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TOPICAL REVIEW

Insights and Recommendations for the Assessment and Design of Fault Diagnosis Methods Applied to Modern Distribution Systems

TALITA M. O. A. CUNHA[1], GABRIELA N. LOPES[2], LEONARDO S. LESSA[1], MOISÉS J. B. B. DAVI[1], MÁRIO OLESKOVICZ[1], (Member, IEEE), AND JOSÉ C. M. VIEIRA[1], (Member, IEEE)

[1]Department of Electrical and Computer Engineering, University of São Paulo, São Carlos 13566-590, Brazil
[2]Department of Electrical Engineering, Federal University of Minas Gerais, Belo Horizonte 31270-901, Brazil

Corresponding author: Talita M. O. A. Cunha (talitamitsue@usp.br)

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ABSTRACT The growing integration of Distributed Generation (DG) and the complexity of modern distribution networks present new challenges in fault diagnosis. Thus, this paper comprehensively reviews fault diagnosis methods in distribution systems, emphasizing modeling aspects for real-world applicability. In addition, this study critically evaluates the tests performed when proposing methodologies for fault detection, classification, and location in both overhead and underground networks, highlighting limitations such as the lack of consideration for variations in operating conditions and DG diversity. Separate analyses are performed for overhead lines and underground networks, which are not easily found in the literature. A bibliometric analysis was performed to identify research trends, revealing a focus on signal processing techniques like Wavelet Transform and the increasing use of machine learning methods. The analysis also emphasizes the importance of robust distribution systems modeling, which includes accurate measurement systems and communication network. The findings aid future research to improve the reliability and efficiency of fault diagnosis systems in distribution networks, address current gaps, and point the way for more practical and adaptable solutions.

INDEX TERMS Distribution systems, distributed generation, fault diagnosis, signal processing, testing system modeling.

I. INTRODUCTION

Power distribution systems are essential to provide reliable and safe energy to consumers. With the increasing complexity of distribution networks, driven by the growing integration of Distributed Generation (DG) sources, such as renewable energy sources, the operational security of these systems has become more vulnerable to faults [1]. These faults, which can be caused by adverse weather conditions, equipment failures, or operational problems, can lead to interruptions that directly affect service quality [2]. In this context, efficient fault diagnosis, including rapid and accurate fault detection, classification, and location, is essential to minimize downtime and improve the reliability of distribution systems.

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Although many studies on fault diagnosis in distribution systems can be found in the literature, these studies still present several limitations that hinder the practical applicability of the proposed methodologies in real-world scenarios [3]. Many studies focus on idealized conditions without considering critical aspects such as variations in operating conditions and the diversity of DG types and controls present in modern networks.

Incorporating DG into distribution networks includes an additional layer of complexity to fault diagnosis studies. DGs can significantly alter the system's behavior during a fault, affecting fault currents and, consequently, the effectiveness of traditional protection and diagnosis methods [4]. Therefore, fault diagnosis studies must consider the diversity of DGs, covering their various topologies and control strategies, and the need to adapt methodologies to scenarios that reflect the actual operating conditions of distribution systems [5].

Furthermore, the proposed methodologies must be evaluated under conditions that consider aspects of the modeling of test systems, including whether they need communication networks, measurement system infrastructure, data synchronization, and signal processing techniques that are robust to topology variations and noise present in real systems [6], [7]. Thus, considering all these aspects, the development of fault diagnosis solutions that are practically applicable is of utmost importance to ensure the reliability and efficiency of modern distribution systems.

Despite advances in fault diagnosis techniques, studies that combine the above-mentioned aspects still need to be available. Therefore, this study provides a comprehensive review of the modeling aspects of articles on fault diagnosis methods in distribution systems, both for overhead and underground networks.

In this context, the contributions of this work are as follows:

- It critically evaluates the methodologies based on the modeling aspects of their tests, highlighting the limitations and challenges in applying these methods in real-world scenarios;
- It provides detailed insights into the requirements and practical considerations for implementing fault diagnosis systems;
- This work serves as a valuable resource for researchers and practitioners aiming to enhance the reliability and applicability of fault diagnosis techniques in modern power distribution networks.

II. BIBLIOMETRIC REVIEW

Despite network modeling parameters being highly relevant for test systems, several studies on fault diagnosis in power distribution networks often omit critical components of the system representation, such as communication needs and data acquisition. Thus, a bibliometric analysis, with filtering stages, was performed to build a critical review of fault diagnosis methods in distribution systems.

The first step was to define the query to search for the articles using online databases. In summary, the search query included the following keywords: fault location and/or fault detection and/or fault and/or classification, distribution systems, and overhead or underground, published after 2003. The search was divided into papers focused on overhead and underground distribution networks. After the search, more than 4014 papers were found in overhead cables and 233 in underground networks.

Given the broad range of topics connecting all the articles, a meticulous process was undertaken to refine the scope of the review, thereby enhancing its analytical precision. This process involved an initial filtering based on the following criteria:

- Articles published in high-quality international journals and conferences were prioritized;
- Recent publications were preferred over older ones so that the review reflected the state of the art, such as the rapid changes in electrical power system topologies;
- Papers containing most keywords in the title and abstract were chosen over those with little relevance to the desired content.

A second filtering stage was applied to the remaining 123 papers from the first filter. The second filtering was performed according to the following rules:

- Papers that truly showcase the test system with relevant modeling information were given priority;
- Articles whose methods were tested on a test system with DG were favored over those that did not include such testing.

This study focuses on the main aspects regarding the appropriate modeling of systems used to evaluate existing fault diagnosis techniques. The analysis is structured into two main dimensions: the methodology and test aspects. The final selection of papers included in this review was based on the presence of detailed information in at least seven of the following modeling criteria:

1) Network configuration (overhead or underground);
2) Presence or absence of distributed generation (DG);
3) Voltage level;
4) Transformer connections (if applicable);
5) Number and type of measurement devices;
6) Protection system characteristics;
7) Use of communication in the measurement infrastructure;
8) Software employed for simulations or analysis;
9) Electrical quantities monitored;
10) Consideration of noise in the measurements;
11) Fault modeling details, including fault types and resistance range.

After the filtering stages, 47 suitable papers were selected for analysis. These papers, which covered a wide range of topics and approaches, provided a solid foundation for a robust and comprehensive analysis. Of these, 33 papers focused on overhead systems and 14 on underground systems,

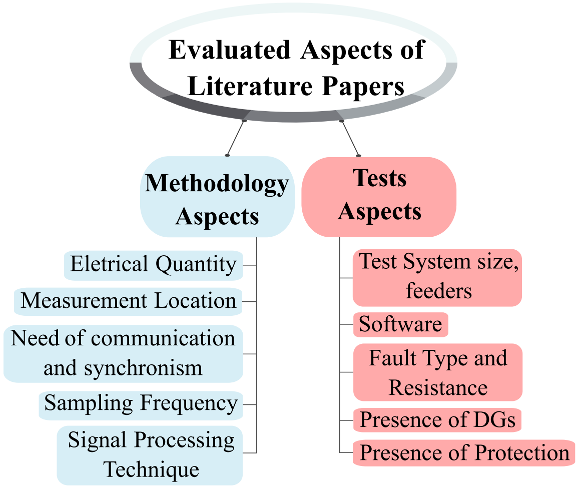

FIGURE 1. Aspects evaluated in the literature papers regarding fault detection, classification, and location in distribution systems.

reflecting the diversity of the literature reviewed. The selected characteristics used to compare and evaluate the fault diagnosis methods are summarized in Fig. 1. It is highlighted that the analysis did not include information such as transformer connection and DG filtering, as most techniques did not provide this information.

Fig. 2 shows a bibliometric network analysis of the search. This bibliometric network shed light on the research trends in fault diagnosis based on the keyword data set found during the article survey filtering. The word network in Fig. 2 illustrates a visualization map of keyword co-occurrence, where larger circles represent higher frequency and, consequently, greater relevance to ongoing research. The results indicate that fault location is the most researched topic in fault diagnosis in distribution systems. In contrast, the most recent issues concentrate on processing techniques and feature extraction, where the Wavelet Transform (WT) stands out. In this regard, interest in using Machine Learning (ML) for fault diagnosis is also demonstrated, which is related to initiatives to overcome the challenges of distributed generation. The following sections provide a critical review of the filtered literature.

III. FAULT DIAGNOSIS METHODS IN OVERHEAD DISTRIBUTION SYSTEMS

This section presents a critical review of articles on overhead network fault diagnosis. It focuses on the methodology and validation tests required to model a test system for fault diagnosis analyses. First, fault detection and classification papers were assessed, followed by fault location studies.

A. EVALUATION OF FAULT DETECTION AND CLASSIFICATION METHODS IN DISTRIBUTION SYSTEMS

Fault detection and classification are critical in power distribution systems to ensure a reliable power supply and safety. The existing methodologies for this purpose are tested in different scenarios with diverse characteristics and require specific aspects of system modeling for their application. This section reviews key methodologies and validation tests from various studies to identify network configuration requirements of test system modeling for fault diagnosis studies. The objective includes identifying potential limitations in testing fault diagnosis methods, which could hinder their applicability in the real world while addressing the identified gaps. The following sections thoroughly describe the aspects and challenges of each methodology.

The authors of [8] proposed a hybrid fault detection system using a cause-effect network and a fuzzy rule-based method, tested against Expert Systems and Artificial Neural Networks (ANN). Simulations in the Electromagnetic Transients Program (EMTP) covered multiple fault scenarios, showing improved speed and robustness with simple implementation. However, the computational processing power of the ANN methods has increased significantly since this study was published. Thus, a new comparison with current conditions would be needed for reliable results.

