A Comparison Framework for Distribution System Outage and Fault Location Methods

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Abstract—Finding the location of faults in distribution networks has been a long standing problem for utility operators, and an interesting subject for researchers as well. In recent years, significant research efforts have been devoted to the development of methods for identification of the faulted area to assist utility operators in expediting service restoration, and consequently reducing outage time and relevant costs. Considering today's wide variety of distribution systems, a solution preferred for a specific system might be impractical for another one. This paper provides a comparison framework which classifies and reviews a relatively large number of different fault location and outage area location methods to serve as a guide to power system engineers and researchers to choose the best option based on their existing system and requirements. It also supports investigations on the challenging and unsolved problems to realize the fields of future studies and improvements. For each class of methods, a short description of the main idea and methodology is presented. Then, all the methods are discussed in detail presenting the key points, advantages, limitations, and requirements.

Keywords: Distribution networks; distributed generation; fault location; outage location; outage management.

1. Introduction

As the final stage of the delivery of electric power, European distribution companies supply 260 million customers of which 99% are residential customers and small businesses [1]. In contrast to their transmission counterparts, distribution networks are made up of branches and tapped laterals delivering electricity to the ultimate point of consumption. Dispersing over vast rural and urban areas, these branched networks are vulnerable to different types of faults initiated by different sources such as adverse weather conditions, bird contacts, vegetation growth and equipment failure [2]. Considering the fact that approximately 80% of all customer interruptions occur due to distribution faults [3], it is essential for every distribution system to efficiently manage the faults, and maintain the quality of service through minimizing the outage time.

These days, the quality of service has emerged as an important issue for residential, commercial and industrial customers, as many functions of modern society depend on electricity. The number and duration of interruptions in European networks are generally low, ranging from about 15 minutes to 400 minutes per customer per year [1]; however, a higher performance is both possible and needed. Finding the most affordable and efficient way to enhance the performance of distribution systems is a major concern, and electricity regulators have made considerable efforts to address the issue.

The performance of a network primarily depends on how it is designed and how it performs when a fault occurs. To improve its performance we can either use underground cables instead of overhead lines or replace bare conductors with insulated conductors. We can, moreover, reduce the fault rate by preventative maintenance such as tree trimming or improve network performance following a fault by adding automatic in-line protection and continuous alternative supply. However, in this manner, the improvement to a service quality level is costly. An alternative more cost saving solution would be exploiting better fault management schemes to minimize the outage times.

In a conventional outage management system, upon the occurrence of a fault and subsequent operation of the protection system, outage mapping is carried out. This is traditionally based on activities such as grouping of customer outage calls to determine the protective devices involved in fault clearing in order to find the outage area. Then, a repair crew has to be sent to patrol the area and walk along the power distribution lines, which can be kilometres, in order to find fault evidence and to ensure safety prior to re-energizing the system. The whole restoration process may take from tens of minutes to hours. In contrast, better measurement and switching infrastructure in today's distribution networks provides the possibility of enhanced fault management schemes [4]. In these systems, having a good estimation of the faulted area narrows down the search space and minimizes the required effort and patrolling time to find the fault. Moreover, it provides the possibility of fast service restoration for the interrupted customers connected to the healthy sections. Therefore, considerable studies have been devoted to the development of methods to locate the faulted area and consequently reduce the average outage time and improve the quality of supply.

There are different distribution system operators (more than 2400 companies in case of Europe [1]) having different policies and development philosophies. Accordingly, there are a wide variety of distribution systems in use today, and a method which is the preferred solution for a specific system might be impractical for another one. This article classifies, compares and reviews a relatively large number of works devoted to the fault and outage area location subject [5-73], and aims to serve as a guide to power system engineers and researchers. The requirements, advantages, and limitations of different methods are presented and compared to help power system engineers, and researchers to select the most appropriate method based on their distribution system and requirements.

In Section 2, we classify different algorithms based on their outputs and required inputs. Section 3 reviews and compares different outage area location methods, while fault location methods are discussed in Section 4 where the details of different classes are presented in different subsections. Section 4 presents the future trends and conclusions are given in the last sections.

2. Classification of Outage and fault location algorithms

When a short circuit fault occurs, protective devices automatically isolate the faulted area from the rest of the electrical network. However, it is usually hard to realize the interrupted portions of the network and the faulted components. Several studies have been carried out on the subject. As illustrated in Fig. 1, the proposed methods can be considered as algorithms which employ the available inputs (i.e. data, measurements) to make an estimation of the output which is the affected area. In terms of their outputs, the studies can be categorized into two main groups. The first group, known as outage area location methods, includes techniques using various available data sources such as customer outage calls or fault indicator signals to estimate the most likely interrupted area [5-16]. The second group of methods utilizes data and measurements to locate the fault which caused the resulting outage [17-73]. Sometimes, outage area location is performed prior to fault location to improve its accuracy.

As shown in Fig. 1, the inputs can be classified into four groups. The non-electrical data comprises customer calls complaining about the outages, experts' knowledge, historical data about the previously experienced events, and weather data such as typhoon information and satellite images. On the other hand, electrical data includes smart meters "last gasp" messages notifying an outage occurrence, data gathered by Supervisory Control and Data Acquisition (SCADA) system such as switches status, fault indication signals, and fault evidence. Network data encompass estimated or measured values of distribution system loads, the type of the overhead or underground conductors in terms of their impedance and capacitance, the length of lines, network topology, and installed devices such as protection components.

In traditional distribution systems, substation voltage and current are the only available measurements mostly having a sampling frequency of 0.4 to 6.4 kHz. However, implementation of some fault location methods, such as travelling waves-based methods, requires measurements with more than 100 KHz sampling rates. Considering the recent advances in metering and communication systems, it is now possible to collect the sparse values measured by instruments such as power quality meters and digital fault recorders installed throughout the network. Moreover, it is possible to synchronize the measured values using the Global Positioning System (GPS) or computer networks. For each distribution system, a certain set of inputs can be provided giving a qualitative criterion for selecting an appropriate method. For example, in modern distribution networks with advanced measurement and communication infrastructure, methods that have the ability to use the emerging equipment to provide better results in terms of accuracy and reliability, would be the preferred solutions; while the same methods would be impractical for traditional systems. Therefore, the required input data is an important criterion which differentiates fault and outage area location methods and determines their practicality for a certain distribution network.

