are compounded by high-impedance failures (HIFs), especially during standalone mode and harmonics. It can be challenging to detect HIFs, which are produced by insufficient contact between conductors and resistive surfaces, particularly when harmonics are present [5].

Finding HIFs has proven to be a persistent problem in power system defense. Previous research [1, 2] concentrated on employing neural network classifiers based on observed parameters for HIF detection. While [4] looked into industrial tactics, Mishra et al. [3] researched mathematical and mechanical methodologies. The purpose of the proposed article is to present a current evaluation of the techniques used in HIF detection, classification, and localization.

HIFs, which can be either passive or active, happen when a conductor unintentionally makes contact with a high impedance substance.

The complexity of HIFs arises from their characteristics, as illustrated in literature .

A. Current with a low level [2, 3], making it challenging to distinguish from a typical rise or decline in the loading level.
B. Irregular arcing [4-6] caused by minimized harmonics and noise in the measuring signal.
C. Unevenness and uncertainty [8] due to the variable abnormal route, causing the magnitude of fault current to cyclically alter.
D. Nonlinearity [5,6] in the connection between voltage and current sinusoidal signals during the HIF condition.
E. Develop and take on [5] from the level where the fault current gradually rises in numerous cycles until it reaches a steady state.

Many research publications heavily rely on High-Impedance Fault (HIF) modeling, as the accuracy of results is closely tied to the modelling method's ability to reproduce the characteristics of faults caused by high impedance. Modeling non-linear behavior, irregularities, unpredictabilities, uncertainties, surges, and take-ons requires sophisticated methodologies in a virtual system. This section explores current modeling methodologies prevalent in the literature.

For HIF diagnosis to address real-world problems, employing real scenarios created in a research lab is a practical approach. In [10], materials such as tree branches, grassy land, and concrete surfaces were used in both dehydrated and soggy conditions to simulate different HIFs. The setup recorded important current and voltage magnitudes using digital data recording equipment.

The second layer of replication is implemented in a simulation environment. This part discusses major models frequently considered in the literature to replicate HIF properties in an Electromagnetic Relay Module (EMT). Classical overcurrent protection devices are plagued by problems, which include the low magnitude of fault current, changes in current levels that depend on the mode, effects from power electronic components giving rise to harmonics, and nonlinearity. Since conventional devices based on fixed threshold settings are restricted due to their limitations, for effective protection, it requires an approach that will use adaptively selected threshold values.

Though it can handle the aforementioned problems within a certain range, this approach is unable to provide sufficient defense against the large and frequent variations in solar irradiance and harmonics caused by nonlinear loading.

II. LITERATURE REVIEW

Undiscovered High Impedance Faults (HIFs) are a serious risk to both public safety and the electrical distribution system as a whole. As a result, scientists are currently looking for methods to identify, categorize, and locate HIFs. The most recent methods for diagnosing HIFs are covered in detail in this section.

As mentioned in [5-7], the current values in 20 kV systems can vary between 1 and 75 A, as outlined in Table 1. This variation is influenced by factors such as the type of conductive material and its moisture content, impacting the fault current associated with high impedance. Research indicates that HIFs account for 5% to 10% of all total system defects. Since the accuracy of results depends on the modeling method's capacity to replicate the characteristics of a fault with greater impedance, High Impedance Fault (HIF) modeling is largely relied upon in many research articles. Non-linearity, irregularity, unpredictability, uncertainty, upsurge, and take on require sophisticated methodologies for modeling in a simulated system. This section provides an overview of the current modeling methodologies employed in the literature.

Addressing real-world issues is the ultimate purpose of HIF diagnosis. Thus, it makes sense to model real-world data in a high-current research lab. In [6], different HIFs were replicated using dry and wet materials such concrete surfaces, grass, and tree branches. Digital data recording technology was used to capture significant voltage and current magnitudes. For the study, the experimental configuration suggested in [10] was used. Despite producing useful study data and closely resembling an HIF, space limitations may make this approach unfeasible for many researchers. In order to replicate real HIF functioning, labs would also need to purchase pricey high-voltage equipment and implement strict safety measures to reduce the risk of HIF arcing. A simulation environment serves as the setting for the second layer of modeling. The three main models utilized in the text to simulate the characteristics of HIF in an electromagnetic relay module (EMT) are explained in detail in this section.