The authors in [9] introduced a semi-supervised method with Decision Trees and K-nearest neighbor co-training. The Wavelet Transform was used for feature extraction. The 10-bus distribution network considered grid-connected and islanded operation modes, and renewable energy distributed generators in the simulations in PSCAD/EMTDC. Although labeled and unlabeled data were handled effectively, the study did not discuss noise interference or whether relay communication, synchronized measurements or centralized processing are required for deployment architecture.

Wavelet transforms were also applied by [10] to develop a multi-agent methodology in radial and meshed networks with distributed generators that enhanced fault diagnosis and isolation. Facilitated by a telecommunication network, the relay agents established an information exchange platform, enabling precise fault diagnosis and area isolation through adaptable protection coordination. The simulations conducted in Simulink encompassed various types of faults and resistances in three-phase systems, lacking noise analysis and standardized simulation parameters to ensure efficiency across different network topologies.

In this context, in [11], an Adaptive Neural Fuzzy Inference System was utilized for fault classification in a non-effectively grounded system. Despite accurate classification results, even if the network configuration changed slightly, performance diminished under heavy loads, highlighting the need for further training and noise interference analysis.

The WT is further explored for fault diagnosis in [12]. This study proposed an overcurrent protection system based on the real-time boundary WT for distribution networks with distributed generation. The proposed wavelet-based overcurrent relays demonstrated advantages over traditional overcurrent protection in trip time and computational efficiency while providing the fault inception time as additional information. However, the influence of DG, which affects the magnitude

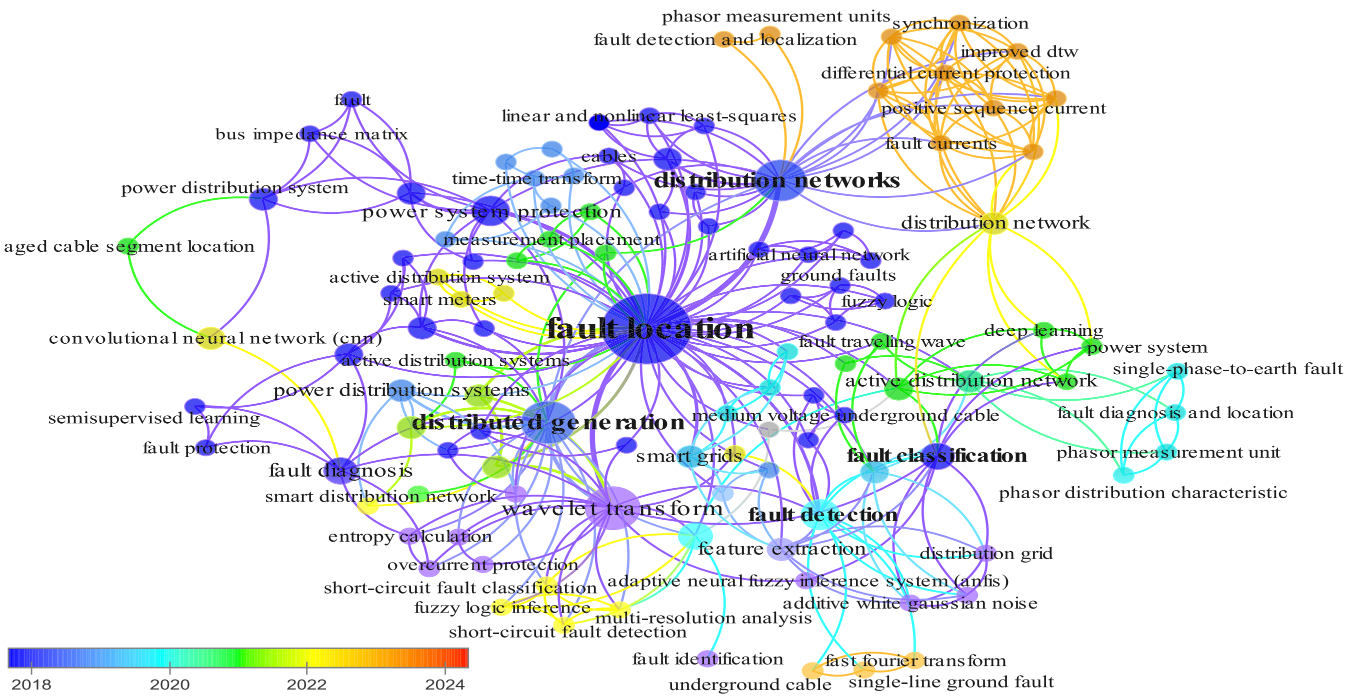

FIGURE 2. The bibliometric map of keywords co-occurrence.

of the fault current, led to a misinterpretation of overcurrent relays in some cases, indicating the need to improve relay coordination and noisy data assessment.

A multi-agent system was proposed to diagnose faults in medium voltage systems with DG units in an open-ring feeder topology [13]. Short-circuit fault simulations were conducted using MATLAB/Simulink. The authors argue the advantages of the proposed protection scheme, as Relay Agents (RAs) can simultaneously send and accept requests and share information with neighboring RAs. They also have access to the Phasor Measurement Unit (PMU) information, allowing faster relay response with more precise identification of faults and reconfiguration actions. Although this study demonstrated enhanced system reliability and reduced fault clearing time, it did not consider high-impedance fault cases and noise interference.

The literature also presents studies where fault detection and classification tasks are combined. For example, [14] combined Stockwell-Transform (ST) and feedforward neural networks for distribution networks. Two test systems with different modeling parameters were designed, one in MATLAB/Simulink and another in Real-time Structured Computer-Aided Design (RSCAD), with fault scenarios simulated accordingly. In the second case, although the system was modeled and simulated in RSCAD/RTDS, the recorded current signals were later processed in MATLAB/Simulink to extract features using ST energy matrices for the neural network. Furthermore, the simulations comprised noise-free and noisy data, which is not shown in most literature. The proposed methodology demonstrated competitiveness compared to other available techniques in the literature, as it achieved an accuracy greater than 99% for fault detection and classification in noisy and noise-free scenarios. However, the study did not consider the implementation of distributed generation, which can significantly impact the sensitivity of the protection system and increase the required training scenarios for the neural network.

Another combined analysis is developed in [15], where the authors evaluated fault detection and classification under various DG scenarios. The first scenario did not consider any DG unit, while the second considered two synchronous generators. The third scenario assumes a photovoltaic (PV) model of 1 MVA as the DG unit. All test system scenarios were simulated in the Alternative Transients Program (ATP), and the resulting signals were processed in MATLAB, considering various types of faults and resistance conditions. The wavelet-based fault detection model achieved an accuracy above 94.9% for all scenarios. In contrast, for the fuzzy inference-based classification model, the accuracy decreased significantly in cases where DG units were considered, dropping from 100% to 95.4%. The results leave room for improvement of the proposed method in determining fault classification when DGs are present and the inclusion of noisy data.

The work of [16] introduced a differential protection method for fault detection and isolation in medium voltage distribution systems with Inverter-Interfaced DG (IIDG). In addition to evaluating the ineffectiveness of traditional protection systems in these cases, this study makes a significant contribution since it is validated in a system with overhead and underground lines. A Dynamic Time-Warping (DTW) distance algorithm combined with a feeder terminal unit protection scheme was placed between the head ends of each section and near the load side. The simulations were conducted in PSCAD/EMTDC with noisy and noise-free data, considering various fault parameters with different fault locations in the test system. Although the feeder terminal units are said to communicate with each other and exchange data, the study lacks a more in-depth discussion of how they receive instructions from the main station according to the network topology and preprocessing.

Tables 1 and 2 summarize the studies analyzed in this section, highlighting their main characteristics. Table 1 reveals that WT is a significant technique for signal processing in fault detection and classification in overhead distribution systems. In addition to having a communication network, most studies take measurements of current and voltage signals at system sections rather than only at substations. The sampling rate may vary, but at least 64 samples/cycle are considered. Table 2 shows that synchronous generators are applied mainly when viewing DG for overhead distribution systems, although some studies also considered photovoltaic sources, IIDG, and induction generators. In addition, the fault resistance ranged from 0 to 300 Ω, and the number of different fault types ranged from 4 to 12. However, the number of feeders is not usually displayed, and the test system configurations are diverse. Another limitation identified was the lack of noise interference analysis, which could affect the usefulness of these methods in real-world networks.

B. EVALUATION OF FAULT LOCATION METHODS IN DISTRIBUTION SYSTEMS

The location of the fault is of paramount importance in fault diagnosis. Effective fault location methods can significantly reduce inspection and service restoration time, reducing downtime and enhancing service reliability. Furthermore, locating an early fault can be a preventive measure against possible permanent faults that could cause equipment failure [17]. There are many fault location methods, though improvements may be needed for their real-world applicability. In addition, it may be essential to consider their requirements when modeling a network to employ similar methodologies. In this sense, this section evaluates the methodology and validation tests of the selected fault location methods. This review organizes the methods based on their fault location approach, as shown in Fig. 3. These methods are thoroughly explained in the following items.

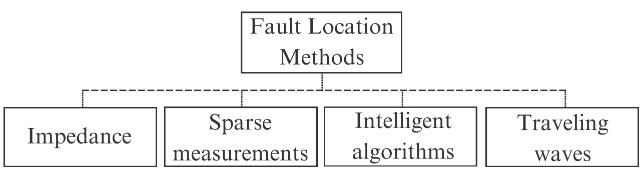

FIGURE 3. Fault location methods for overhead lines.

1) METHODS BASED ON IMPEDANCE

This section focuses on the study of fault location methods based on impedance. This methodology is based on obtaining the apparent impedance or reactance to estimate the electrical distance between the fault and measurement points. This approach relies on short-circuit analysis theory, in which the substation voltage and current can express the impedance between the substation and the faulty location. In this sense, the selected papers regarding this approach are analyzed in this section, and their main characteristics are identified.