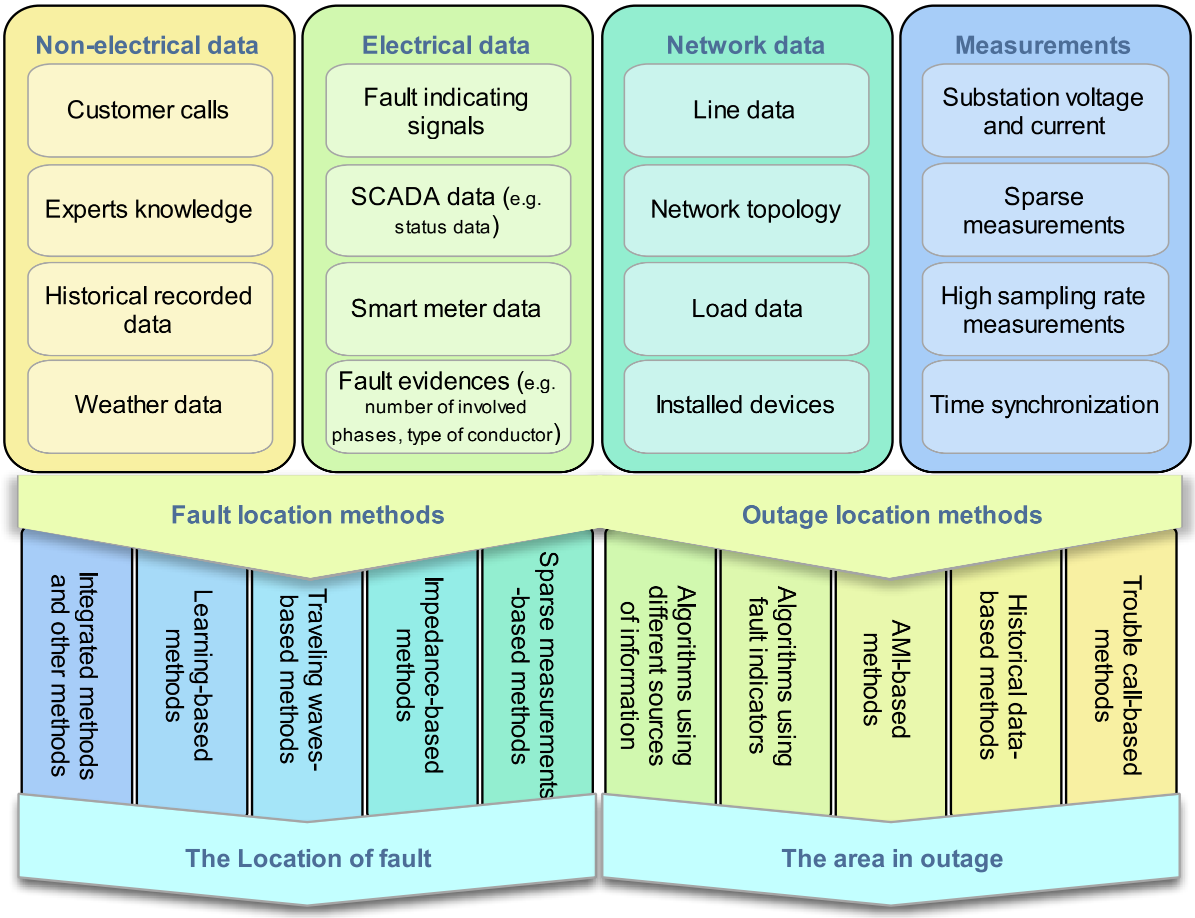

Fig. 1. Inputs and outputs for different classes of fault and outage area location methods

Hereinafter, different fault and outage area location methods are classified based on their inputs and their main idea. A number of proposed methods in each class are reviewed, and for each work, the key points, pros, and cons are presented to support power system engineers and researchers to choose the most appropriate method based on their distribution system and requirements.

3. Comparison of outage area location methods

Outages are mainly caused by permanent short circuit faults. In radially operated distribution networks, when a permanent short circuit fault occurs, protective devices close to the fault automatically isolate the faulted area and customers downstream of the protective device will experience an outage. The outage area is usually unknown and outage area location algorithms aim to identify it. Based on the required inputs and their main idea, the proposed methods to locate the outage area can be classified to trouble call-based methods [5-7], historical data-based methods [8,9], algorithms using fault indicators [10,11], methods based on Advanced Metering Infrastructure (AMI) in modern distribution networks [12,13], and algorithms using a combination of different sources of information [14-16].

In conventional distribution systems, operators' reaction to localize outages mostly depends on trouble calls, made by the customers whose electricity service is interrupted. Utilities usually have a list of all customers along with their telephone numbers and geographical locations. By matching the information obtained from a sufficient number of calls along with feeder configuration diagrams and maps, operators try to determine the upstream transformer from which the customers are served, the protective devices involved in fault clearing and the outage area.

During the process, personnel have to manage a significant number of customer calls requesting their lights back on. In [5], the Interactive Voice Response (IVR) system is offered as a solution to receive a high volume of data in a more efficient and economical way. In addition to IVR system, there are some algorithms developed to reduce the time and effort required for call management. For example, artificial neural networks are used in [6] for fast pattern recognition and classification of trouble calls. In [7], the authors propose a rule-based expert system to emulate the behaviour of an experienced operator managing received calls and locating the outage areas. Methods based on the trouble calls, regardless of the employed techniques, have the following disadvantages:

- For faults occurring during the night-time, there would be a little number of customer calls which makes the outage location process either difficult or impossible;
- False or fake reports are hard to realize;
- The whole process is time-consuming.

However, because of its conceptual simplicity and practical feasibility, the trouble call-based outage area location methods are the ones most commonly used.

The methods proposed in [8,9] rely on the historical recorded data, including the faulted equipment (e.g., transformer), and causes (e.g., fire alarm). In [8], the authors use the historical data and rough set theory as a data-mining tool to derive useful patterns, and rules to relate the faulted element with the observations during feeder outages and the surrounding environments. The method proposed in [9] uses experts' knowledge and historical data to construct a Bayesian network which imitates the causal relationships between the faulted equipment and the evidence. After being developed, the Bayesian network can be employed to realize the possible faulted devices based on the observations during feeder outages, and help to find the outage area. The historical data-based methods can employ any sources of evidence to enhance their performance; however, they require an extensive amount of recorded fault scenarios for years, which would not be available, especially for the recently developed networks.

Deployment of fault indicators is another alternative solution which has attracted attentions, especially during the past two decades. Fault indicator is a device which can be located at some convenient point to give a visual (e.g. mechanical flag, LED lamp) or remote identification of faults. The fault area can be easily located by visual or remote inspection of fault indicators status as illustrated in Fig. 2. In a large-scale distribution network, installation of fault indicators would be a great help to quickly find the fault; however, it is not economical to install a fault indicator at each line segment. In [10], the authors propose a method for optimal placement to reduce the required number of indicators and customer interruption cost in the same time. When the optimal number and location of the fault indicators are obtained, methods such as the proposed techniques in [11,14], can be employed to analyse the reported statuses and locate the outage area. In [74], the authors discuss the reliability and economic benefits of installation of fault indicators in a distribution network, and they show how a limited number of such indicators can help utilities to reduce outage duration and improve service reliability. The main problem of using fault indicators is its required investment. However, as described in [75], the decrease in outage costs (e.g. cost of unserved energy) usually justifies the required installation investments.

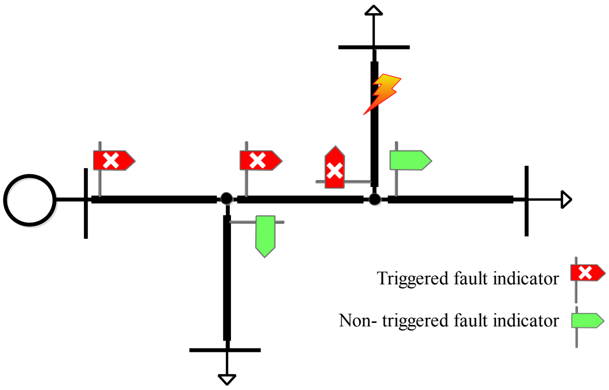

Fig. 2. Faulted area detection using fault indicators

There are a wide variety of fault indicators in use. They provide either earth fault indication or phase fault indication or both. Some are suitable for overhead systems, whereas others are designed for underground networks. There are also some indicators suitable for compensated neutral systems. For closed loop networks or when Distributed Generators (DGs) are connected to the network, directional fault indicators are required to correctly locate the faulted line section. They indicate whether the detected fault is in the upstream direction or the downstream direction. In [76], the authors describe different types of fault indicators and discuss the related issues.

In modern distribution networks, AMI for processing smart meter data, or the earlier version, Automated Meter Reading (AMR) system, gives remote access to the utilities to read consumer consumption records, check alarms, and observe meters status remotely and provides a new source of information for outage area location [12,77]. By meters “last gasp” messages or periodic polling via the AMI system, it is possible to detect a sustained outage and estimate the most likely area of fault. The overall procedure is similar to the trouble call-based methods; however, the benefit of last gasp messages is that the operators do not need to wait for a sufficient number of customer calls to locate the outage areas. Moreover, the predicted outage location can be verified using the on-demand read capability of smart meters.

In [12], the authors discuss the technical and operational considerations of an AMI-based outage area location system. The most common concerns would be the time latency and reliability of last gasp messages. Moreover, outage data gathered from the meters, due to its low quality, cannot be directly fed into the outage management systems. Addressing this issue, the authors of [13] propose a filtering method to prevent false outage notifications, and to improve the quality of outage data. The filtered outage data can be utilized in combination with customer calls to provide a more reliable and more efficient estimation of the outage area.

There are also some outage area location methods trying to integrate different possible inputs to find the best result. In [14], the authors propose a method for medium-voltage faulted line sections identification using fault indicators and another method for faulted area location in low-voltage distribution systems using the customer electric information acquisition system and the trouble calls. The method proposed in [15] employs multiple sources of information such as customer trouble calls, automated meter reading system, and distribution system SCADA and combines the gathered data to locate outages. The method proposed in [16] follows a similar procedure but it first uses the fuzzy logic to filter wrong outage notifications from the provided outage data. The output of the fuzzy filter, which includes a reduced and more accurate amount of outage data, is then employed to locate the outage area. Finally, the outage area is confirmed using the on-demand read capability of smart meters. Applying these methods has its own advantages, especially not relying on a certain source of data; however, the requirement of several different inputs limits the practical application. Table 1, compares different classes of outage area location methods in terms of their requirements, advantages and limitations.