Single Variable Resistor

Using the following formula to determine the arc resistance, where R0 is the resistance system's initial error, t is the time, and τ is the user-defined time-constant, [6–8] projected this replica to replicate the arc discharge distinctiveness of a fault scenario based on Cassie and Mayr's theory [9,10]. This comes up to give a random layer for the replicated HIF. However, the asymmetrical and non-linear feature of the defect is not accurately characterized.

In differential protection techniques, such as pipeline leakage detection, the comparison of outgoing and incoming current flows is employed, and this approach is sensitive to HIF. Implementing differential protection in distribution networks, with multiple generating sites and loading buses, is challenging. Several alternative methods have been proposed to address HIF detection. One approach discussed in [4] involves capturing a falling conductor before it contacts a surface with high impedance, but it may be economically unfeasible. Another technique introduced in [3] utilizes Fast Fourier Transform (FFT) to study single- phase feeder currents, considering even and odd harmonic components. This method is noise-sensitive and requires a noise reduction system.

The method proposed in [4] suggests using Stockwell Transformation (ST) to monitor the third harmonic of a sinusoidal current input, which monitors its phase angle. However this takes about 150 milliseconds to detect a fault. In [5], a novel approach combines maximum overlap discrete wavelet packet transformation with empirical mode decomposition to extract the change in inter-harmonic energy, which denotes a possible existence of a hidden inter-harmonics. However, success across real operating conditions for each of the HIF types in uncertain.

III. PROPOSED METHODOLOGY

In the context of microgrid protection, the task of protection is complicated by the varying fault current levels of DERs, the different current characteristics in the different modes of operation of a microgrid, and the difficulties caused by nonlinear loading. A prompt and reliable safety plan is necessary since fault current levels are extremely low and are affected by the onset of HIFs under harmonics and the intermittent nature of PV irradiance, particularly in standalone mode.

Designing an effective protection system is a significant challenge in the widespread deployment of microgrids. The protection system must respond to faults in both the utility grid and the microgrid itself. In the event of a fault on the utility grid, the microgrid should act swiftly to protect critical loads. The speed of isolation depends on customer dependence on the microgrid. Charged loads do not depend on specific customer loads but rely on the speed of isolation and are determined by load characteristics and conditions. .

Wavelet Transform

The proposed protection technique collects three-phase instantaneous current data from the relaying bus and extracts discriminating features using the Discrete Wavelet Transform (DWT). In both grid-connected and standalone modes of operation, the collected features are subsequently fed into the Bagging Tree classifier to carry out fault detection and classification tasks. The following subsections provide a detailed description of the steps taken in creating the recommended protection algorithm:

Wavelet Transform for Voltage-Current Patterns:

Wavelet transform techniques are utilized to gather and study voltage-current patterns during line faults and disturbances.

When removing unnecessary information from raw time-domain DC voltage-current profile data, wavelet feature extraction techniques are utilized to obtain discriminating traits.

After a fault, the DWT is specifically used to extract crucial information from time-domain voltage-current data.

By dividing signals into several time-frequency domains, DWT collects vital information and makes accurate defect identification possible.

The mother wavelet's translation shift and dilation compression split the signal into different scales that correspond to different frequency patterns.

Advantages of DWT:

DWT has gained popularity for extracting useful information from non-stationary signals, providing information about time and frequency domain representation.

DWT is well-suited for online verification due to its shorter execution time, ensuring faster response times.

DWT is known for distinguishing between healthy and defective conditions, thanks to noise reduction properties and the correct trade-off between accuracy and complexity.

DWT remains popular in transmission line protection due to its ability to analyze sampled voltage and current signals by decomposing them into approximation and detail using high-passes and low-pass filters.

Selection of Wavelets:

The Wavelet Toolbox program provides a variety of wavelets for both continuous and discrete analysis, including orthogonal wavelets and B-spline biorthogonal wavelets for discrete analysis.