A significant impedance-based fault location method was developed by [18] to locate faults in medium voltage distribution systems (13.8 kV). Despite not having a distributed generator connected to the system, the proposed methodology is based on a recent solution widely used for fault diagnosis: Intelligent Electronic Devices (IEDs). The study considers IEDs at the beginning of each feeder, keeping measurements only at the system substation. The fault diagnosis modules are connected to the same bus through a computer. An important aspect is that IEDs need communication when measuring voltage and current signals to calculate power flow during the fault. The simulations were carried out in ATP modeling the 11 types of fault, modeled with impedances of 0 to 20 Ω with incidence in six different buses. Although promising, the method is not evaluated in systems with DG, requires device communication, and needs updated system information. These are essential concerns when one aims to apply these methods in practice.

In [19], the authors used a methodology based on impedance to locate faults in DSs with DGs (in this case, a synchronous generator). The novelty of the method is that voltage and current measurements are placed at both the substation of the system and the DG bus, and the power flow of the two measurements is considered. The test system is the IEEE 34 node (24.9 kV), and the faults were modeled using ATP as Single-Line-to-Ground faults (SLG) with impedance from 0 to 40 Ω and Line-to-Line (LL) and three-line faults (LLL) from 0 to 15 Ω. Although they do not provide many details about the system, the tests consider the random variations in the system loading. The results show that the method is affected by the change in load. One of the main advantages of this technique is that it does not use the DG parameters, which are commonly unknown, to estimate the fault distance. Therefore, such a methodology can be helpful when considering the uncertainties of electrical systems, which can also occur in the generation of wind farms, for example.

The fault location method proposed by [17] uses the voltage phasors measured at the substation and DGs to estimate the fault location. For this, the authors modeled the IEEE 34-node test system using PSCAD/EMTP software and added two wind generators, modeled as induction generators. All 11 types of faults were modeled with resistance varying between 0 and 25 Ω. The signals were measured with 256 samples per cycle, and the fundamental

TABLE 1. Aspects about the methodology of fault detection and classification methods for overhead distribution systems.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[8]	Current/ Voltage	Substation	Yes	-	-
[9]	Current and voltage	Substation / System sections	-	64 samples/cycle	Wavelet Transform
[10]	Current	System sections	Yes	20 kHz	Wavelet Transform
[11]	Current and voltage	Substation	-	10 kHz	Wavelet Transform
[12]	Current and voltage	System sections	-	400 samples/cycle	Wavelet Transform
[13]	Current	System sections	Yes	10 kHz	-
[14]	Current	System sections	-	-	Stockwell Transform
[15]	Current	System sections	Yes	180 samples/cycle	Wavelet Transform
[16]	Current	System sections	Yes	-	-

- Information not mentioned by the authors or test not performed.

TABLE 2. Aspects about the tests performed to validate fault detection and classification methods for overhead distribution systems.

Reference	Test System Size (bus)	Voltage Level	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[8]	4-bus	11.4, 69 kV	RTDP/ EMTP	No	4	-	-	Yes	15
[9]	10-bus	0.48, 13.8 kV	PSCAD/ EMTDC	No	11	0.1 to 10 Ω	PV	Yes	-
[10]	11-bus/ 16-bus	13.2, 66 kV	Simulink	No	10	10 to 250 Ω	IGs/SGs	Yes	-
[11]	IEEE 34-bus	-	PSCAD/ EMTDC	No	10	0 to 1.5 kΩ	-	-	-
[12]	IEEE 30-bus	11, 33, 132 kV	RTDS	No	8	0 to 5 Ω	SGs	Yes	-
[13]	10-bus	11 kV	ATP/ MATLAB	No	12	-	SGs	Yes	1
[14]	1-Line/ IEEE 13-node	0.575, 25, 120 kV/ 0.48, 4.16, 115 kV	RSCAD/ MATLAB	Yes	4	-	-	Yes	-
[15]	IEEE 34-bus	24.9 kV	ATP/ MATLAB	No	4	1 to 300 Ω	SGs/ PV	-	-
[16]	3-bus	10 kV	PSCAD/ EMTDC	Yes	4	0 to 60 Ω	IIDG	Yes	1

- Information not mentioned by the authors or test not performed. [a] PV: Photovoltaic, [b] IIDG: Inverter-Interfaced Distributed Generator, [c] IG: Induction Generator (e.g., wind turbine), [d] SG: Synchronous Generator

phasor was extracted using the Fourier Transform (FT). The main downsides of the methodology are that it requires synchronization via GPS and does not test for other types of DGs. The fault resistance can be low compared to the values tested in other studies.

Another impedance-based approach is shown in [20], in which the authors modeled a DS with two DG types. One is an average model of a 1.5 MW DFIG wind turbine, and the other is three similar average models of a 400 kW photovoltaic farm. The DGs are connected to the 20 kV grid through transformers modeled using Simulink. The method is based on the system's power flow, using current and voltage measurements at the system substation and the DGs. Although the methodologies use only the fundamental signals extracted by the FT, the signals are acquired with 250 samples per cycle. This methodology stands out because it works for different types of DG without needing their parameters. In addition, it does not require synchronizing the measurements.

Some methodologies test the methods with even more DG types; [21] published one example using the IEEE 34-nodes test system (24.9 kV) modeled in ATP. The authors added three DGs to the system: one DG based on synchronous generators and two IIDGs. They propose an impedance-based methodology that requires measurements at the DGs. Only current measurements must be synchronized, which is a good solution. The faults were modeled with impedance ranging from 0 to 100 Ω. The method has many contributions. One is to evaluate the influence of variations in fault resistance and fault location on the algorithm. Moreover, the DG measurement error is analyzed, as it can occur in different electrical systems. Tests considering other DG types, such as wind-based ones, require further studies.

The fault location method proposed by [22] also considers different DG types to test their algorithm: two synchronous machines and one inverter-interfaced DG unit (photovoltaic). The authors modeled a 17-bus system using EMTP-RV, whereas depending on the system's circuit breaker (CB) status, a single-source or a multiple-source topology is alternatively assumed. The solution considers two measurement locations acquiring synchronized voltage signals with a sampling frequency of 1 kHz during steady-state and 20 kHz when a transient is identified. It uses a filter and the FT to extract the fundamental voltage phasors. They model all fault types from 2.5 to 50 Ω. The main challenges for implementing this technique in actual networks are considering other types of DGs, the requirement of synchronized measurements, and the circuit break status. Moreover, evaluating the methodology when varying the system's loading and DG penetration level can be necessary for future studies applying similar approaches.

The paper published by [23] presents an approach that provides two different solutions for fault location, depending on whether the system has access to synchronized measurements. The authors test the methodology in three test systems. The input signals are the current and voltage measurements at the DGs and the substations. The system was modeled using the EMTP-RV software, evaluating the method with all 11 fault types and fault resistances from 1 to 50 Ω. The measurements are acquired with 20 kHz, and the algorithm is based on first using a filter with a cutoff frequency of 420 Hz and then using the FT to extract the fundamental phasors. Although the methodology presents meaningful solutions, due to not requiring synchronized measurements, which are not always possible, the method was only tested in systems with synchronous generators. Thus, other DG types can be pushed to prove the method's applicability to other systems.

An enhanced impedance-based fault location method is proposed in [24] for active overhead and unbalanced distribution systems with IIDGs. It combines discrete/status data and analog measurements from μ-PMUs and legacy devices. A probabilistic Petri-net model identifies the faulted section, narrowing the search space and improving efficiency. Then, the impedance-based estimation uses voltage and current phasors to locate the fault precisely. The IEEE 34-node (24.9 kV) is used as the test system, including two IIDGs at nodes 15 and 25 (via transformers), a μ-PMU at node 8, and a legacy meter at node 23. The system operates without a traditional protection scheme but includes protective devices (reclosers, Directional Fault Indicators - DFIs) and smart meters. SLG, LL, and LLG faults are modeled at 10 locations with resistances from 0 to 20 Ω. PSCAD is used for simulation, considering noise, pseudo-measurements, and uncertainties in loads and line parameters. The method remains effective under unbalanced conditions, measurement errors, and sparse μ-PMU deployment. However, its performance may degrade when limited or no measurements are available downstream of the fault.

After thoroughly evaluating existing impedance-based fault location methods, two tables were developed: one considering the main aspects of the papers' methodology and another regarding the technical aspects of the algorithms' validation tests.

Thus, Table 3 shows the main elements of the impedance-based methods. It can be seen that most methods use current and voltage as input signals. When DG is in the system, all methods consider measurements on them, requiring a communication channel. Considering 50 Hz systems, the sampling frequency varied between 16 and 400 samples per cycle. Moreover, the apparent impedance is calculated using voltage and current phasors, extracted mainly using the FT. This is justified because the FT is widely used in power system protection; it is a rapid alternative to extracting the fundamental components of frequency, amplitude, and angle.

After evaluating the methods' characteristics, Table 4 was developed to compare the main aspects regarding the tests used to validate the chosen impedance-based methods. Table 4 shows that the studies consider test systems with different sizes and protection systems. Most methods use systems with only one feeder and do not evaluate the algorithm's performance with noisy measurements. Transient-analysis software, such as ATP, Simulink, PSCAD, and EMTP, is always chosen to model the test systems. When modeling the faults, a specific range is usually considered; in this case, it mainly varies between 0 and 100 Ω. The DG types connected to the systems also changed as the authors modeled wind, inverter interface DGs, and synchronous and photovoltaic generators.

2) METHODS BASED ON SPARSE MEASUREMENTS

Incorporating multiple voltage and current measurements along distribution feeders represents an alternative approach for fault location. When a fault occurs, there is a voltage drop in the system. This voltage drop can have different values depending on the fault distance from the measurement device. These values can be compared to determine the fault proximity to a specific measurement device, which can be used to decide the fault location. Recognizing that solution, some authors developed methods based on sparse measurements along the system nodes. Some of the main ones are selected and evaluated in this section. The central focus is on the requirements for system modeling when using this approach.