Table 1. Comparison of the reviewed outage area location methods

Method	Requirements	Advantages	Limitations
Trouble call-based methods [5-7]	• Customer calls • Network topology • Experts knowledge	• Practicality • Simplicity • No extra installation cost	• Time-consuming • Requiring a sufficient number of calls
Historical data-based methods [8,9]	• Historical data • Weather data • Network topology • Experts knowledge • Fault evidences	• Can use any source of recorded information • No extra installation cost	• Requiring an extensive amount of recorded data
Algorithms using fault indicators [10,11]	• Fault indication signals • Network topology	• Reliability of results • Practicality • Simplicity	• Cost of deployment
AMI-based methods [12,13]	• Smart meters data • Network topology	• Reliability of results • Practicality (if smart meters are already installed)	• Requiring a large number of deployed smart meters • Latency or reliability of smart meter messages
Algorithms using different sources of information [14-16]	• Customer calls • Smart meters data • Network topology • SCADA data	• Not relying on a certain source of data	• Requiring different inputs

4. Comparison of fault location methods

While the outage area location methods are employed to find the status of the protective devices and consequently the outage area, fault location methods aim to locate the permanent faults which caused the resulting outage. Fault location methods can also be applied to non-permanent faults. Approximately 75-90% of distribution network faults are temporary in nature [3]. Identification of their location provides the possibility of making remedial actions to avoid future sustained interruptions, and hence further improves the reliability by infrastructure enhancement.

There are a wide variety of methods currently employed to locate transmission network faults (e.g. [78,79]). However, fault location in distribution networks faces new problems compared with the same task in transmission lines. Transmission lines are mostly equipped with dedicated protections, measurement devices and fault locators. In contrast, distribution networks usually have laterals and load taps along their lines, which complicate the fault location procedure. Some of the fault location problems and challenges in distribution networks are listed here:

- Geographic dispersion of distribution networks over a vast area;
- Existence of non-homogeneous lines;
- Presence of laterals, load taps and sometimes single and two phase loads;
- Limited measurements, typically only available at substations;
- Dynamic topology of distribution networks;
- The effect of fault resistance which is usually non-negligible;
- Multiple fault location in distribution networks due to presence of several branches;

Considering the above-mentioned problems and limitations, a variety of fault location methods have been proposed specifically for fault location in the distribution systems. Based on the required inputs and their core idea, distribution network fault location methods can be classified into impedance-based methods [17-29], algorithms based on sparse measurements [30-37], travelling waves-based methods [38-47], learning-based methods [48-54], and integrated methods [55-62].

Table 2. Comparison of the reviewed fault location methods

Method	Requirements	Advantages	Limitations
Impedance- based methods [17-29]	• Substation voltage and current • Network topology • Line and load data	• Practicality in traditional and modern systems	• Multiple location estimation
Methods based on sparse measurements [30-37]	• Substation voltage and current • Sparse measurements and communication system • Network topology • Line and load data • Synchronization*	• Ability to use the emerging equipment to provide better results	• Not applicable to traditional networks
Methods based on travelling waves [38-47]	• Measurements with very high sampling rate • Network topology • Sparse measurements and communication system* • Synchronization*	• Independent of network data • Accurate results for single transmission and distribution lines	• Requiring measurements with very high sampling rate • Difficulties in distribution networks with several branches and short lines
Learning-based methods [48-54]	• Substation voltage and current • Sparse measurements and communication system * • Measurements with very high sampling rate* • Network topology • Line and load data	• Short execution times • Generalization capability	• Requiring a large amount of data for training • Training should be repeated by any changes in distribution network topology
Integrated methods [55-62]	• Substation voltage and current • Network topology • Line and load data • Sparse measurements and communication system * • Measurements with very high sampling rate*	• Ability to integrate different methods to overcome their limitations	• Need the requirements of all of the methods which are integrated

*This input is required by some but not by all the methods in the class.

Table 2 presents a comparison among different classes to provide a general overview of the requirements, limitations, and superiorities of different methods. In the following, different proposed algorithms in each category are reviewed and compared in detail. The discussions begin with the impedance-based methods which are the most mature class, and the subject of most of the literature on this subject. The sparse measurements-based algorithms will be then reviewed. Similarly to the first class, these algorithms are also based on the fundamental frequency component of measured values, but they have different requirements and algorithms. Despite the first two classes, the third class of methods is based on the high-frequency travelling waves. The discussions continue with this class of methods and follows with the learning-based and integrated methods. Finally, a number of methods which do not fall into the above classes are also reviewed.

4.1. Impedance-based methods

The impedance-based fault location algorithms use the fundamental frequency voltage and current measurements available at the substation, and information such as network topology, line data, and load data, to find the fault location. Unlike the transmission lines, distribution feeders usually have many intermediate loads, while voltage and current measurements are available only at the substation. Therefore, the impedance-based methods start the fault location process from the first line section, and iteratively solve the equations which describe fault steady state condition for all line section, one by one, to make an estimation of the distance to the fault. The faulted circuit can be analysed either in phase domain or using symmetrical components. The algorithms proposed in [17,19,24,28,29] use the symmetrical components method to transform the faulted circuit to three entirely separate sequence networks and simplify the analysis. However, in distribution networks, due to the presence of unbalanced loads and lines, the sequence impedance matrix has nonzero off-diagonal elements, and the assumption of separation of sequence networks from each other does not hold [20]. In [18,20-23,25-27] the faulted circuit is analysed in phase domain. For example, in [21], the authors present the following equation to estimate the location of a phase to ground fault (AG) in a line section, having the sending end voltage $Vs = [V_a, V_b, V_c]^T$ and upstream current phasors $Is = [I_a, I_b, I_c]^T$:

$$d = \frac{V_a^r (I_a^i - I_L^i) - V_a^i (I_a^r - I_L^r)}{A(I_a^i - I_L^i) - B(I_a^r - I_L^r)} \tag{1}$$

where the superscripts *(r, i)* denote the real and imaginary parts, I_L is the during-fault load current and A and B are defined using the following equations at which Zl is the line impedance matrix:

$$A = Zl_{aa}^r I_a^r - Zl_{aa}^i I_a^i + Zl_{ab}^r I_b^r - Zl_{ab}^i I_b^i$$
$$+ Zl_{ac}^r I_c^r - Zl_{ac}^i I_c^i$$
$$B = Zl_{aa}^r I_a^i + Zl_{aa}^i I_a^r + Zl_{ab}^r I_b^i + Zl_{ab}^i I_b^r$$
$$+ Zl_{ac}^r I_c^i + Zl_{ac}^i I_c^r$$

Similar equations can be obtained for other types of faults at which I_L and d are unknown values. With an initial guess of the fault location or I_L, most of the impedance-based algorithms iteratively solve the faulted line section equations to find the unknown values. If the calculated fault distance is beyond the line section length, it means that the fault is not in that section and the process should be repeated for the next section with the calculated voltage and current values at the section head. Based on this procedure, impedance-based algorithms search all other line sections until the fault location estimate converges to a distance less than the line section length.

In addition to having many line sections and intermediate loads, power distribution systems are typically composed of a main feeder and laterals making branched configurations. To consider the laterals, the methods proposed in [23,25-27,29] calculate equivalent systems for *n* possible power flow paths, where *n* is the number of laterals, and solve the fault location equations for each equivalent system, section by section. The equivalent systems are made by transformation of the lines and loads outside the path, into equivalent constant impedances along the system. For example, Fig. 3 shows 2 of 5 possible equivalent systems for a sample distribution network. In [23,29] the equivalent impedances are calculated by computation of equivalent of parallel and series impedances, representing line and loads. However, the power flow-based method proposed in [25-27] is more appropriate for large scale branched distribution networks. Prior to fault location, these algorithms perform a power flow using pre-fault substation voltage and currents, and calculate the equivalent impedances Z_{p-q} in each node applying Eq. (2):

$$Z_{p-q} = \frac{V_p}{I_{p-q}} \tag{2}$$

where V_p is the pre-fault voltage at node *p* and I_{p-q} is the pre-fault current flowing from node p to node q.