Selection of the appropriate wavelet depends on the properties of the signal or image and the specific application.

Different wavelet families have varying features such as symmetry or anti- symmetry, the number of vanishing points, regularity, and the presence of a scaling function.

Fourier transform-based analysis is available for select analysis and synthesis wavelets in the Wavelet Toolbox program.

Multi-Resolution Analysis with Wavelet Transform:

The Wavelet transform offers multi-resolution analysis, providing resolution in both time and frequency for a given signal or image.

It allows for the reconstruction of a temporal and scale-localized approximation of the input signal. Overall, the integration of DWT and Bagging Tree classifier forms a robust protection algorithm for fault detection and classification in microgrid operations.

Generation of fault and other operating scenarios

In the current study, the microgrid system is simulated to generate diverse scenarios. The voltage-current waveform at the relaying bus is extracted, considering a wide range of fault parameters, including fault resistance, inception angle, fault location, and other operating conditions such as load variation. Multiple fault types, including string to string, string to ground, and distribution line faults, are considered, and various fault and no-fault cases are generated for feature extraction.

Development of protection scheme

As previously stated, different fault currents and distinct behaviors of the current for DERs and two operating modes for microgrid nonlinear loading create complexities in terms of effective protection. Furthermore, a quick and dependable protection plan is needed to address the issues of very low fault current levels, especially in standalone mode, which arise from the initiation of High Impedance Faults (HIFs) under the effect of harmonics and intermittency in PV irradiance. A method, which is based on the hybrid architecture of DWT and Bagged Decision Tree, has been developed to deal with these issues and fulfill the protection requirements for standalone and grid-integrated operations.

The proposed protection technique uses the Discrete Wavelet Transform to extract unique features from the three-phase instantaneous current signals received from the relaying bus. These retrieved characteristics are used as inputs to the Bagging Tree classifier for fault detection and classification processes in both grid-connected and standalone modes of operation. The next subsections go into greater depth on the steps that were taken to develop the proposed protection algorithm.

Feature extraction using discrete wavelet transform

Wavelet tools are used to collect and analyze voltage-current patterns during line faults and disturbances. After removing redundancy, wavelet-based feature extraction techniques were applied to raw time-domain direct current (dc) voltage-current profile data to extract specific features. Specifically, in this study, the DWT was utilized to derive information that can be taken out of the time-domain voltage-current data post fault.

The DWT proves to be helpful in breaking the signal into different time-frequency domains that help collect vital data. It compresses the mother wavelet's dilation in time and translates time shift, splitting the signal into many scales that correspond to various frequency patterns.

Bagging Tree based Fault Detector and Classifier

According to the previous section (III), the input dataset's characteristics were designed using the data generated thus far, which included high impedance fault parameters, resistance, inception angle, and position, as well as healthy cases like nonlinear switching and varying loading conditions. The complete feature extraction process utilizing the DWT is shown in Fig. 3.1. They are then used to train the Bagging Tree classifiers for tasks including defect identification and discrimination.

The Bagging Tree-based classification model is intended for completion of the tasks in the classification of defect identification. Module fault identification and discrimination offer information about the status of the distribution line, together with any flaws in the system. The relay isolates the problematic area by initiating a trip signal to the breaker appropriate for the fault and type of defect under consideration and determined by the output from the module. Due to the properties of faster implementation and performance gains in larger datasets, Bagging Tree has recently become a very important data mining technique for most of the classification problems.

However, the predictive performance of Bagging Tree is often inferior to other data mining technologies like Support Vector Machines (SVM) and deep neural networks. For complex datasets, Bagging Tree may fail to produce satisfactory testing results. To address this limitation, instead of employing a single Bagging Tree for a specific classification task, an ensemble of trees is used. This ensemble approach overcomes the potential bias introduced by a single Decision Tree (DT), ensuring that the classifier output is incorporated into the final result. The most commonly used ensemble approach is bagging, in which the full training data is partitioned into subsets using a sampling and substitution procedure, and the same learner and a distinct learner train these subsets.