The fault location method proposed by [25] is based on a measurement technique available in the market at that period, with a sound theoretical footing. The algorithm is based on current and voltage measurements at the interconnection of DG units. The signals are acquired with a sampling frequency of 48 kHz, and the FT is used to extract the phasors from them. To validate the method, the authors modeled a 60-node test system (12.47 kV), varying the number of DG sources (modeled as impedance and source) connected to different buses. Different fault situations were modeled considering fault resistances from 1 to 50 Ω. The method achieved positive results but required synchronized measurements, and the DGs were not modeled according to their complexity.

The fault location method proposed by [26] uses an RTDS to test its algorithm, which is closer to real-life conditions. It uses real-time measurements to locate the fault, considering a communication network to link the various PMUs distributed along the test system nodes. As downsides, the authors do not inform the sampling frequency used to acquire the current and voltage measurements, only consider the fault modeled with 0 Ω, and the DGs are only photovoltaic systems. Thus, there is room to improve the technique.

The approach published in [27] uses the pre and post-fault voltages of measurable nodes and output currents of energy sources recorded by PMU to locate the fault. Using Matlab, the authors modeled the IEEE 123-nodes test system under fault resistances from 1 to 100 Ω. The algorithm is based on sparse measurements by micro-PMUs, optimally placed at the terminals of the three-phase nodes and the DGs (which are IIDGs). The algorithm achieves good results, even when adding noise from 0.1 to 1% in the measurements, a test not often assumed by other authors. Testing this methodology in systems with other DG types may be relevant for future studies. Moreover, the authors do not comment on the sampling frequency required for the method to function.

TABLE 3. Aspects about the methodology of fault location methods for overhead distribution systems: impedance-based methods.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[18]	Current and voltage	Substation/ feeder beginnings	Yes	-	Power flow calculation
[19]	Current and voltage	Substation and DGs	Yes	-	-
[17]	Voltage	Substation and DGs	Yes	256 samples/cycle	FT
[20]	Current and voltage	Substation and DGs	No	256 samples/cycle	FT
[21]	Current and voltage	Substation and DGs	Yes, for current	-	-
[22]	Voltage	Substation and DGs	Yes	1 kHz/ 20 kHz	FT
[23]	Current and voltage	Substation and DGs	Yes, if possible	20 kHz	FT
[24]	Current and voltage	Substation, Node 8 (µ-PMU), Node 23 (legacy)	Yes (partially)	-	FT + State Estimation

- : Information not mentioned by the authors or test not performed.

TABLE 4. Aspects about the validation tests of fault location methods for overhead distribution systems: impedance-based methods.

Reference	Test System Size (bus)	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[18]	>100	ATP	-	11	0-20 Ω	No	No	8
[19]	34	ATP	-	11	0-40	SG[a]	No.	1
[17]	34	PSCAD	-	11	0-25 Ω	Wind Generator	No.	1
[20]	98	Simulink	-	11	2-50 Ω	DFIG[b]/ PV[c]	No.	1
[21]	34	ATP	-	11	0-100 Ω	IIDG[d]/ SG	-	1
[22]	17	EMTP	-	11	2.5-50 Ω	IIDG/ SG	Yes, CBs[e]	1
[23]	23, 100, 123	EMTP	-	11	1-50 Ω	SGs	Yes, CBs[e]	1
[24]	34	PSCAD	Yes	SGL, LL, LLG	0–20 Ω	IIDG	Reclosers, DFIs, SMs	1

- : Information not mentioned by the authors or test not performed./ [a] SGs: Synchronous Generators/ [b] DFIG: Doubly fed induction generator. In this case, it represents wind generators. / [c] PV: Photovoltaic Generator /[d] Inverter-Interfaced Distributed Generator/ [e] CBs: Circuit Breakers

Some techniques link two or more fault location methodologies. That is the case of the method proposed by [28], which can be considered a junction of sparse measurements and impedance-based fault location techniques. The procedure is based on generating an impedance matrix using only the series impedance of the distribution lines, which is used to locate the fault along with the pre and during-fault voltage phasors at a few buses. To validate the methodology, the authors modeled a 134-bus test system (13.9 kV) with three different types of DGs connected to it - an induction generator, a synchronous generator, and a photovoltaic unit. All faults are modeled with fault impedance of 0.5 and 10 Ω. Micro-PMUs connected to different buses only need to record the voltage measurements with 16 samples per cycle. The voltage phasors are extracted using the FT, and a Gaussian noise with a 0.5% mean is added to the measured signals, which is essential for actual conditions. As can be seen, the technique has accuracy greater than 90% and can be tested for other systems, such as wind farms. Future studies can include testing for higher fault resistances, as different methodologies test for up to 100 Ω.

The authors of [29] proposed a hybrid fault location technique based on the impedance method and sparse measurements. The process can work in two ways: if the network is observable, it uses the pre-fault recorded information and the measured data; if not, it uses only the recorded micro-PMU data loggers. Similar tests can be modeled when developing a similar fault location algorithm. The authors modeled the IEEE 34-node test system to evaluate the method, considering all fault types and fault resistances from 0 to 100 Ω. The authors use micro-PMUs distributed along the feeder but do not comment on the need for a communication network or the sampling frequency required to measure the current and voltage signals. The DGs considered are photovoltaic, but their generation variation is not evaluated.

Like the impedance methods, Table 5 shows the main aspects of sparse measurement-based fault location methods. It shows that most methods use both current and voltage as input signals. Thus, their measurement must be included when modeling systems with similar approaches. Usually, there are multiple measurement locations requiring a communication channel. Therefore, the viability of these requirements must be previously analyzed before applying a methodology in an actual system. Moreover, some authors do not comment on the sampling frequency required for the technique, an essential characteristic of implementing the algorithms in new systems. Lastly, the FT is the primary tool to extract the phasors used for the fault location.

Table 6 shows that methods based on sparse measurements are usually validated in larger systems, considering transient analysis software. Only two selected papers considered noise in the measurements [27], [28]. It is a critical analysis, as measurements performed in distribution systems usually have white Gaussian noise, which occurs through all signal frequencies [30], [31]. Therefore, it is essential to consider an inherent noise system for a method's real applicability. In addition, the methods were validated with the eleven fault types, mainly with fault impedance between 0 and 100 Ω. Modeling only solid faults (0 Ω), as in [26],

TABLE 5. Aspects about the methodology of fault location methods for overhead distribution systems: methods based on sparse measurements.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[25]	Current/voltage	DGs	Yes	48 kHz	FT
[26]	Current/voltage	Substation, DGs and system nodes	Yes	-	FT
[28]	Voltage	Substation, DGs and system nodes	Not necessarily	16 samples/cycle	FT
[29]	Current/voltage	Substation, DGs and system nodes	Yes	-	-
[27]	Current/voltage	Three-phase end nodes and DGs	Yes	-	-

- Information not mentioned by the authors or test not performed.

TABLE 6. Aspects about the validation tests of fault location methods for overhead distribution systems: methods based on sparse measurements.

Reference	Test System Size (bus)	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[25]	60	PSCAD/ EMTDC	-	11	1-50 Ω	Source	No	1
[26]	37	RTDS	-	11	0	PV[a]	No	1
[28]	134	-	0.5%	11	0.5-10 Ω	IG [c], SG[d] and PV	No	1
[29]	34	Matlab	-	11	0-100 Ω	PV	No	1
[27]	123	Matlab	0.1-1%	11	1-100 Ω	IIDG[b]	No	1

- : Information not mentioned by the authors or test not performed./ [a] PV: Photovoltaic /[b] IIDG: Inverter-Interfaced Distributed Generator /[c] IG: Induction Generator, in this case, from a wind turbine /[d] SG: Synchronous Generator

might hinder real-world applicability. Table 6 also shows that all systems only had one feeder, without considering a protection system, and that many types of DG were evaluated. We highlight using an induction generator by [28], representing a wind generator. In general, this information emphasizes the common aspects required when modeling a system to apply similar approaches, which directly impact the number of measurement devices that need to be added when modeling a test system, including the conditions mentioned.

3) METHODS BASED ON INTELLIGENT ALGORITHMS

Intelligent algorithms, Artificial Intelligence (AI), or ML algorithms can learn and make decisions based on data and past experiences. They can automate complex tasks and adjust their behavior over time, improving their performance as they are exposed to more information. As fault location can be a classification problem, many authors have used intelligent algorithms in their methodologies to locate faults. Therefore, in this section, we select the primary papers with this purpose, always aiming to analyze what characteristics they require when modeling a system to apply the method and the tests necessary to validate the technique.

An example of an AI-based methodology is shown in [32]. The authors proposed an algorithm with different modules, one for classifying power quality events and the other for detecting faults, classifying, and locating. For this, it uses the fuzzy-ARTMAP neural network. The fault location algorithm is tested in a system with 134 buses, with one measurement at the substation and four distributed throughout the system. The input signals are the voltage and current, and the FT is used to extract the phasors from them. The system is modeled using the ATP software via the ATPDraw interface, and faults are simulated with resistances from 10 to 40 Ω. Although promising, the technique requires smart meters with remote terminal units, which are not always present in electrical networks. It also requires previous knowledge of the topology and generation of the system, which can change over time. The test system only contains synchronous generators, so the methods' function with other DG types need to be tested. In conclusion, considering smart meters and including the aspects that the authors neglected is imperative when modeling test systems for similar techniques.

Some methodologies, such as the one published in [33], focus on fault location in DSs with DGs but only consider measurement (in this case, an IED) at the system substation. In this paper, the Pattern Search method provides the location of the fault using the network parameters and DGs' equivalent circuit. The authors evaluated the methodology by modeling a 12-bus (13.8 kV) system and fault resistances from 0 to 50 Ω using ATP. Although using only one measurement is preferable, the method must use detailed models of the feeder line sections, load impedance, and equivalent circuits of the DG for proper functioning, which is not always possible. The tests only consider the DGs as synchronous generators. Thus, analyses with other DG types can be the focus of future work on this approach.