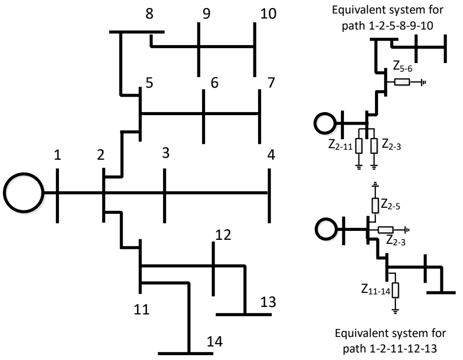

Fig. 3. A branched network and 2 of 5 equivalent systems for 5 power flow paths

While all of the impedance-based fault location methods rely on the same fundamental concepts and assumptions, there are some features and differences which influence their performance and range of application. Table 3 presents a comparison among different aspects of the impedance-based methods to highlight their differences.

The details and assumptions of different impedance-based methods in load and line modelling influence their performance. Almost all impedance-based fault location methods use static load models, but they are different. The methods presented in [17,20,21,23-27,29] use a constant impedance load model, while the algorithms proposed in [18,19,22] employ voltage dependent load models to simulate different types of customer loads. In distribution systems, load data is often obtained by processing historical customer consumption data and due to customer behaviour uncertainties, it is difficult to estimate the exact values at fault instant. Considering that the fault current is often much greater than the load current, the load uncertainty seldom deteriorates the fault location accuracy considerably; however, as the fault resistance increases and the load and fault currents become comparable, the effect of estimation errors would get more prominent.

In order to make an accurate estimation of fault location, an appropriate line model has to be used. In the case of short distribution lines, the shunt capacitances are negligible and the short line model is usually accurate enough. However, for long overhead or underground lines, the effect of the shunt admittance becomes greater, and it can result in estimation errors if it is not modelled correctly. Locating a fault in an underground cable system that consists of more conductor types such as core, sheath, and armour requires broader aspects of consideration and analysis [24,26]. In general, an accurate modelling of distribution network lines will improve the accuracy of results especially for underground distribution networks or for high impedance faults. On the other hand, very detailed models would increase the complexity and computational burden. Moreover, unavailability of detailed data usually restricts the practical application of sophisticated models. Therefore, when the system topology, the available data, the computational platform, the required accuracy and computational time are determined, these factors can be considered as criteria to select an appropriate fault location method. In [80] the details and assumptions of different impedance-based methods in line and load modeling are discussed and they are well compared.

Table 3. Comparison of the reviewed impedance-based algorithms

Method	**Domain**	**Load model**	**Line model**	**Fault types considered**	**Consideration of distribution networks nature**			
					Load taps	Laterals	Unbalances	Non-homogeneity of lines
Girgis et al. [17]	Sequence domain	Constant impedance	Short	All[a]	✓[e]	✓	✓	✓
Zhu et al. [18]	Phase domain	Voltage-dependent	Short	LG[b]	✓	✓	✓	✓
Das et al. [19]	Sequence domain	Voltage-dependent	Long	All	✓	✓	✓	✓
Choi et al. [20]	Phase domain	Constant impedance	Short	LG	—[f]	—	✓	—
Lee et al. [21]	Phase domain	Constant impedance	Short	LG	✓	✓	✓	✓
Senger et al. [22]	Phase domain	Voltage-dependent	Short	All	✓	✓	✓	✓
Choi et al. [23]	Phase domain	Constant impedance	Short	LL[c]	✓	✓	✓	✓
Yang et al. [24]	Sequence domain	Constant impedance	Distributed parameter	LG	✓	—	—	✓
Salim et al. [25]	Phase domain	Constant impedance	Short	All	✓	✓	✓	✓
Filomena et al. [26]	Phase domain	Constant impedance	π-line model	3ph[d] LG	✓	✓	✓	✓
Salim et al. [27]	Phase domain	Constant impedance	π-line model	All	✓	✓	✓	✓
Das et al. [28]	Sequence domain	Not required	Short	LG	—	—	—	—
Dashti and Sadeh [29]	Sequence domain	Constant impedance	Distributed parameter	All	✓	✓	✓	✓

[a]**All**: All shunt fault types, [b]**LG**: Line to Ground fault, [c]**LL**: Line to Line fault, [d]**3ph**: Three-phase fault
[e]✓: Considered, [f]—: Not considered

4.1.1. The problem of multiple estimations

Impedance-based methods calculate the impedance seen from the measuring point (i.e. head of the main feeder) and search the network for the points with the same impedance as possible fault locations. In other words, these methods draw a circle centred at the measuring point with the radius of the seen impedance and find all intersections with network line sections as probable locations. Therefore, as shown in Fig. 4, due to the tree branched structure of distribution networks, these algorithms result in the identification of multiple fault location candidates for a single fault, having the same impedance from the measurement point of view.

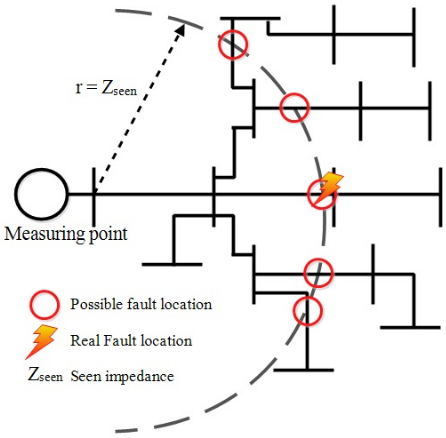

Fig. 4. The problem of multiple estimations

In [18,21], the authors propose a fault diagnosis algorithm using extracted information from the recorded current pattern to identify the actual fault location from the set of candidates. In this algorithm, by investigating the current waveform recorded at the substation, the protective devices involved in fault clearing are specified (e.g. two recloser fast operations followed by the opening of a sectionalizer). Consequently, by knowing the placement of various protective devices, the actual fault location is identified as the one with the same upstream protective devices. In cases where the preceding protective devices are the same for more than one fault candidates, a comparative analysis is made between the change in the measured current of the main feeder head and the sum of the affected customers load current for each candidate. This is actually an additional evidence for identification of the most likely location.

In [81], the installation of fault indicators is proposed as another solution for the multiple estimations problem. As shown in Fig. 2, if a fault occurs, all indicators upstream of the fault location will indicate a fault condition; therefore, the correct fault location would simply be the one with all the indicators from the path from the substation reporting the fault. Of course, utilizing fault indicators increases the implementation cost, and also requires a communication network, but if fault indicators are already installed and available, they would be the preferred solution for the multiple estimations problem.

In modern distribution networks with better measurement and communication infrastructure, smart meters data would be another option to identify the actual fault location among the possible candidates.

Smart meters can provide the required information to find the correct solution. Other solutions such as using the load current information in unfaulted phases [82,83] and diagnosis based on the injection of two sinusoidal signals with different frequencies [84] are also proposed in the literature. Moreover, it is also possible to combine the information provided by any of the outage area location methods, reviewed in Section 2, with the fault locator results to identify the most likely fault location. Similarly, approaches such as [85] and the methods reviewed in Section 4.5, integrate different fault location methods to overcome the multiple estimation problem.

It should be noted that the impedance-based algorithms are not the only fault location methods that face the multiple estimations problem. Any algorithm based on the substation measurements which estimates the distance to the fault instead of the fault location would report multiple locations with the same distance.

4.2. Methods based on sparse measurements

Inspired by the recent advances in communication systems, and development of measurement instruments such as power quality meters and digital fault recorders, another class of fault location methods is proposed that utilize the measurements provided by sparse meters installed throughout the network. Using the fundamental power frequency component of recorded signals, sparse measurements-based methods can be considered as a subcategory of the impedance-based algorithms; however, these methods have a different procedure. Most of these algorithms are based on the fact that each fault causes voltage sags with different characteristics at different nodes [30-33]. Therefore, by measuring the voltage sags at some nodes, it would be possible to locate the faulted node. These class of algorithms, commonly known as voltage sag-based fault location methods, have a simple procedure. They assume the fault at all nodes, one by one, perform a set of calculations for each node and find the voltage sags at nodes having measurements. Finally, they investigate the level of similarity between the measured and calculated voltage sags for all nodes to find the one with the minimum difference as the nearest node to the fault. However, since there is no prior knowledge about the fault, its resistance or current should be estimated before or during the calculations.