Algorithm Flowchart

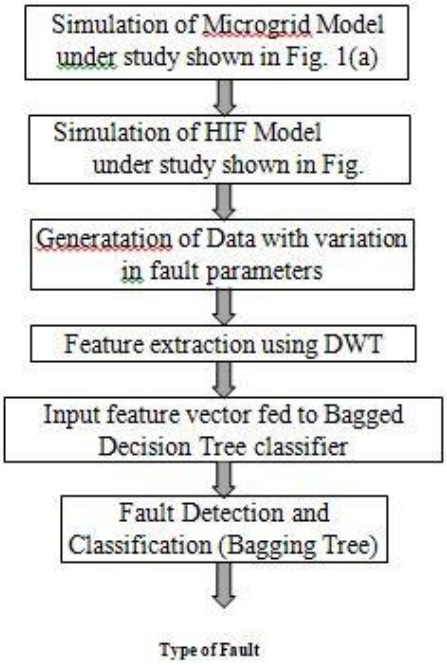
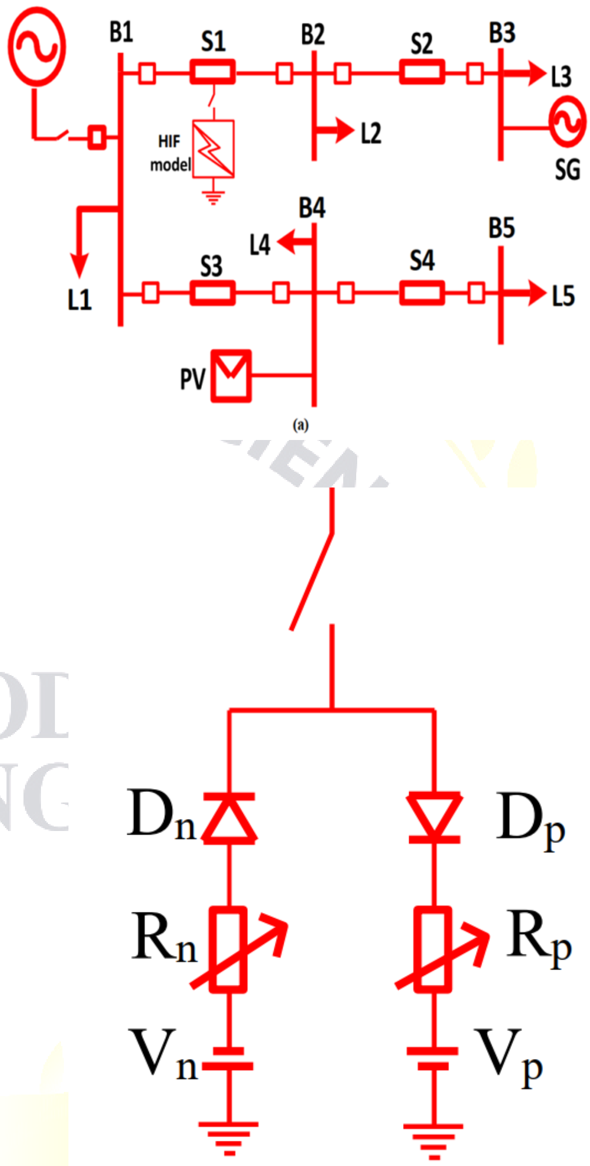


Figure 3.1: Proposed protection scheme flowchart

IV. RESULT ANALYSIS

A single line schematic of the microgrid that is the subject of this work is shown in Figure 4.1(a) . The MATLAB/Simulink system was used for the modeling and simulation. The microgrid, which has DERs, PV, and SG-based generators, is rated for 34.5kV, 60Hz. Two lines make up the distribution network, which is divided into four sections (S1, S2, S3, and S4), each of which is 20 kilometers long. The loads that are connected to the distribution system are L1, L2, L3, L4, and L5. In the independent mode, both DERs are turned on to supply the loads, however in the grid-connected mode, the synchronous generator (SG) is left unplugged.



