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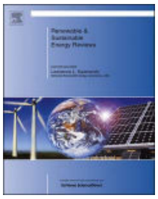

Fault location and detection techniques in power distribution systems with distributed generation: A review

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ABSTRACT

Distribution systems are continuously exposed to fault occurrences due to various reasons, such as lightning strike, failure of power system components due to aging of equipment and human errors. These phenomena affect the system reliability and results in expensive repairs, lost of productivity and power loss to customers. Since fault is unpredictable, a fast fault location and isolation is required to minimize the impact of fault in distribution systems. Therefore, many methods have been developed since the past to locate and detect faults in distribution systems with distributed generation. The methods can be divided into two categories, conventional and artificial intelligence techniques. Conventional techniques include travelling wave method and impedance based method while artificial intelligence techniques include Artificial Neural Network (ANN), Support Vector Machine (SVM), Fuzzy Logic, Genetic Algorithm (GA) and matching approach. However, fault location using intelligent methods are challenging since they require training data for processing and are time consuming. In this paper, most of the techniques that have been developed since the past and commonly used to locate and detect faults in distribution systems with distributed generation are reviewed. Research works in fault location area, the working principles, advantages and disadvantages of past works related to each fault location technique are highlighted in this paper. Hence, from this review, the opportunities in fault location research area in power distribution system can be explored further.

1. Introduction

Fault in a distribution system is an unpermitted deviation from its standard operating conditions. It may be caused due to various reasons, such as physical contact between lines that creates a short circuit path, momentary contact of animals or birds, or contact due to wind and trees. Some faults exist for a short period of time and return to normal operating state. They are called temporary faults. Another type of fault is permanent fault, which will remain until the short circuit is identified and removed. If temporary faults are not cleared, eventually they will change into permanent faults sooner or later. Some of the reasons for permanent faults are cable insulation failure due to improper maintenance, objects falling on overhead lines and lines falling on earth.

There are four main types of fault which can occur in distribution systems; they are single line to ground fault (SLGF), double line to ground fault (DLGF), line to line fault (LLF) and three-phase to ground fault (LLLGF). Single line to ground fault occurs when one of the three phase conductors of a distribution system is touching ground due to wind, animal contact or a line falling on the ground. SLGF occurs at the rate of 70% in distribution systems [1]. Line to line fault occurs when high wind causes one phase to touch another phase while 15% of fault in distribution system is due to line to line fault [1]. In DLGF, two phases will be involved instead of one phase as in SLGF scenario, where 10% of fault in distribution systems is due to double line to ground fault [1]. Three-phase to ground fault may be caused by equipment failure, tower falling on ground or a conductor touching the other phases. In general, this type of fault is not common and least frequent at the rate of 5% in distribution systems [1]. Even though the fault is not common, the occurrence of LLLGF is dangerous with very large fault current. Hence, in order to prevent damage to equipment and loss to customer, faults have to be spotted quickly.

From a survey in [2], it was found that more than 80% of the interruptions in distribution systems are caused by faults. When a fault happens at the feeder laterals or at any location along the feeder, a circuit breaker at the main feeder will disconnect the source from the main feeder. Hence, customers connected along the main feeder will experience a power outage. This power outage degrades the quality of power supply. The average cost for an outage duration of 1 h was USD3 for residential customers, USD1200 for commercial and USD82000 for

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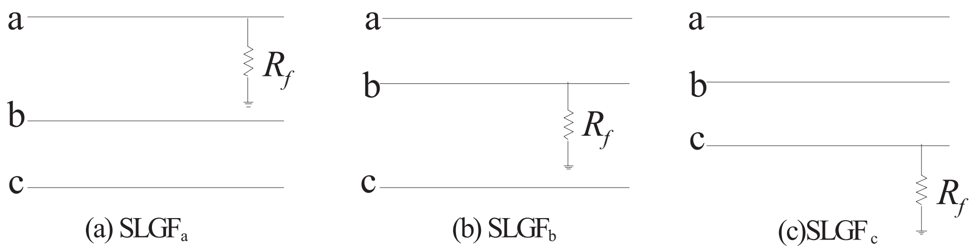


Fig. 1. (a) Single line to ground fault at phase a (SLGF$_a$), (b) single line to ground fault at phase b (SLGF$_b$) and (c) single line to ground fault at phase c (SLGF$_c$).

large industrial customers [3]. Hence, it is very important for the utility to identify the fault as quickly as possible to minimize the impact of fault, power outage and interruption time.