The fault location method proposed in [32], estimates the fault current by summing the fault current contributions from all sources (i.e. substations and distributed generators). The algorithm considers the fault with the estimated fault current at each node and uses the distribution system three-phase bus impedance matrix to calculate the change in the three-phase voltages at all measurement nodes. Finally, by comparing the measured and calculated voltages, the method identifies the faulted node. This algorithm follows a simple procedure; however, its approximate estimate of fault current affects the accuracy of the results. In [34], the authors propose a method with similar principles, but instead of estimating the voltage changes, the proposed algorithm uses the three-phase bus impedance matrix and measured voltages to estimate the fault current. For each node, it calculates different values for the fault current by using each measured voltage, and then identifies the faulted node by comparing the calculated currents. For the faulted node, all of the estimated fault currents should have almost the same value, which is close to the real value. The proposed method overcomes the fault current estimation problem mentioned for the previous algorithm, but, it requires a large number of meters to provide acceptable results.

The method proposed in [30] models the fault as a special load temporarily connected at the faulted node and performs a backward-forward load flow to calculate the fault current and also the voltage sags at nodes having measurements. In each load flow iteration, the algorithm calculates the fault current using (3) and injects it at the analysed node to find the voltage sags.

$$I_f = I_s^m - \sum_{i=1}^{n} I_i \tag{3}$$

where I_s^m is the during-fault current measured at the feeder root node, n is the number of loads and I_i is the current of the i^{th} load.

During the fault location process, the proposed algorithm assumes the fault at each node, one at a time, performs a backward-forward load flow updating the fault current at each iteration and calculates an error index e for each node, such as the one shown in Eq. (4). The node with the smallest e would be the closest node to the fault.

$$e_j = \frac{\sum_{i=1}^{m} \left| \Delta V_i^m - \Delta V_{i,j}^c \right|}{V_n} \tag{4}$$

where ΔV_i^m and $\Delta V_{i,j}^c$ are the measured and calculated voltage sags at i^{th} measurement node for fault at j^{th} node, m is the number of measurements and V_n is a the rated voltage.

This algorithm requires a limited number of voltage measurements; however, in some cases, especially when no measurements are taken from the downstream of the faulted node, it is not able to differentiate neighbouring nodes to find the correct solution. In [33], the authors try to resolve this problem by introducing a revised error index for selecting the faulted node:

$$e_i = \frac{\sum_{i=1}^{m} \left| \Delta V_i^m - \Delta V_{i,j}^c \right|}{V_n} + \alpha \frac{\left| \angle Z_x^j \right|}{2\pi} \tag{5}$$

where α is a constant weighting factor and $\angle Z_x^j$ is the angle index defined by:

$$\angle Z_x^j = \angle V^j - \angle I_f^j \tag{6}$$

where $\angle V^j$ and $\angle I_f^j$ are the calculated angle of node voltage and fault current at node j.

Due to the resistive nature of electrical faults, the angle difference between the fault voltage and current is near zero. Therefore, $\angle Z_x^j$ has the least value in the fault location, improving the error index, and enabling the algorithm to differentiate between neighbouring nodes. However, the assumption of the equality of node voltage and fault current angles in Eq. (6) only holds for single-line to ground faults limiting the application of the proposed method for the other types of fault.

In [31], the authors propose a new method trying to estimate the fault resistance before performing the calculations. For each node the algorithm firstly applies a fault with zero resistance ($R_f=0$) and calculates the fault resistance estimation error ε using a set of short circuit analysis.

$$\varepsilon = \left|I_s^c\right| - \left|I_s^m\right| \tag{7}$$

where $|\, I_s^c \,|$ and $|\, I_s^m \,|$ are the magnitudes of the calculated and measured fault currents at the head of the main feeder.

If ε is greater than a predefined error tolerance, the algorithm increases R_f and repeats the calculations. The search continues as an extrapolation/interpolation procedure to find R_f for which ε meets the error tolerance. After estimation of the fault resistance, the algorithm applies it to the node under investigation and explores the similarity between the measured and calculated voltage sags. The node with the maximum similarity (i.e. the node with minimum difference between the measured and calculated values) is selected as one end of the faulted line. In the next step, the algorithm considers the lines connected to the selected node and moves the fault with previously calculated R_f along the lines to find the fault. The proposed algorithm solves the problem of the algorithm proposed in [30] in differentiating between neighbouring nodes; however, it requires measurements capable of providing synchronized voltage phasors. Moreover, the described method for the estimation of the fault resistance is only for faults having a single fault resistance (i.e. single-line to ground, and line to line faults). For the other type of faults, there are three or four fault resistances to be estimated which complicates the calculations.

In [86], the authors perform a set of sensitivity analysis to study the adverse effect of DG and factors such as imperfections of measuring instruments on voltage sag-based methods. They conclude that fault resistance and load data error are the most influential factors, while measurement errors and DG penetration level are not as influential. The sensitivity analysis reveals that inaccurate load data and contribution of DG to the fault current, if not considered, leads to wrong estimates.

The method proposed in [35], incorporates all the measured values into calculations through a state estimation-based algorithm in order to improve accuracy and performance in face of uncertainties and imperfections. The algorithm first assesses the input data and eliminates the gross measurement errors. It then assumes the fault at each of the suspected nodes and performs a set of state estimations to find the nearest node to the fault location. By incorporating all available measuring resources into calculations, the method significantly reduces the impact of random measurement errors and load estimation uncertainties and improves the accuracy and robustness of the results. However, compared to the previously load flow-based methods, such as the method proposed in [30], the state estimation-based method requires more computational time.

The authors in [36] exploit compressive sensing technique, an emerging signal processing method, for fault location in distribution networks. The pre- and during- fault voltages are measured by a few smart meters or phasor measurement units to produce the voltage sag vector. The voltage sag vector and the impedance matrix are then used to form an underdetermined equation system with infinite feasible solutions. However, since the entries of the injection current vector are all zero except for the coefficient corresponding with the faulty point, l1-norm minimization method is adopted to recover a unique sparse current vector solution even under noisy condition. In [37], the authors extend the application of proposed idea in [36] to locate the single, double and triple faults in distribution networks. Similar to the method employed in [36], given the pre- and during-fault voltages captured by smart meters/PMUs and the impedance matrix, the sparse injection current vector is recovered. With this assumption that single faults only occur in the system, the nonzero values in the recovered injection current vector are manipulated by a k-nearest neighbourhood to estimate a single fault location. In order to locate the simultaneous faults, the Fuzzy-C mean method is used to cluster the nonzero values of the recovered current vector in four groups. The group centres estimate the four possible faulty points in the system. If single, double, or triple faults occur, one, two, or three of the four estimated points, respectively, are closest to the actual fault location(s). Although these methods show better performance in different conditions with respect to the voltage sag-based algorithms, they require more meters to provide acceptable results.

The Requirement of the sparse measurements installed along the feeder would limit the application of this class of methods especially in conventional distribution networks; however, recent advances in metering and communication systems have provided new opportunities to enhance fault location methods. Accordingly, fault location algorithms with the ability to benefit from the sparse measurements to meet the modern distribution systems requirements (e.g. accurate and reliable estimations), would be the future preferred solutions. The common advantage of this class of methods is their simpler and more straight-forward procedures compared to impedance-based methods and providing a single estimation of the fault location, while their typical disadvantages and limitations are listed and compared as what presented for the reviewed methods in Table 4.