The method proposed by [34] uses artificial immunological systems with few variables to locate the fault. It uses only the three-phase voltage measurement at the substation and the DGs as input signals. The method is evaluated using the IEEE 34-node test system, and the faults were modeled with fault impedances from 5 to 15 Ω, which are lower than most of the other papers analyzed. Although the method works in a system with changing topology, the network only had synchronous generators connected to it. Thus, for real applications, considering other DG types may be necessary. Furthermore, the authors do not mention the sampling frequency or whether it uses a signal processing technique. It is vital information to replicate a methodology and must be included when modeling new tests.

The fault location method proposed in [35] is based on using Micro-PMU in the substation and the DG to perform the voltage spectrum analysis to locate the fault using the Support Vector Machine (SVM) algorithm. An 11-bus test system is modeled using Simulink/Matlab to validate the technique, with 0 to 50 Ω faults in all buses. The voltage signals are acquired at 5 kHz. The main contribution of the method is that it does not require knowledge of the system parameters. However, the downsides are that the authors only used synchronous generators to test the technique and that it requires a communication link, measuring equipment, and wireless sensors, which may increase errors and costs. Considerations such as the DG changing penetration and the system's varying topology and loading can be necessary for future real applications.

The fault location method proposed by [36] uses the Gaussian process regression to find the fault location. For this, the authors modeled in EMTP-RV a 15-node (11 kV) test system with faults ranging from 0 to 100 Ω at various locations. The test system has a synchronous generator and a photovoltaic generator connected via an inverter. The technique presents promising results, even compared to other machine learning-based algorithms. However, the algorithm's input data are measurements by IEDs distributed along the system with a sampling frequency of ten thousand samples per cycle, and there is no methodology to determine the best measurement location. Moreover, although the method is evaluated with different DG penetration levels, it does not consider the system's different topology and loading, which may be necessary to verify the applicability of methodologies that require training.

The method proposed in [37] applies a Swin-Transformer (S-T) network for threshold-free location of single-phase ground (SPG) faults in a 10-kV resonant grounding distribution system composed of overhead and underground lines, and no distributed generation (DG). Simulations are conducted in PSCAD using a five-feeder network with measurements taken at switching nodes. Three-phase voltages and currents are processed to synthesize zero-sequence voltage (ZSV) and current (ZSC), applying Fourier transform-based correction for CT phase errors and DC bias removal. The method relies on RGB images, combining the derivatives of synthesized ZSV and ZSC as inputs to the S-T. Faults with 0 to 10 kΩ resistances are modeled, including high-impedance cases. Despite the protection scheme not being specified, the method performs well under noise (as low as 20 dB), asynchronous sampling, and delayed triggering, and is validated through simulations, full-scale 10-kV lab tests, and field data using COMTRADE files. However, the approach assumes measurements at multiple nodes and shows reduced accuracy with larger sampling offsets. In addition, it has not been tested with DG or dynamic topologies, and its computational complexity and SPG-only focus may limit broader applicability.

In summary, Table 7 shows the main aspects of the methodologies based on intelligent algorithms, aiming at the elements necessary to replicate them. Table 7 reveals that some methods only need voltage signals as input. Moreover, the comparison table highlights that, in addition to using intelligent algorithms, most methods require various measurement spots, which can become expensive and require a communication network. These aspects must be analyzed when implementing an algorithm in real systems. In general, the FT remains the most used signal processing technique to extract the phasor used in the algorithms.

Table 8 shows the aspects regarding the tests to validate the selected fault location methods based on intelligent algorithms. The size of the test system varies considerably among the papers. The software used is Simulink, ATP, and EMTP, which can provide the waveforms, including the transient period. No technique considered noisy input signals diverging from actual measurements [30]. Additionally, most systems only modeled the DGs as synchronous generators, revealing the need to test the algorithms with systems with other generator types. The 11 fault types were modeled, varying the fault resistance between 0 and 100 Ω. Overall, this evaluation highlights that many contributions can still be made regarding intelligent algorithms applied for fault location and that there are many requirements to model the systems to use similar approaches.

4) METHODS BASED ON TRAVELING WAVES

Traditionally applied to the location of transmission line faults, traveling wave theory is applicable in estimating fault distances in distribution systems. It associates fault events with the injection of waves into the power system, propagating through the network and reflecting at various points, including line terminations, feeder connections, and fault locations. These transients have distinct characteristics that determine the location of the fault. Traveling wave methods prioritize high-frequency components unaffected by fault type, incidence angle, resistance, or network parameters such as capacitance and neutral grounding. Based on the importance of these applications, this section evaluates the main aspects of traveling wave-based methods applied for fault location in DSs. Once again, the main goal is to establish the elements that the process requires when modeling a test system to use an algorithm and to establish how comprehensive the tests are to validate the methods when aiming at an actual application.

In addition to proposing a fault location method based on traveling waves in distribution systems, the authors of [38] presented a new approach to determine measurement locations in the system with various criteria. The authors tested the methodology using the IEEE 34-Node test system modeled in ATP, with faults and measurements applied at different nodes, and two synchronous generators connected to the system. The technique is based on acquiring voltage signals at a sampling rate of 1 MHz, synchronized via GPS, followed by the application of the WT using the Daubechies 4 (db4) mother wavelet to extract the wavefronts and estimate travel time. However, the study does not address relevant parameters such as the fault resistance value, the type of DG, or the wave incidence angle. While these factors

TABLE 7. Aspects about the methodology of fault location algorithms for overhead distribution systems: intelligent methods.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[32]	Current/voltage	System Nodes	Yes	128 SPC	FT
[33]	Current/voltage	Substation	No	-	-
[34]	Voltage	Substation and DGs	Yes, synchronized	-	-
[35]	Voltage	Substation and DGs	Yes	5 kHz	FT
[36]	Current/voltage	System Nodes	Yes	10k SPS	-
[37]	Current/voltage	Switching nodes	No	5 kHz	FT

- : Information not mentioned by the authors or test not performed./ SPC: samples per cycle/ SPS: samples per second.

TABLE 8. Aspects about the tests performed to validate fault location methods for overhead distribution systems: intelligent methods.

Reference	Test System Size (bus)	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[32]	134	ATP	-	11	10-40 Ω	SGs	-	1
[33]	12 (radial/meshed)	ATP	-	11	0-50 Ω	SGs	-	1
[34]	34	Simulink	-	11	5-15 Ω	SGs*	-	1
[35]	11	Simulink	-	11	1-50 Ω	SGs	-	1
[36]	15	EMTP	-	11	0-100 Ω	SGs/ IIDG**	Yes, circuit breaker	1
[37]	5	PSCAD	20-50 dB	1	0–10 kΩ	None	-	5

- : Information not mentioned by the authors or test not performed./ * SGs: Synchronous Generators / ** IIDG: Inverter-Interfaced Distributed Generation

may not significantly impact the locator's accuracy under ideal conditions, their consideration is crucial to assess the robustness and practical applicability of the proposed method in real-world operating scenarios.

Another traveling wave-based technique is presented in [39], with the main contribution being the first experimental validation of an electromagnetic time-reversal method through live tests. The authors installed a high-frequency high-voltage (HFHV) transducer at the system substation to acquire current signals at a sampling rate of 500 kHz, with the possibility of post-phase correction up to 4.5 MHz. The test system comprises 40 nodes, including 10 underground cable segments. Fault scenarios were also simulated in EMTP-RV using fault resistances of 0 and 30 Ω. However, the study presents some limitations: the method was not tested in systems with DG and the impact of signal noise was not discussed.

Another example of a fault location method for distribution systems based on traveling waves is presented in [40]. The methodology showed satisfactory performance when tested on two different systems, with 19 and 34 buses, each including two inverter-based DG units. The tests evaluated all fault types with fault resistances ranging from 10 to 100 Ω at various buses, requiring synchronized voltage measurements at the end of each terminal branch. These measurements were assumed to be obtained using Digital Fault Recorders (DFRs) installed at each terminal bus, operating in synchronized pairs to enable fault location. The data acquisition was carried out at a sampling frequency of 5 MHz, which, although high, is typical for traveling wave-based methods. The first level of detail from the wavelet transform was extracted using the Daubechies 3 (db3) mother wavelet. Further studies may be needed to evaluate the method's performance under measurement noise and with other types of DG technologies.

In [41], a different method based on traveling waves is proposed. In contrast to previous approaches, it uses only current measurements to locate the fault. The current signal was decomposed using an improved variational mode decomposition method. Then, kurtosis is estimated, and the ST is calculated based on the optimal modal components. To validate the method, the authors modeled a 14-bus test system with sparse measurements at 10 kHz. The test system has DGs represented as DFIG generators. In addition to being a distinct approach, the authors do not provide information about fault resistance or analyze the method's behavior when the fault characteristics change. Moreover, the study tests did not comprehend noise in the measurements, and there was no methodology to determine where the measures should be placed.

The traveling-wave fault location method proposed by [42] presents one of the most comprehensive validation procedures among the reviewed studies. The authors evaluated the methodology across a range of scenarios, including both transmission and distribution systems, as well as radial and meshed network configurations. The transmission system model includes a wind farm interfaced through a full-size converter, while the distribution network incorporates multiple photovoltaic generation units. The tests account for varying levels of DG penetration. The systems were modeled using EMTP, and fault scenarios included short circuits with fault resistances ranging from 2 to 200 Ω, offering a broader assessment compared to other studies. Voltage measurements were simulated with additive noise (70 dB) and sampled at 10 MHz, with digital fault recorders placed at the end of each branch. The WT was employed for signal processing. A primary challenge in the practical application of this method lies in the requirement for high-sampling-rate measurement data.