The information about fault in a distribution system can be obtained at the operation centre using protective device operation or using end user information. Since the past, power utilities have been practicing conventional techniques for fault identification. The most common conventional technique is based on visual inspection and trial-and-error switching. For a small area, foot patrol is practiced to search the possible fault location while for a larger scale area, automobile or helicopter is commonly used. This approach of fault location through visual inspection is suitable for overhead lines. However, for underground cables, the fault line is not noticeable. Also, trial and error method is a manual process of switching the relay to on/off condition until the circuit breaker trips. It depends on the network operator's fault finding experience to locate the faulted section. However, this process is time consuming and on long run will damage the performance of cables. Due to these problems, various fault location methods have been introduced for the purpose of expediting the process of locating faults.

In this paper, most of the techniques developed since the past and commonly used to locate and detect faults in distribution systems with distributed generation are reviewed. The working principles, advantages, disadvantages and review of past works related to each technique are described and compared. Hence, from this review, the opportunities in fault location research area in power distribution system can be explored further.

This paper consists of five sections. Section 1 covers the introduction of fault and its types in distribution system. Section 2 describes the types of fault commonly encountered in power distribution systems. Section 3 presents review on the existing conventional fault location techniques, which include travelling wave based and impedance based methods. The working principles of each method with its advantages and limitations are discussed. Section 4 describes some of the existing artificial intelligence techniques in fault location in distribution systems. The advantages, disadvantages and review of past works related to each technique are described and compared. Finally, Section 5 summarises the techniques of fault location and detection methods that have been developed to date.

2. Types of fault

There are two types of fault which are usually encountered in distribution systems, namely balanced faults and unbalanced faults, also known as symmetrical and asymmetrical faults respectively. Many faults that occur in power systems are unbalanced faults. Faults can also be categorised as series and shunt faults [4].

2.1. Series fault

Series fault occurs when unbalanced series impedance presents on a line. It represents an open conductor. Series fault occurs when a power system network has a broken line or impedance in one or more than one lines. Series faults are categorised by using frequency and its voltage rise and current reduction at the faulty phases.

2.2. Shunt fault

Distribution systems generally experience shunt fault. Phase-overcurrent relays and ground-overcurrent relays are commonly used for detecting and isolating the faulted circuit in a distribution system. The important characteristic of shunt fault is the increment in the current and fall in voltage and frequency. For a three phase line, shunt faults are classified as single line to ground fault (SLGF), double line to ground fault (DLGF), line to line fault (LLF) and three-phase to ground faults (LLLGF).

2.2.1. Single line to ground fault (SLGF)

Single line to ground fault (SLGF) is also known as short circuit fault. It occurs when one phase of transmission line makes contact with ground or neutral wire. Some of the reasons for SLGF are wind, falling trees or any other incident. Three types of SLGF are shown in Fig. 1 where a–c represent the phases and R_f represents fault resistance. 70% of faults in network are classified under this category.

2.2.2. Line to line fault (LLF)

Line to line fault occurs due to high winds or when two conductors are short circuited. It may occur at overhead or underground transmission systems. Fig. 2 represents line to line fault on three phase line conductors. One of the characteristics of LLF is the magnitude of fault impedance may vary over a wide range, resulting it difficult to predict its lower and upper and limit. 15% of faults in network are considered as line to line fault.