Table 4. Comparison of the sparse measurements-based algorithms

Method	Requirements	Maximum range of accuracy	Limitations
Pereira et al. [30]	• Sparse Voltage measurements • Communication system	Nearest node to fault location	Not capable of finding the correct solution in some cases
Lotfifard et al. [31]	• Sparse synchronized Voltage measurements • Communication system	Fault location	Complicated calculations for 3ph and LLG faults
Brahma [32]	• Sparse synchronized Voltage measurements • Communication system	Fault location	Approximate estimate of fault current affects the accuracy
Dong et al. [33]	• Sparse Voltage measurements (Synchronization for better accuracy) • Communication system	Nearest node to fault location	Only applicable to purely resistive single-line to ground faults
Trindade et al. [34]	• Sparse Voltage measurements (Synchronization for better accuracy) • Communication system	Nearest node to fault location	Requires more meters to provide acceptable results
Jamali and Bahmanyar [35]	• Sparse synchronized measurements • Communication system	Fault location	More time-consuming compared to the similar methods
Majidi et al. [36]	• Sparse Voltage measurements (Synchronization for better accuracy) • Communication system	Nearest node to fault location	Requires more meters to provide acceptable results
Majidi et al. [37]	• Sparse Voltage measurements (Synchronization for better accuracy) • Communication system	Nearest node to fault location	Requires more meters to provide acceptable results

4.3. Travelling wave-based methods

Methods based on travelling-wave theory have long been studied for transmission line fault location. Following the advanced measurement infrastructure and communication systems development along with utilities willingness to faster and more accurate fault location, these methods gained more and more attention. As shown in Fig. 5, when a fault occurs, it generates high frequency travelling waves of currents and voltages propagating away toward both ends. At points of discontinuity, such as open circuit, short circuit, or line terminals , a part of the incident wave reflects back while another part travels into the beyond the discontinuity [87,88]. The waves reflect back and forth between the fault point and the two terminals until the post-fault steady state is reached.

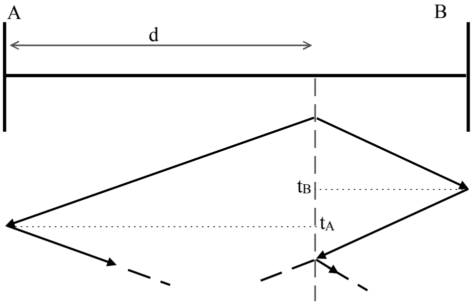

Fig. 5. Travelling voltage and current waves: lattice diagram for a fault at distance *d* from *A*

Let t_A and t_B represent the travel time from the fault to the line terminals calculated by investigating the changes in the signals recorded at line terminals. Assuming that the recorded signals are fully synchronized, the delay between the detection times at the two terminals can be determined by Eq. (8).

$$t_d = t_A - t_B \tag{8}$$

And the distance to the fault can be calculated as follows:

$$d = \frac{L - ct_d}{2} \tag{9}$$

where L is the length of the line, d is the distance to fault from A, and c, is the velocity of the travelling waves.

This is the main idea of the travelling wave-based fault location methods for transmission lines [79]. Inspired by the algorithms implemented for transmission networks, several fault location methods have been proposed for distribution networks with almost the same principles. For each fault location, the recorded transients contain some dominant characteristic frequencies as a function of the travelling paths length and the propagation velocities giving valuable information about their location. However, the interpretation of the transients, especially for branched distribution networks, is computationally difficult. Therefore, the travelling waves-based methods mostly rely on additional signal processing techniques such as wavelet transforms to simplify the analysis. The wavelet transform is a linear transformation very similar to Fourier transform which allows a time-frequency representation of the signal that offers very desirable time and frequency localization. This property is particularly useful for time localization of fault transients having short-lived high-frequency components superposed on power frequency continuous waveforms.

The two-end fault location method proposed in [79] for the transmission lines is employed by [39] to locate distribution network faults. This work supposes that time-synchronized fault transient detectors based on Discrete Wavelet Transform (DWT) are already installed at the substation and at all load terminals which are able to capture the arrival time of the transient and report the detected times. Therefore, after the occurrence of a fault, having the topological data of the network, the fault location can be estimated based on Eq. (9) and using the recorded times. In [41], the authors use a high-pass filter to extract fault transients and test double-ended and single-ended fault location methods proposed for transmission lines for a distribution network. They first calculate the incident and reflected transients, and then cross-correlate them to find the arrival time of the first and second incident waves in order to estimate the fault location. Both of the methods proposed in [39] and [41] assess the possibility of using standard techniques developed for transmission systems to locate faults on a small distribution system. However, in real distribution networks, there are several discontinuities adding several reflections to the transient waves arising from the fault. This makes it infeasible to apply transmission fault location methods to distribution level. Moreover, the installation of a sophisticated measurement infrastructure such as the one employed in [39] is not practical for the distribution level.

In [38], the authors propose a method which relies on the successive identification of the arrival of the travelling high-frequency voltage signals at the node where the locator is installed. The high-frequency components are extracted using digital band-pass filters and the time difference between the first and the subsequent received transient signals are used to identify the fault position. The method proposed in [40] is based on similar principles but it uses high-frequency current transients. It first identifies the probable the fault section by interpretation of the time interval between the arrival of first and subsequent peaks in the high-frequency current signals. After identification of the fault section the method simulates the fault on different points along the section and investigates the similarity between the simulated and recorded waveforms through cross-correlation in order to find the fault location.

In [45], a method is proposed for fault section estimation and fault distance calculation based on frequency spectrum components of fault generated transient recorded at the beginning of the main feeder. The proposed method uses the Clark transformation to transform the fault transient voltage signals from phase domain into modal domain to perform frequency analysis. Simulating the faults in different locations of the laterals for each path in the distribution system, an offline database is constructed. The method compares data obtained by analysing the fault generated voltage transients with the database data to determine the section and the distance of the fault. Although the method provides acceptable results, it requires updating its database by any changes in distribution network topology.

In [42], the authors propose the application of the Continuous Wavelet Transform (CWT) to recorded voltages to find the characteristic frequencies of fault transients. They investigate the possibility of matching the CWT-identified frequencies with the calculated frequencies for fault at different locations to provide useful information about the fault location. In [43] the limitations of the conventional CWT are discussed and an algorithm is proposed to build specific mother wavelets directly inferred from the recorded fault-originated voltage transients. This proposed method improves the performance of the method presented in [42] and it provides acceptable results for a distribution network with different laterals and load taps.

In [44], the authors propose the integration of the frequency-domain information with the time-domain information provided by the CWT to improve the performance of the algorithm proposed in [43]. Experimental tests are performed on a reduced-scale single-phase cable feeder and also on a single-phase feeder with one lateral at the middle. The results imply that in both cases the proposed method improves the accuracy of the algorithm proposed in [43]; however, the addition of a single lateral considerably affects the performance of the algorithms. The proposed method is further tested using the fault transients recorded in a real distribution network. The obtained results validate the applicability of the idea for the identification of the faulted line section.

The authors in [46] propose an approach based on the capture, time stamping, and retrieval of the fault induced high-frequency transient to overcome the shortcomings of travelling wave-based methods on branched networks. The proposed method can locate a fault anywhere on a network, even on branches, if a fault recorder is located on each branch termination. In [47], the authors present an approach using continuous and discrete wavelet transform which requires a fewer number of fault recorders. An algorithm is proposed for placement of the measurement units. Having the recorded voltage transients, the DWT is used to estimate the difference between arriving times of transients in different measurement units to locate faulted section. Then, depending on the determined fault section, the accurate location of the fault is calculated based on the mentioned time difference or the frequency content of the voltage transients captured by CWT.

The travelling wave-based fault methods are mostly independent of network data such as line impedance and load demands, and hence they are insensitive to modeling errors. They provide accurate results for single transmission and distribution lines. However, distribution networks normally have short lines and a large number of laterals and load taps which reflect travelling waves. Therefore, the use of the travelling wave-based algorithms in distribution networks requires measuring devices with very high-frequency sampling rates. For example, the methods presented in [43,44], employ meters with 10 MHz sampling frequency and the approaches proposed in [46,47] use accurately synchronized fault recorders with 1 MHz sampling frequency installed in different locations. Although recent developments in transducer technology enabled high sampling rate recording of transient signals, such measurements are costly for the distribution network level. Moreover, studies have shown that in distribution networks with several laterals and load taps, the travelling wave-based methods may have difficulties in locating the faults. Therefore, despite their maturity in transmission lines, the use of the travelling wave-based methods in distribution networks is still a field for future studies and developments.