In summary, Table 9 reveals the requirements to apply the selected methodologies in other conditions. The methods used voltage or current signals as input. Most algorithms used two-end measurements (requiring communication among devices). The process of [39] is the exception, requiring measurement only at the substation. We highlight the

TABLE 9. Aspects about the methodology of fault location algorithms for overhead distribution systems: traveling wave methods.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[38]	Voltage	System nodes	Yes, synchronized	1 MHz	Wavelet (db4)
[39]	Current	Substation	No	500 kHz - 4.5 MHz	-
[40]	Voltage	Terminal nodes of every lateral	Yes, synchronized	5 MHz	Wavelet (db3)
[41]	Current	Every system bus	Yes	10 kHZ	S-Transform
[42]	Voltage	Terminal nodes of every lateral	Yes, synchronized	10 MHz	Wavelet (db4)

- : Information not mentioned by the authors or test not performed.

TABLE 10. Aspects about the tests performed to validate fault location methods for overhead distribution systems: traveling wave methods.

Reference	Test System Size (bus)	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[38]	34	ATP	-	11	0	SGs[b]	-	1
[39]	41	EMTP	-	3	0-30 Ω	-	-	2
[40]	19/34	EMTP	-	11	10-100 Ω	IIPV[a]	-	1
[41]	14	-	-	11	-	DFIG[c]	-	1
[42]	123	EMTP	Yes, 70 dB	11	3-200 Ω	PV and Wind Generator	-	1

- : Information not mentioned by the authors or test not performed. /[a] IIPV: Inverter-Interfaced Photovoltaic Generator/ [b] SGs: Synchronous Generators / [c] DFIG: Doubly fed induction generator. In this case, it represents wind generators.

need for higher sampling rates to apply traveling wave-based methodologies. The last aspect is that most of the techniques analyzed used WT with the mother wavelet Daubechies 4 (db4) to extract the waves. One exception is [41], which used the Stockwell Transform output matrix as the algorithm metric.

Lastly, Table 10 presents the main aspects regarding the tests performed to validate the selected fault location methods based on traveling waves. There is no consensus on the variation in the test system size, but most authors use EMTP or ATP to model the system. When modeling faults, evaluating all their types and a more comprehensive fault impedance range, as in [42], can be crucial to their use in real networks. Considering only phase-to-ground [39] or solid faults [38] may hinder the algorithm's effectiveness. In addition, the techniques were evaluated in systems with different types of DG, such as synchronous, photovoltaic, and wind generators.

IV. FAULT DIAGNOSIS METHODS IN UNDERGROUND NETWORKS

Diagnosing faults in underground distribution cables is a difficult task. Several factors contribute to these difficulties, such as the significant charging current associated with these cables, variations in cable construction, and their differences due to the various grounding and bonding methods [43]. In addition, most researchers focus only on overhead line fault diagnosis in the literature. Besides, the few papers found during the database survey stage that focus on methodologies for fault diagnosis in underground distribution cables, including those addressing modern technologies like smart grids, lack sufficient modeling details or omit critical parameters necessary for reproducing the results. Consequently, the number of papers published on underground networks is low, drawing attention to their underrepresentation in the state of the art. However, many distributed generation systems, such as wind farms, have an underground part. This section presents an analysis of existing methodologies in the literature for fault diagnosis in underground networks. Analogously, the insights presented for overhead lines, fault detection, and classification are discussed first, then the approaches for fault location methodologies are elaborated.

A. FAULT DETECTION AND CLASSIFICATION METHODS IN UNDERGROUND NETWORKS

This section reviews fault detection and classification methodologies in underground distribution systems.

The work in [44] aimed to monitor and analyze the behavior of the recorded data of incipient faults that lead to failure in underground distribution systems. The system consisted of four feeders fed from the same bus at 230/13.2 kV. The monitoring system comprised an IED per feeder, a substation server, a communication network, a local human-machine interface, and a local data depository. In this case, the IEDs were protective relays, which collected three-phase voltage and current data at a sampling rate of 1920 Hz over ten months, stored in COMTRADE files. One hundred and forty-one incipient faults were monitored in the feeder. This study demonstrated features that could indicate failure-predictive maintenance. It was argued that by analyzing positive and negative current peaks during a fault, polarity is not a significant determining factor for fault initiation. It also showed that faults occurred when voltage was at its peak, while instantaneous peak fault currents were five times the values for RMS load current. Another finding was that conventional protection systems would not detect incipient cable failures of a spike-like nature because their duration was less than half a cycle.

The authors of [45] proposed a method that combines the discrete wavelet transform and the probabilistic neural network for fault classification in underground distribution systems. A 5.8 km underground distribution system with a load of 225 MW, a system frequency of 50 Hz, and a nominal voltage of 115 kV was considered for the tests. Current signals were inputted for SLG, LLG, LL, and three-phase fault simulations with fault resistance of 10 Ω and fault locations ranging from 1 to 5 km at a sampling rate of 200 kHz. Fault signals were generated in ATP / EMTP, while fault analysis was performed in MATLAB/Simulink. The methodology used was shown to be an alternative for fault classification in underground cables with a higher accuracy than neural networks with the radial basis function.

Analogously, in a more recent work, [46] used the same test system as the one used in [45]. The simulation parameters and characteristics were also maintained, as shown in [45]. However, this time, the proposed fault classification method was based on a combination of discrete wavelet transform and fuzzy logic. The applied methodology demonstrated another feasible option for fault classification in underground cable, as it showed an average accuracy of 89.50%. However, in this work, the analysis of noise interference in data collection should be considered.

The authors in [47] focused on an incipient fault detection two-stage methodology based on Cumulative SUM CU-SUM and Adaptive Linear Neuron ADALINE for underground distribution systems. The 20 kV distribution system consisted of four overhead lines and one underground cable, which is the focus of the analysis. Three-phase current signals were used as input data for simulations of multicycle incipient faults, subcycle incipient faults, transient event load changing, and single-line-to-ground faults developed in the EMTPWorks environment. The proposed method presented an alternative for areas affected by background noise as it applied a noise-resistant CU-SUM algorithm. In addition, high performance, accuracy, and high speed precision are other advantages. Although promising, the approach studied did not consider all fault types, such as LLG and LLLG. Another source of future research is the misinterpretation of transient fluctuations in healthy phases that could lead to incorrect fault isolation.

In [48], the authors introduced a fault classification method based on a convolutional neural network for underground distribution systems with distributed generation. The test system was an underground distribution system consisting of three buses, three transformers, two 25 km pi-section lines DL1 and DL2, and a total load of 12 MW integrated with two DG units of 9 MW each. It had three voltage levels at the three buses, one to three, ranging from 66 kV/20 kV in transformer T1 and 400 V/20 kV in transformers T2 and T3. The protection scheme consisted of three relays, one on each system bus. Relay R-1 sampled raw three-phase voltage and current signals at a sampling frequency of 3.84 kHz and a system frequency of 60 Hz. Ten types of three-phase faults were simulated in MATLAB with fault resistance ranging from 0.01 to 100 Ω. One advantage presented was the elimination of data preprocessing, as it only required raw data, improving the method's computational reliability and reducing computational burden. Furthermore, since it applied a 10-fold validation, it is suitable for robust and generalized fault classification with an accuracy of 99.52%. However, offline training of the model was computationally expensive.

The methodology developed in [49] introduced a fault identification method based on a supervised machine learning algorithm applied to communication-free protective relays for a closed-loop distribution system with distributed generation. The test system consisted of 20 buses with a total load of 10 MVA operating at a nominal voltage of 22.9 kV, where two photovoltaic systems were incorporated as DG units. The protection scheme consisted of nine circuit breaker relays, two placed at the substation and the others in the feeders. Three-phase voltage and current signals were sampled in each relay at 64 samples/cycle. Eleven types of three-phase faults were simulated in PSCAD with fault resistance ranging from 0 to 188.5 Ω for low impedance short circuits and 188.6 to 1320 Ω for HIFs. The work's main contribution was using communication-free protective relays featuring Long-Short-Term Memory (LSTM) networks to improve cybersecurity and protection selectivity by removing the dependency on optical communication networks and protection settings. Each protective relay can determine whether to trip and classify the fault using this method. Besides, it also promoted a reduction in the cost of the communication system. The precision of the protection system under different operating conditions was significantly high for fault protection and fault classification, above 96% and 93%, respectively. Furthermore, it was also influential in the diagnosis of HIFs. However, the study did not consider noisy data, which could affect the accuracy of the fault diagnosis.

The authors of [50] presented a mathematical analysis and modeling of three-phase open circuit and SLG faults based on the Fast Fourier Transform (FFT) for an underground cable system of a distribution network. The test system had a 20 km underground cable network operating at a nominal voltage of 11 kV. Three-phase voltage and current signals were input data and processed through FFT. Considering four underground system cables, SLG faults were simulated in MATLAB/Simulink. The method demonstrated that faults significantly affected underground cables, and using distortion sensors for voltages and currents could lead to earlier fault detection. In addition, it also showed the need to select three-wave cycles (before, during, and past fault timing) for proper fault detection. However, this work does not assess the impact of noisy data or detail the communication network and specification of the measuring equipment. Furthermore, more research is needed to evaluate the method's performance with other fault situations since it only considers SLG faults.

The work of [51] focuses on detecting incipient faults in underground medium-voltage cable systems using time–frequency analysis of grounding wire currents (GWCs). The system operates at 10 kV with low-resistance grounding and includes inverter-based DGs. A multi-conductor field-circuit equivalent model is developed, considering electromagnetic coupling and arc dynamics based on the

Cassie model. Using a transient equivalent circuit, the method extracts 250 Hz components from the GWC to distinguish short-cycle and multi-cycle incipient faults without synchronization. The test network includes 12 underground cable feeders modeled in PSCAD/EMTDC, with faults simulated across various distances and time-varying resistances (1 to 10 Ω). The model demonstrates robustness against fault conditions, DG penetration levels, and environmental noise, with detection accuracy above 99% in both simulations and field tests. However, the accuracy of arc modeling decreases in systems with different grounding modes, such as ungrounded or arc-suppression coil grounding, suggesting that further refinement is needed in such scenarios.