2.2.3. Double line to ground fault (DLGF)

Double line to ground fault will occur when a falling tree connects

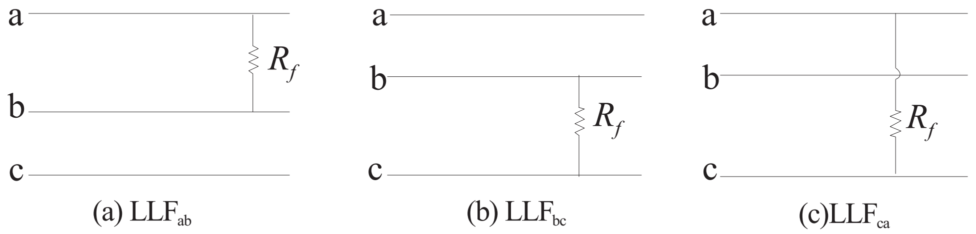
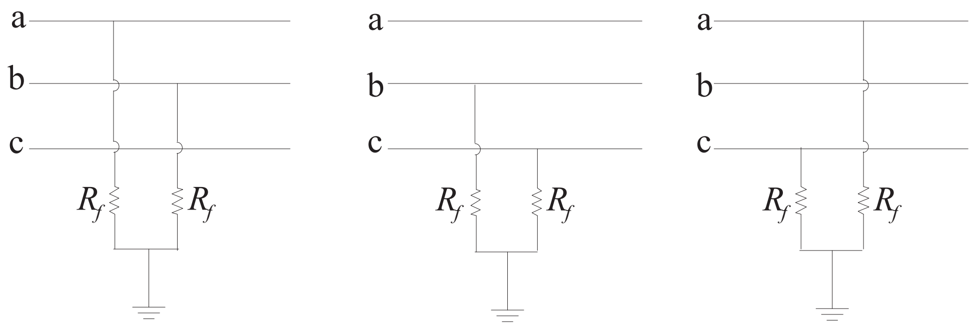


Fig. 2. (a) Line to line fault at phase a and b (LLF$_{ab}$), (b) line to line fault at phase b and c (LLF$_{bc}$) and (c) line to line fault at phase c and a (LLF$_{ca}$).



(a) DLGF_{ab} (b) DLGF_{bc} (c)DLGF_{ca}

Fig. 3. (a) Double line to ground fault at phase a and b (DLGF_{ab}), (b) double line to ground fault at phase b and c (DLGF_{bc}), and (c) double line to ground fault at phase c and a (DLGF_{ca}).

two phases with the ground. Fig. 3 represents double line to ground fault on three phase conductors. A DLGF is a serious event, which results in a significant asymmetry and it may become a three-phase fault if it is not cleared in a certain time. 10% of faults are classified as DLGF.

2.2.4. Three-phase to ground fault (LLLGF)

Three-phase to ground fault (LLLGF) is also known as symmetrical fault. It may occur due to an equipment failure, falling tower or a line connecting the remaining phases. In real scenario, LLLGF does not often exist and occupies only 5% of line faults. It is the most dangerous fault although it is the least fault occurrence. Fig. 4 shows a general representation of three-phase to ground fault. The characteristics of three-phase to ground fault are voltage level equals to zero and the fault current is very large.

The percentage occurrence of each fault type and its severity are shown in Table 1. The fault severity can be expressed in terms of the fault current magnitude and its potential of resulting in damage. In power systems, a three-phase to ground fault is the most severe and is caused due to simultaneous short circuit between all three lines while the least severe fault is a single line to ground fault. Also, the percentage occurrence of fault due to other elements of power systems is shown in Table 2.

Table 1
Severity of fault occurrence.

Fault	Percentage of Occurrence	Severity
SLGF	70%	Less severe
LLF	15%	Less severe
DLGF	10%	Less severe
LLLGF	5%	More severe

Table 2
Fault occurrences due to power system elements.

Power System Element	Percentage of fault occurrence (%)
Transformers	10
Overhead lines	50
Underground cables	9
Switch Gear	12
CT, PT relays, Control equipment etc.	12
Generators	7

3. Conventional fault location techniques

3.1. Introduction

In general, electric power systems consist of generation, transmission and distribution through power systems. Electric power is generated in a power generation plant and transmitted to distribution stations through transmission lines. The transmitted power is distributed through distribution systems, which supply the required power to consumers. The main objective of power system networks is to supply continuous power to customers.