4.4. Learning-based methods

All of the previously discussed fault location methods are based on post-fault mathematical calculations. Learning-based or training-based methods such as neural networks are proposed as alternatives with less online computation. An Artificial Neural Network (ANN) is an information-processing system inspired by biological neural networks. They are able to capture and represent complex input/output relationships. The output is usually the distance to the fault and the inputs comprise of the measured voltages and currents. ANN-based methods have an offline training phase in which they employ a large set of simulation or real scenarios as samples for training. Once trained, they can be employed to predict the fault location based on the real-time provided inputs. Besides, they present very short execution times, and they have generalization capability which means they are able to provide satisfactory results for unseen input-output patterns.

Distribution networks usually have several branches, which may experience different types of faults at various loading and source short circuit levels. Therefore, the relationship between the measurements and the fault distance is highly complex and difficult to be captured by a single ANN. In [48], the authors propose the use of a Support Vector Machine (SVM) to break the complexity of the fault location problem by classification of different fault types and source short circuit levels. A separate neural network is then trained for each class to estimate the reactance to the fault from the measuring point, using the three-phase steady-state voltage and current measurements as inputs.

In [49], the authors propose a neural network-based fault locator for distribution networks including distributed generation. To reduce the impact of the fault impedance on the fault location accuracy, the ratio of the injected fault currents of DGs to the substation current are selected as input. A separate multi-layer perceptron neural network is then trained for each type of fault to estimate the distance to the fault from all DGs and the main source as output.

As described in Section 4.3, based on the distribution system topology and the location of the fault, the recorded transient signals contain certain characteristic frequencies as a function of the length of the travelling paths and the propagation velocities; however, the interpretation of the transients is difficult. ANN can be employed as a powerful tool which is able to capture and represent the complex relationship between the fault location and the information content of the transients usually extracted using wavelet transform. The method proposed in [50] uses the wavelet transforms to take some characteristic features of the current patterns obtained from the measured signals registered at the substation. It then employs the extracted features to train an Adaptive Neuro-Fuzzy Inference System (ANFIS) to predict the zone where the fault is located. In [51] Wavelet transform is used to extract the high-frequency and low-frequency components of voltage and current transients. Wavelet is integrated with the fuzzy neural network to form a Wavelet Fuzzy Neural Network (WFNN) to find the location of single-line to ground faults in an industrial distribution system.

The method proposed in [52] uses the wavelet transform to decompose the recorded transient voltages. The information provided by the wavelet analysis is then employed as the input of a feed-forward neural network in order to estimate the distance to the fault. The authors in [53] follow a similar procedure using the wavelet transform to extract useful information from the recorded fault transients. A three-layer feed-forward ANN and a fuzzy logic system are then employed to classify the type of fault and calculate its distance.

Contrary to the former methods, the method proposed in [54] uses a Support Vector Regression (SVR) method to capture the relation between the information extracted from the fault transients and the fault location. SVR integrates the characteristic information of amplitude, time and frequency extracted by

DWT to estimate the fault location. In comparison with ANN-based methods, the SVR achieves very good performance with few training samples; however, this reference employs a very small network for testing the performance of the proposed approach. Table 5 compares the mentioned methods in terms of their required inputs, outputs, the considered fault types.

Besides their accuracy, short execution time and generalization capability, the main shortcoming of the learning-based approaches is the requirement of numerous actual or simulated fault cases for training. Training is usually an offline process, but the problem is that it has to be repeated due to possible changes in distribution network topology. Moreover, similar to all the other fault location methods, the learning-based methods which are based on the substation measurements, estimate the distance to the fault instead of the fault location, and therefore they report multiple locations having the same distance.

Table 5. Comparison of the reviewed learning-based methods

Method	Inputs	Outputs	Type	considered fault type
Thukaram et al. [48]	Three-phase steady-state voltage and current	Line reactance to fault	Feedforward ANN	All shunt faults
Javadian et al. [49]	Ratio of injected fault currents of DGs to substation current	Distance to fault from all DGs and the main source	Feedforward ANN	All shunt faults
Mora et al. [50]	Patterns obtained from measured substation current	Faulted zone	ANFIS	All shunt faults
Chunju et al. [51]	High frequency and low-frequency components of voltage and current transients	Distance to fault	WFNN	Line to Ground fault
Pourahmadi-Nakhli et al. [52]	Energy content of voltage transients around the characteristic frequencies	Distance to fault	Feedforward ANN	Line to Ground fault
Rafinia and Moshtagh [53]	Information extracted through DWT and analysis of the recorded transients	Distance to fault	Feedforward ANN	All Series & shunt faults
Ye et al. [54]	Time delay and ratio between the first wavelet transform modulus maxima of modal components in each scale	Distance to fault	SVR	All grounded shunt faults

4.5. Integrated methods

Integrated methods aim to combine different classes of fault location methods to overcome shortcomings such as multiple fault location estimation.

The scheme proposed in [55] is a combination of different methods. The fault is detected and classified using a wavelet-based technique. An impedance-based method is employed to identify all different possible fault locations, and an artificial neural network-based method estimates the faulted section to identify the most probable location. The method proposed in [56] has a similar idea. It uses a combination of a classification technique and an impedance-based method to estimate the type and location of the fault. The classifier is based on a Learning Algorithm for Multivariable Data Analysis (LAMDA) to find the faulted zone and identify the correct location between different estimated fault locations.

The method proposed in [57] employs the DWT to extract the travelling wave information of the high-frequency components of the recorded fault transients and then it uses this information to identify the fault path. Once the fault path is identified, the method simplifies the network representing the non-faulted laterals as equivalent impedances. Finally, the fault location along the identified path is estimated using the phasors of the substation current and voltage signals and an impedance-based algorithm. In [58], the authors integrate an impedance-based method with a travelling wave-based method to overcome the multiple estimations problem. They first employ an impedance-based algorithm in order to estimate the fault distance and find all possible locations. The characteristic frequencies associated with each possible fault location are then calculated and a transient analysis is performed to identify the most significant frequency components of fault-generated travelling waves. Finally, correlation analysis is performed in both frequency domain and time domain to find the correct solution. In [59], the authors follow a similar approach. At first, an impedance-based algorithm is proposed to find all possible fault locations and then two methods are proposed to determine the real location of the fault. Both methods simulate the same type of faults in each possible fault location and record the voltage at the beginning of the feeder. To find the real fault location, the fist method compares the measured and simulated voltage samples, while the second method matches the frequency spectrum of recorded and simulated faults transients.

In [60], the authors propose an impedance-based fault location method for distribution systems in the presence of DG which overcomes the requirement of fault type identification by using only one fault location equation. For each possible fault location, by injecting the fault current which is determined by the proposed impedance-based algorithm, during-fault voltages at substation bus and each DG unit are calculated. The measured and calculated voltages for all identified locations are then compared to find the one with the minimum difference as the correct solution. The method of [61] has a similar idea. Using an impedance-based algorithm, first, all possible fault locations and the related fault impedance values are calculated. Then, having the fault impedance values, the faults are applied at each of the reported points and the one with the maximum similarity between the calculated voltage sags and measured voltage sags is identified as the correct solution. The work presented in [62] proposes the use of smart meters with voltage monitoring capability to find the area where the voltage magnitude is low due to the proximity of fault. The proposed method builds a low voltage zone to identify the actual fault location and to improve the performance of the impedance-based methods. Although the presented iterative approach can successfully limit the number of fault locations reported by the impedance-based algorithm, its performance for high impedance faults is not analysed.

It is noteworthy that such combinations, besides their advantages, also bring disadvantages such as more requirements. While, the common advantage of mentioned integrated methods is their ability to overcome the multiple estimation problem, their additional requirements compared to impedance-based algorithms can be listed as what presented in Table 6.

Table 6. Comparison of the requirements of the reviewed integrated methods

Method	Requirements
Salim et al. [55]	Training data
Mora-Florez et al. [56]	Tainting data
Magnago and Abur [57]	Measurements with higher sampling rate
Gazzana et al. [58]	Measurements with higher sampling rate
Dashti and Sadeh [59]	Measurements with higher sampling rate
Alwash et al. [60]	Sparse voltage measurements
Bahmanyar et al. [61]	Sparse voltage measurements
Trindade and Freitas [62]	Sparse voltage measurements

4.6. Other methods

In this part, a number of methods which have not been covered by the above-mentioned reviewed classes are discussed. In [63], the authors propose a fault location method based on the voltage sag profile, measured at the primary substation. The proposed method first applies the fault at different locations with different fault impedances to establish a database. When a fault occurs, a number of possible fault sections and fault resistances interval are identified by comparing the measured voltage sag magnitude and phase angle with the previously calculated values in the database. Then, the most likely fault resistance and fault distance are estimated by solving the voltage sag profile equations between the voltage sag magnitude, its phase angle, and the fault distance. The voltage sag profile recorded at a single location would not provide the required information to locate the fault, especially for high impedance fault and the proposed method provides multiple locations for a single fault. Therefore, the authors propose a method to rank the possible fault locations. Moreover, the method relies on a massive database for different fault types, impedances, and locations which has to be updated whenever there are changes in the system such as network reconfiguration.