Tables 11 and 12 summarize the studies analyzed in this section, highlighting their main characteristics. These methodologies offer valuable information about fault detection and classification in underground distribution systems. Table 11 shows that the signal processing technique is based on FFT or WT. Furthermore, most studies require current and voltage data, while the sampling frequency varies over a broader range. Table 12 shows that MATLAB and ATP software are used as simulation tools. However, the display of the test system and simulation parameters is not standardized in the literature. Another drawback found in this review is the absence of noise interference analysis, which underscores the need for further research to enhance the reliability and applicability of these methods in practical underground network scenarios.

B. FAULT LOCATION METHODS IN UNDERGROUND NETWORKS

As mentioned above, few papers have been published on fault diagnosis in underground networks. Therefore, this section presents a bibliographic review of the primary fault location methods applied in underground distribution systems. As there are only a few papers, they were not separated according to the methodology as done for the overhead line procedures.

The first approach selected was [52]. The authors presented a method for locating faults in hybrid transmission lines: overhead lines that contain underground cables in a part of the system. Although applied to transmission systems, it can be helpful, as most IIDGs, such as wind parks also have hybrid lines. The methodology is based on voltage measurements at only one end of the line measured with 200 kHz. The traveling wave time was obtained by statistical calculations of the TT transform and the ST response matrix. The system was simulated in EMTP, and the authors modeled 11 types of faults with various inception angles and resistances ranging from 0.5 to 100 Ω.

Regarding medium-voltage underground networks, the authors of [43] presented the first steps in locating faults in a system without side branches. The method is based on the measured impedance, and the location is obtained by measuring the voltage signal with only 1600 Hz at one end of the line and extracting the fundamental phasor using FT. To validate the approach, the authors modeled an 11-bus test system (11 kV) in Simulink, simulating SLG faults at its nodes with impedance ranging from 0 to 120 Ω. The method requires the system configuration and cable line parameters to work. Adding the presence of distributed generators, noise in the measurements, and side branches may be necessary for practical applications.

A different approach is shown in [53]. It uses intelligent methods to locate different types of faults in underground systems. The fault types considered are high-impedance ground faults, ungrounded series, and ungrounded and ground shunt faults. The method measures voltage and current signals, calculates the WT with the mother wavelet db4 to the 8^{th} level of detail, and then extracts statistics from it. These statistics are input for an ANN and a Fuzzy Logic System (FLS). The ANN and FLS results are compared to verify which produces the best results. The authors used EMTP to model a 14-bus (20 kV) system without and with a DG to test the method. Short-circuit faults are modeled with fault resistances ranging from 0 to 10 Ω. The technique offers potential solutions for faults in underground cable systems. For practical applications, it may be tested in the presence of noisy signals and other types of DG.

Another method based on impedance is proposed by [54], aiming to detect and locate incipient faults in underground distribution systems. The method is based on first calculating the voltage at the fault location and the Total Harmonic Distortion (THD) for all possible fault distance values. The signals are measured only at the substation with a sampling frequency of 10 kHz, and the FT is used to calculate the THD. To test the method, the authors modeled a 13-bus (20 kV) underground test system in PSCAD, with fault resistances ranging from 0.1 to 40 Ω. The technique's main advantages are considering signals with no noise, 60 and 50 dB, and using only one measurement location. The method requires the system configuration and parameters, and predetermines an arc model to locate arc faults. However, arcing faults have some random characteristics due to the electric arc, and using its model in the fault location method may compromise the results under actual conditions. Moreover, future studies can aim to analyze the strategies in systems with other types of DGs.

There are also methodologies to locate faults in underground networks based on sparse measurements. The method proposed by [55] uses sparse measurements along underground systems (in this case, a 12-bus network) to locate the fault. The paper presents the communication channel characteristics between the relays, considering the GOOSE (Generic Object-Oriented Substation Events) message exchange. In this approach, the relay sends messages to its central processing unit, which can be either a protective relay or a separate industrial computer. However, the authors did not specify the sampling frequency for measuring voltage and current signals or evaluate the influence of noise on them. They considered a DG in the system but did not specify

TABLE 11. Aspects about the methodology of fault detection and classification methods for underground distribution systems.

Reference	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[44]	Current/ Voltage	Substation	Yes	1920 Hz	FFT
[45]	Current	-	-	200 kHz	Wavelet Transform
[46]	Current	-	-	200 kHz	Wavelet Transform
[47]	Current	-	-	4 kHz	FT
[48]	Current/ Voltage	Bus 1 - Relay	Yes	3.84 kHz	-
[49]	Current/ Voltage	Substation/ System sections	Yes	64 samples/ cycle	FFT
[50]	Current/ Voltage	Substation	-	-	FFT
[51]	Current	Cable ends	No	3.2 kHz	Short-Time FT

- : Information not mentioned by the authors or test not performed.

TABLE 12. Aspects about the tests performed to validate fault detection and classification methods for underground distribution systems.

Reference	Test System Size (bus)	Voltage Level	Software	Noise	Fault Types	Fault Resistance	Number of Feeders
[44]	1	13.2 kV	-	No	11	-	4
[45]	1	115 kV	ATP/ MATLAB	No	4	10 Ω	-
[46]	1	115 kV	ATP/ MATLAB	No	4	10 Ω	-
[47]	1	20 kV	EMTPWorks	No	5	-	-
[48]	3	0.4, 20, 66 kV	Simulink	No	10	0.01 to 100 Ω	-
[49]	20	22.9 kV	PSCAD	No	11	0 to 1320 Ω	7
[50]	1	11 kV	Simulink	No	1	-	-
[51]	12	10 kV	PSCAD/ EMTDC	Yes	2	1–10 Ω	12

- : Information not mentioned by the authors or test not performed.

its type. They also did not comment on the impedance or type of the fault. Providing these pieces of information can be essential for applying the method in other networks.

In [56], the authors proposed a method that uses traveling waves to detect, classify, and locate faults in underground distribution systems. This method not only diagnoses faults but also optimizes relay coordination. The fault location technique is based on traveling waves measured from two terminals. The authors modeled an 11-bus test system (20 kV) using Matlab/Simulink, with various measurements taken from its nodes to validate the method. Although the approach has numerous advantages, it should be noted that the test system does not include a DG, the measurement noise was not evaluated, and the authors did not comment on the fault resistance.

Table 13 summarizes the main characteristics of fault location methods for underground networks. It shows that most methods use current and voltage measurements as input. It is important to note that approaches that require more than one measurement need communication channels, which must be considered when implementing a technique. Moreover, traveling wave methods require a higher sampling frequency than the other methods, and their availability must be previously acknowledged. Lastly, the authors use different signal processing techniques to extract the metrics to locate the fault, such as the Time-Time, Stockwell, Fourier, and Wavelet Transforms. These techniques and their computational cost can be evaluated before implementing a method to solve a problem.

As in the other parts of this study, a table was developed on the technical aspects of the tests performed to validate the methodologies. Table 14 reveals that the test systems modeled to evaluate fault location methods in underground systems are usually short (less than 16 buses) with one feeder, disregarding the network protection system. The algorithms are evaluated in scenarios using transient analysis software. However, the noise in the measurements is not included in the tests, except for [54], which considers noise of 50 and 60 dB, the average noise in power distribution systems [30], [31]. The fault modeling is another concern, as there is no consensus on the fault impedance. Some techniques only modeled one phase to ground faults [43], [55]. Only solid faults (0 Ω) [55], [56] were developed, which may not always be accurate in actual conditions. Lastly, Table 14 reveals that the solutions that considered DGs in the test system only modeled them as current sources, which do not represent all of their characteristics. Therefore, further analysis must be developed to find a fault location solution that comprehends all the conditions under which an underground system can be subjected. Consequently, these conditions must be included when modeling an approach to develop new fault diagnosis algorithms.

V. INSIGHTS ON STATE-OF-THE-ART SHORTCOMINGS AND RECOMMENDATIONS FOR ANALYSIS AND DEVELOPMENT OF FAULT DIAGNOSIS METHODS APPLIED TO DISTRIBUTION SYSTEMS

Once the critical literature review of the aspects required by fault diagnosis methods in distribution systems was carried out, the limitations identified in the state-of-the-art are:

- Limited evaluation of the noise interference in the method performance: The analysis of noise's influence on the investigated methods' performance is often neglected. This condition tends to compromise the validation processes of fault diagnosis methods since the measured signals are superimposed with noise of

TABLE 13. **Aspects about the methodology of fault location algorithms for underground distribution systems.**

Reference	Methodology	Electrical Quantity	Measurement Location	Communication?	Sampling Frequency	Processing Technique
[43]	Impedance	Voltage/ Current	Substation	No	1600 Hz	FT
[53]	Intelligent Techniques	Voltage/ Current	Substation	No	256 samples/cycle	Wavelet (db4)
[54]	Impedance	Voltage/ Current	Substation	No	10 kHz	FT
[55]	Sparse Measurement	Voltage/ Current	System Nodes	Yes	-	FT
[52]	Traveling wave	Voltage	Substation	No	200 kHz	TT and S Transforms
[56]	Traveling wave	Current	System Nodes	Yes	4096 samples/cycle	Wavelet (db4)

- : Information not mentioned by the authors or test not performed.