However, fault may occur in distribution systems, which is unavoidable due to natural causes of wind or any other incidents. A fault causes current to pass through an improper path, which will damage the equipment and lead to power interruption [5]. Hence, in order to maintain continuous power supply and reliable service to consumers, faulty line has to be identified and isolated from the system. The fault severity depends on the fault current, short circuit location and voltage level. Various researches on fault analysis have been done over years and fault location techniques are proposed to find fault in distribution systems. Faults in distribution systems with distributed generation can be identified using conventional methods such as travelling wave based, impedance based method and artificial intelligent methods. A review of existing methods for fault location is presented in the following section.

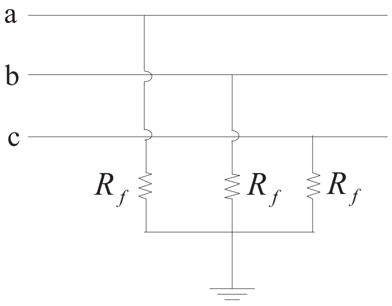


Fig. 4. Three phase to ground fault.

3.2. Travelling wave method

Travelling wave method is based on the principle of transmission and reflection of the travelling waves between the line terminal and the

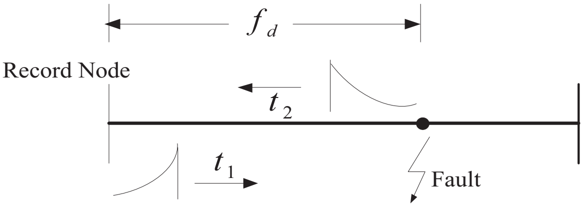


Fig. 5. Travelling wave method.

fault location. This method is shown in Fig. 5, where t_1 is the time taken for the travelling wave from the measurement node to the fault location, t_2 is the time taken for the reflected wave from the fault location to the measurement node and f_d is the fault distance which needs to be identified. The fault distance is identified using

$$f_d = \frac{\nu * (t_2 - t_1)}{2} \tag{1}$$

Travelling wave method requires high speed data acquisition devices, sensors, fault transient detectors and Global Positioning System (GPS) to capture the transient waveform for fault location. In [6], an investigation on the lightening related fault was analyzed. The time of arrival of generated travelling wave by fault was identified using GPS. The accuracy of the method depends on the accuracy of the estimated values of line parameters, such as line inductance and capacitance. The advantage of this method is that, it is not affected by the load variance, high grounding resistance and series capacitor bank.

Travelling wave based on fault locators for overhead lines are classified into single terminal and two terminal locations. These two types were analyzed and compared in [7], which described the merits and demerits of each method. It shows that two-terminal location method has broad prospects than single terminal method. The proposed travelling wave fault location method is fast and gives accurate fault location and can reduce the power loss. A single terminal fault location method using the time domain and frequency domain characteristics of the fault was proposed in [8] for transmission lines. The method calculates fault distance based on the determined time and velocity. It shows that the travelling wave method is not affected by fault type, resistance, distances and inception angles.

A method without using GPS timing was suggested in [9], which recorded the transient wave at the bus bars using wavelet de-noising. The transient wave has information about the fault and its statistical parameters which are utilized to locate the fault. However, this method yields higher error compared to the fault location using GPS although the cost was reduced by omitting a GPS receiver. A real time travelling wave-based fault location method was proposed in [10]. The method was based on two terminal travelling wave and links both the ends of a transmission line by a communication system. The advantage of the method is that it can be used in either synchronized or unsynchronized two terminal data. A double terminal fault location method was proposed in [11]. The method uses a combination of travelling wave principle with wavelet transform to locate fault. The method finds the distance to the fault point by determining the time of initial travelling wave reaching both ends of the line. Simulation results show that the method locates fault point effectively and precisely.