(b)

Figure. 4.1: Microgrid under investigation (a) Diagrammatic representation (b) Suggested HIF model

The peculiar phenomena occurring in HIF include arcing and nonlinearity. To verify the designed protection strategy for cases generated by the appearance of HIF, a simple model of 2-diode HIF is simulated in Fig. 4.1(b). It uses DC sources, nonlinear variable resistances, and two anti-parallel diodes. The fault model's variable resistors stand in for the fault resistances, while the DC source simulates the air's voltage initiation in relation to the conductor and ground surface. An asymmetrical fault current profile can be simulated by varying the resistor's value.

The distribution line parameters are considered as depicted in Figure 4.2. The simulation of fault cases has been conducted using a three-phase fault simulator block in Simulink (Figure 4.3). This block enables the variation of fault parameters such as fault resistance, fault location, and switching time.

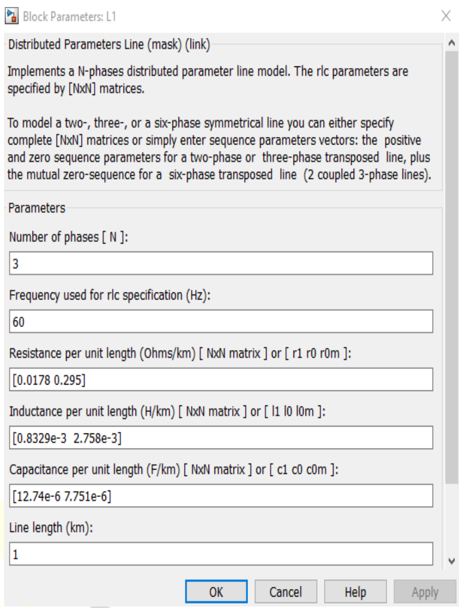


Fig 4.2: Distribution line parameters

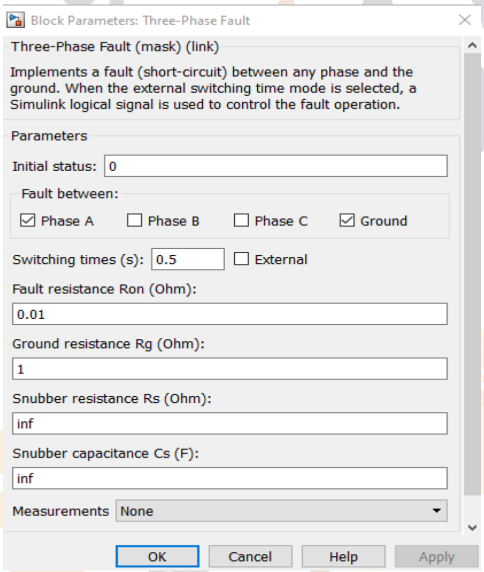


Fig 4.3: Three-phase fault simulator block

A variety of fault scenarios have been used to examine the varied behaviors of the faults taken into account in the suggested protection plan.

Performance of Bagging Tree Based Protection Algorithm

Several fault and operational conditions, including most of fault characteristics and no-fault situations (nonlinear switching of load and loading variation), are used to test the proposed protection method. To determine whether it can achieve the objectives of protection, the effectiveness of the protection module designed for fault identification and discrimination has been tested.

HIFs, due to the extremely low amplitude of the fault currents and their non-linear voltage-current characteristic present detection challenges in a distributed network. Although the current amplitude in HIF is extremely low, it should not be neglected because electra conductors reaching down on the ground surface would likely cause human life risk or arcing events create the chance of fire. The effectiveness of the suggested approach in correctly identifying HIF scenarios has been evaluated in order to allay these worries. The following subsections contain the full performance analysis.

Performance of Bagging Tree Classifier

As discussed earlier, the application of Discrete Wavelet Transform is used to decompose the information extracted from current and voltage data derived from different types of faults in the distribution line as well as the PV array. This information is thereafter used to train a classifier based on the Decision Tree methodology to classify the type of fault that has occurred in the system. The proposed study generates a sizeable dataset to train and test the data-mining model, using Decision trees to build an accurate and robust classifier for fault detection and classification.