TABLE 14. **Aspects about the tests performed to validate fault location methods for underground distribution systems.**

Reference	Test System Size (bus)	Software	Noise	Fault Types	Fault Resistance	DG Type	System Protection	Number of Feeders
[43]	11	Simulink	-	3	0-120 Ω	-	-	1
[53]	14	EMTP	-	11	0-10 Ω	DG*	-	1
[54]	13	PSCAD	50/60 dB	-	0.1-40 Ω	-	-	1
[55]	12	-	-	1	0	DG**	-	1
[52]	2	EMTP	-	11	0.5-100 Ω	-	-	1
[56]	16	Simulink	-	11	0	-	-	1

- : Information not mentioned by the authors or not performed the test./ *: The DG was modeled by a source/ **: The DG model was not specified.

different levels in real-world conditions. Furthermore, a few studies that consider noise in signals show its potential impact on the accuracy of the methods.

- Limited investigations regarding the impact of DGs and actual operating conditions: Although some studies in the literature considered the influence of DGs on the performance of the fault diagnosis methods, it was also noted that only particular types of DG are assessed. In other words, most studies do not consider the diversity of existing controls and topologies for DGs [5], [57], making the analysis incomplete. Moreover, actual operating conditions that include load level variations or even topological changes are almost always neglected, which tends to compromise the application of the techniques in practical scenarios, especially in distribution systems where such variations are common.
- Lack of standardization concerning the fault parameters adopted to validate the methodologies: Most papers have an apparent discrepancy concerning the fault parameters used to validate the proposed methods. Many studies focus only on specific fault types (only single-phase or three-phase faults, for example), others only on bolted faults, and some with excessively high or limited values for fault resistances. These issues make it difficult to compare the performance of different fault diagnosis methodologies directly, since these parameters directly impact their results.
- Limited explanation of the computational and technical complexity required to apply the proposed methodologies in practical scenarios: The practical implementation bias of the proposed approaches is often overlooked. For instance, methods based on convolutional neural networks or even LSTM algorithms barely discuss the high computational cost and extensive training that such approaches require. Proposals based on multiple measurement points, assuming synchronized measurement at the different points, often ignore that installing GPS or even the structure required for communication between different measurement points can be costly and, in practical cases with limited resources, unfeasible.

In this context, based on the insights regarding the literature shortcomings, recommendations are outlined below to support the analysis and development of new fault diagnosis solutions applied to distribution systems:

- Analyze noise interference in the methods' performance: Consider detailed studies on noise interference in the proposed fault diagnosis methods. In addition to revealing the robustness of the methodologies when applied to actual systems, these analyses can enable the integration or improvement of techniques that reduce noise levels in the measurement data [58]. Typically, such analyses in the context of electrical systems use Gaussian white noise with Signal-to-Noise-Ratio (SNR) varying between 40 and 60 dB [30], [31].
- Evaluate the impact of DGs and actual operating conditions more comprehensively: investigate the impact of different controls and DG topologies on the fault diagnosis proposal's performance. These should include synchronous and inverter-based DGs, considering the main inverter-based generator topologies (Full-Converter and Doubly-Fed Induction Generators, for example, [57]) and also the different control strategies for these units [59]. Furthermore, it is essential to consider typical operating conditions in distribution systems, including load variations and, especially, system topology variations, to ensure the applicability of the developed techniques to different system configurations.
- Investigate practical fault parameters for the proposed algorithms' performance analyses: Establish practical values for performance analyses, mainly for the fault

resistances considered but also encompassing all the main fault types. In the case of distribution systems, resistances of up to approximately 50 ohms are generally evaluated, except for high-impedance faults, which is a separate study topic [60]. Regarding fault types, including single-phase, two-phase ground, and three-phase faults, it is necessary to map the influences of this variation on the methods' performance. These recommendations are intended to help validate the methodologies' generalization capacity for diagnosing faults in distribution systems.
- Consider the practical issues of applying the proposed methods in real-world situations: prioritize strategies that balance precision and complexity to maximize their practical applications. This balance involves the computational complexity required by the methods and the structural complexity required, including the measurement, synchronization, and communication requirements. Furthermore, periodic comparisons are essential to obtain a snapshot of advances in, for instance, intelligent methods or even advanced measurement and communication technologies, guaranteeing that the proposal of new fault diagnosis methods is aligned with improvements in structural and computational processing areas.

VI. CONCLUSION

This study's review of fault diagnosis methods highlights that accurate modeling is the cornerstone of effective fault detection, classification, and location in distribution systems. It also reveals the diversity of available approaches and their respective strengths and limitations. Each stage of the diagnostic process places unique demands on the system model, necessitating a balance between model complexity and practical implementation feasibility.

The findings encourage that, mainly for fault detection, effective models account for noise, DG integration, and operational variations to minimize incorrect or non-operation of the protection and fault diagnosis systems. Although impedance-based methods offer simplicity and lower infrastructure requirements, their susceptibility to noise and DG impacts underscores the need for more resilient models that accurately reflect the network's dynamic behavior. However, techniques based on intelligent algorithms, such as convolutional neural networks and machine learning systems, have shown promising results in accuracy and adaptability, especially in complex systems involving multiple DG types. However, these approaches require substantial computational resources and robust communication infrastructure to support real-time data processing and synchronization.

In fault classification, the focus shifts to capturing the specific electrical signatures of different fault types. Accurate classification is based on high-quality models with detailed electrical parameters such as fault impedance, phase angles, and load characteristics. WT and artificial intelligence methods require precise modeling to differentiate between similar fault types under varied conditions. The presence of DG further complicates the classification, as it introduces additional variables that must be considered in the model.

Fault location methods are highly dependent on the fidelity of the system model, mainly when using advanced techniques like traveling-wave-based localization. These methods require high-resolution models that incorporate accurate line parameters, measurement synchronization, and the effects of DGs. The practical challenges of implementing these models include the need for high-frequency data sampling and robust communication infrastructure, which can be costly and technically challenging in large-scale systems.

Finally, insights and recommendations on the modeling frameworks used for fault diagnosis were provided, allowing their adaptability to modern distribution networks' diverse and dynamic nature. Standardizing validation tests and incorporating real-world conditions, such as noise, DG variability, and system reconfiguration, into the modeling process will enhance the applicability of these diagnostic methods. Moreover, exploring hybrid approaches that combine the strengths of various techniques can lead to robust and computationally efficient models. The modeling challenges and gaps identified throughout the analysis will serve as the foundation for future methodological advancements. Subsequent research can build upon these findings to design and validate new diagnostic approaches that address the practical issues and needs of power distribution systems identified in this work.

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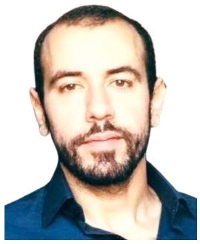
TALITA M. O. A. CUNHA received the B.Sc. degree in energy engineering from the Federal University of Grande Dourados (UFGD), Brazil, in 2017, and the M.Sc. degree in mechanical engineering from the State University of Maringá (UEM), Brazil, in 2020. She is currently pursuing the Ph.D. degree with the University of São Paulo (EESC-USP), with research in wide-area monitoring and fault diagnosis in wind farms. Besides, she is an Electrotechnical Technician at UFGD. During the undergraduate program, she participated in an exchange program at the University of Exeter, U.K., from 2014 to 2015. Her areas of research interests include energy efficiency, renewable energy systems, wide area monitoring and protection, and power quality.

GABRIELA N. LOPES received the B.Sc. degree in electrical engineering from the Federal University of Mato Grosso, Cuiabá, Brazil, in 2018, and the M.Sc. and Ph.D. degrees from EESC, University of São Paulo (USP), Brazil, in 2020 and 2024, respectively. Her areas of research interests include high impedance faults, signal processing, power system protection, and power quality.



LEONARDO S. LESSA received the bachelor's degree in electrical engineering from the Faculty of Engineering of Ilha Solteira (FEIS), São Paulo State University (UNESP), in 2017, and the master's degree in electrical engineering from the Faculty of Engineering of São João da Boa Vista (FESJ), UNESP, in 2020. He is currently pursuing the Ph.D. degree with São Carlos School of Engineering (EESC), University of São Paulo (USP). His main research interests include electromagnetic transients, fault location, system modeling, and intelligent algorithms applied to distribution systems with distributed generation.

MOISÉS J. B. B. DAVI received the B.Sc. degree in electrical engineering and the M.Sc. degree in technological innovation from the Federal University of Triângulo Mineiro, in 2014 and 2021, respectively, and the Ph.D. degree in electrical engineering from São Carlos School of Engineering (EESC), University of São Paulo (USP), Brazil, in 2025. He has extensive experience in power system protection, IED commissioning, electromagnetic transient simulation and analysis, and oscillography interpretation. His research interests include protective relaying, power system transients, advanced power system modeling, fault location techniques, and the control and protection of renewable energy systems.

MÁRIO OLESKOVICZ (Member, IEEE) received the degree in electrical engineering from the Federal University of Santa Catarina (UFSC), Brazil, in 1995, and the M.Sc. and Ph.D. degrees in electrical engineering from São Carlos Engineering School (EESC), University of São Paulo (USP), Brazil, in 1997 and 2001, respectively. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering (EESC/USP). He works in the electrical engineering area, focusing on power systems (generation, transmission, distribution, and microgrids), power quality, and power system digital protection.

JOSÉ C. M. VIEIRA (Member, IEEE) received the degree in electrical engineering–electrotechnics emphasis from the Federal University of Uberlândia, in 1996, the master's degree in electrical engineering from the State University of Campinas, in 1999, and the Ph.D. degree in electrical engineering from the State University of Campinas, in 2006. Since October 2007, he has been an Assistant Professor at the Department of Electrical and Computer Engineering, School of Engineering of São Carlos, University of São Paulo. He has experience in electrical engineering, with an emphasis on power systems and has worked mainly on the following topics: distributed generation, electrical system protection, electric power distribution, and high-voltage direct current (HVDC) transmission systems.

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