The method proposed in [64] is based on the fuzzy sets to combine all inexact, uncertain information sources such as operator knowledge, information on the estimated fault distance, the operation of fault detectors and weather conditions (e.g. wind, temperature, thunderstorms) in a formal way to help in the fault location. The heuristic knowledge and all information about the fault situation are modeled as various membership functions of fuzzy sets. By combining these fuzzy sets, first, the faulted zone is identified and then the most possible faulted lines are obtained.

During the fault, the elements of the network bus impedance matrix are functions of the fault location. The method proposed in [65] presents two types of fault location methods for non-radial and radial overhead distribution systems which are based on solving a set of equations based on the bus impedance matrix elements, expressing the substation voltage and current as a function of the fault location and fault resistance. The algorithm has to be applied to each line section providing a list of possible fault locations and requires some additional information, such as customer outage reports or fault indication signals in order to find the most probable location.

As discussed in Section 4.2, voltage sag-based methods have to estimate the fault resistance or current during or before performing the process of fault location. Moreover, they have to examine all system nodes to find the faulted one. In [66], the authors propose a fault location algorithm for distribution networks with DG, which considers the fault location process as an optimization problem where the fault location and fault resistance are unknown variables. They developed a genetic algorithm-based technique to obtain an optimal solution for this problem. The proposed method bypasses the fault estimation step and searches a limited number of nodes to find the faulted one.

5. Towards the future

The next generation electrical distribution systems are expected to integrate new emerging technologies to increase system reliability and sustainability. Advanced digital meters, low-cost communication systems, and distributed generation are examples of proven technologies which will play an effective role in distribution systems improvement to enhance their ability to address the changing needs of utilities and their customers [89]. The next-generation grids should be able to provide desired functionalities of modern networks such as self-healing, high reliability, improved power quality, and advanced energy management.

The future networks will have self-healing mechanisms. They will be able to identify and isolate the faulted components, and automatically restore supply to the customers affected by the fault with no or little human interventions [90]. Therefore, as the main function of fault management systems, outage and fault location methods will play an important role in satisfying the emerging requirements of the future network. While, in conventional fault management systems, the outage or fault location functions were supposed to give a rough estimate of the faulted area to reduce the patrolling time, an advanced fault management system requires accurate and reliable methods to realize fast service restoration. The question which arises is how to achieve these functionalities using the new emerging technologies. On one hand, different methods can benefit from the emerging meters and advanced communications infrastructure to achieve better performance; on the other hand, using a wide variety of new technologies such as DG and storage complicates the calculations.

Outage location can provide a primary estimation of the affected area and can help to expedite service restoration through switching operations. Among different outage location methods, algorithms using fault indicators and AMI-based methods have the ability to exploit the communication infrastructure and new information sources in future distribution systems to provide accurate and reliable estimations of the outage area. Moreover, it will be possible to employ multiple sources of available data to increase data redundancy and consequently reliability of results.

Compared to outage location methods, fault location algorithms can provide more precise results. Most of the previously proposed fault location methods are designed for conventional radial distribution networks. In future electrical distribution systems, the ability of an algorithm to use the emerging technologies to satisfy the requirements and respond to emerging challenges would be a key factor in the selection of the most appropriate method. One of the main challenges is high penetration of dispersed generation and storage. Recently, several methods are proposed for fault location in distribution networks with distributed generation. For example, the methods in [67,68] are modified impedance-based methods. In [60], a similar method employs the voltages measured at DG terminals to overcome the multiple fault location estimation problem. In [32,86], the authors propose algorithms which use sparse voltage measurements while the methods proposed in [54,69,70] are learning-based approaches. In [71] a method is proposed to locate the faulted section using a superposition-based approach based on the pre-calculated short-circuit results. The method proposed in [72] is based on appropriate numbering of the fault sensing devices installed in the faulted feeder and the fault current direction. The authors in [73] propose an algorithm based on a time domain numerical analysis which uses a data window moving from pre-fault to post-fault in time domain and considers the dynamic behaviour of DG during-fault transients. In [66], a genetic algorithm-based technique is developed to find the fault location through an optimization process. Table 7 compares all of the mentioned methods in terms of their advantages and limitations.

In addition to high penetration of distributed generation, the effect of measurement errors, communication network uncertainties along with the requirements such as accuracy and reliability are also important challenges which the future methods are supposed to fulfill.

Table 7. Comparison of different fault location methods proposed for distribution systems with distributed generation

Method	Type	Advantages	Limitations
Jamali and Talavat [67]	Impedance-based	• Do not require the DG terminal measurements	• Only for synchronous machine-based DG
Orozco-Henao et al. [68]	Impedance-based	• Does not require the synchronized voltage phasors at DG terminals	• The method is sensitive to measurement errors and load data inaccuracies*
Alwash et al. [60]	Integrated	• Overcomes the requirement of fault type identification	• Analysis of the effect of measurement errors can help to further prove the method
Brahma [32]	Sparse measurements-based	• Algorithmically simple	• Inaccurate fault current estimation affects the accuracy of the results especially in the case of low fault resistance
Chen et al. [86]	Sparse measurements-based	• Algorithmically simple	• Sensitive to load data inaccuracies • Complicated for 3ph and LLG faults
Javadian et al. [69]	Learning-based	• Very short execution time	• Requires training data and retraining by any change in network topology
Zayandehroodi et al. [70]	Learning-based	• Very short execution time	• Requires training data and retraining by any change in network topology • The effect of fault impedance is not considered
Rafinia and Moshtagh [53]	Learning-based	• Very short execution time • Classifies and locates all types of shunt and series faults	• Requires training data and retraining by any change in network topology • Requires measurements with comparatively higher sampling frequency
Jamali et al. [66]	Others (uses Genetic algorithm and sparse measurements)	• Compared to [31,86], bypasses the fault impedance estimation step and searches a limited number of nodes to find the fault	• Just tested for networks with a limited number of nodes.
Brahma and Girgis [71]	Other (Compares Fault current contribution from each source with currents previously calculated by short-circuit analysis)	• Algorithmically simple	• Sensitive to fault resistance; • Requires a large amount of offline short-circuit analysis
Conti and Nicotra [72]	Algorithms using fault indicators	• Algorithmically simple	• Requires fault sensing devices in all Secondary Substations
Jamali and Talavat [73]	Others (Based on a time domain numerical analysis using a full order synchronous machine model)	• Do not require the DG terminal measurements	• Only for synchronous machine-based DG

* In most of the similar proposed methods the effect of measurement errors and load data inaccuracies are not studied

6. Conclusion

Considerable research and studies have been devoted to fault and outage location methods as one of the most affordable and efficient ways to enhance distribution systems resilience in the face of threats. However, the appropriate selection of a method is a difficult and extensively time-consuming task due to the large variety of methods. Nevertheless, it is an important issue as it can significantly affect the level of service reliability. This selection depends on different factors such as the topology of the distribution system under study, the available data and measurements, and the desired functionalities and objectives. In this paper, we provided a practical classification and comparison of a relatively large number of methods to support power system engineers and researchers, to choose the right method based on their requirements and the available data and measurements.

In the future smart distribution systems where better measurement and communication infrastructures are deployed, from one side, fault and outage area location algorithms can exploit the new information sources to provide better results; from the other side, issues such as the integration of distributed generations and microgrids which can be operated either in grid connected mode or in stand-alone mode, complicates the calculations. Moreover, the future methods should be accurate and reliable enough to meet the future distribution systems requirements in terms of continuity of supply. Therefore, exploring the applications of the emerging technologies to enhance the performance of the fault and outage area location methods is a fertile field for future studies. In this regard, the required investments and the reliability and techno-economic benefits of different schemes still require broad investigations.

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