The Decision Tree model is trained and tested on various datasets, including fault characteristics and other operational scenarios. For example, in a (70–30) dataset, 70% of the data is used for training and 30% for testing.

The confusion matrix generated for the aforementioned system, illustrating the training performance of the proposed classifier, is depicted in Figures 4.4, 4.5, and 4.6. This delivers comparison results between actual faults in the system and the estimated faults during testing for that dataset. Class labels can be defined as follows. Class label '1' represents the no-fault class whereas class labels '2,' '3,' and '4' all represent the involvement of different phases A, B and C respectively.

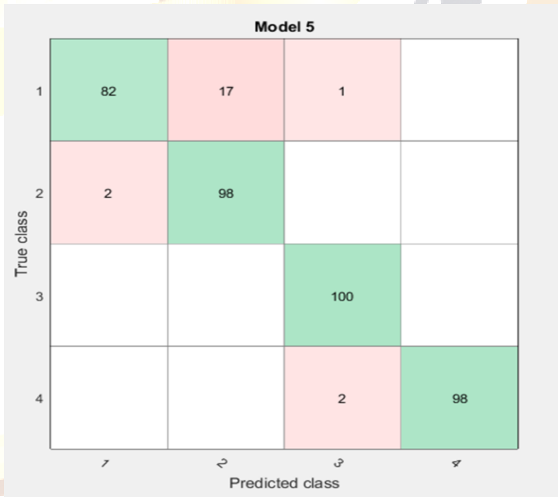


Figure 4.4 : Confusion matrix comparing the actual and anticipated classes

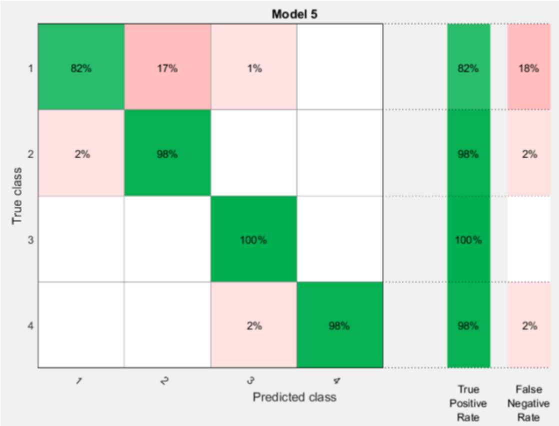


Figure 4.5: A matrix of confusion illustrating the difference between the true positive and true negative rates

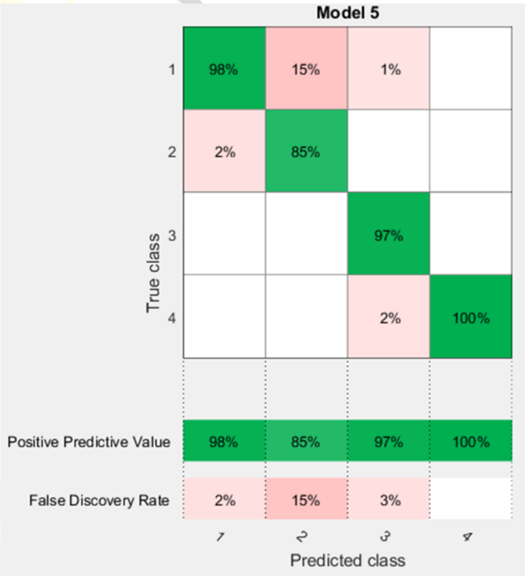


Figure 4.6: Confusion matrix illustrating the relationship between false discovery rate and positive predictive value

CONCLUSION

Traditional overcurrent relays face difficulties in fault identification due to the features of High Impedance Faults (HIF), where the resulting fault current level is only marginally greater than the typical amperage drawn from the load. While these problems may not always be diagnosed, concerns arise regarding public safety, as accidental contact with the human body could lead to dangerous electric shocks, fires, or life-threatening injuries if exposed to the fault conditions. Specific properties associated with HIF development, such as low current, intermittent arc discharge, unpredictability, asymmetry, non-linearity, accumulation, and shoulders, present obstacles in HIF diagnosis.

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