From the review, it can be noticed that travelling wave method is more widely used in transmission lines but not in distribution lines. The reason is due to the presence of lateral branches and sub-branches in distribution systems. The advantage of the method is that it is independent of the network configuration and devices installed in the network. The disadvantage of this method is that it requires devices such as GPS and sensors to capture transient waveform, which makes the method costly to be implemented. From a network capability project plan in Australia [12], the capital cost required for commissioning of the travelling wave fault locators ranges between \$877k and \$1895k in the analyzed networks of 220 kV and 330 kV and \$2,211k in case of snowy lines.

3.3. Impedance based method

Impedance based methods are popular among electric power utilities because they are simple and economical compared to travelling wave method. The basic principle of the impedance based method is using the impedance value as seen from the measurement node for fault location. It uses the voltage and current data for impedance calculation. This method is further classified as one-end method and two-end method. The one-end method uses the substation voltage and current for fault location. The two-end method uses the voltage and current at both ends of the distribution system for fault location identification.

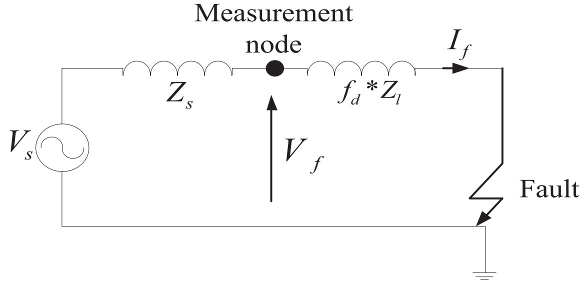


Fig. 6. Impedance based method.

Fig. 6 shows the concept of impedance-based method using a simple circuit model, where V_f and I_f correspond to the voltage and current during fault, Z_l is the line impedance per unit length, f_d is the fault distance from the measured node, V_s is the source voltage and Z_s is the source impedance. Based on Ohm's Law, voltage and current from the measurement node can be used to find fault distance using Eq. (2),

$$f_d = \frac{V_f}{I_f \times Z_l} \tag{2}$$

Different approaches are followed for finding the fault distance considering all types of fault such as SLGF, LLF, DLGF and LLLGF and for different fault resistances. Various methods such as reactive component method, Takagi algorithm and Girgis method have been developed in the past. The objective of these methods is to estimate the location of the fault on radial distribution systems.

Reactive component method estimates the apparent reactance of the line from the measurement node to the fault and then converts the calculated reactance to distance. Sant and Paithankar [13] calculated the ratio of the reactive component of the apparent impedance to the reactance of the line for fault location. They also studied the effect of line capacitances on the fault location [14]. However, the limitation of this method is that the fault resistance was not considered. Hence, this method is not valid for practical cases and is likely to have substantial errors.

Takagi algorithm uses fundamental frequency of voltage and current before and during a fault [15]. The method uses Thevenin equivalent using voltage and current of a faulty line to locate a fault. However, the fault distance was identified using the assumption that the phase angle of the line current and the fault current is equal. Hence, the equation works for homogenous systems. The method was tested in practical transmission line systems and reported to operate satisfactorily.

Girgis et al. [16] derived an equation which is more suitable for distribution systems. In this method, the fault distance and fault resistance are solved by identifying the imaginary and real parts of the apparent impedance equation. The method also proposed an iterative procedure to calculate the voltage and load current at each bus during the fault, based on the known voltage and current at the measured bus. A similar procedure was used in [17–19], which used an iterative approach for fault current calculation. Hence, there is a possibility of calculation error due to repetitive iteration.

A direct approach was presented in [20], which can be used for both balanced and unbalanced systems. The fault-location equations use line impedance matrix, load impedance matrix and fault admittance matrix. The method utilizes matrix inverse lemma for directly solving complicated three-phase circuit equations. However, this method was used only for SLGF. An extended method using direct circuit analysis for line to line fault was proposed in [21] with unbalanced operation of distribution feeders. Since distribution loads vary over time, a compensation technique of load variation considering both angle and magnitude was also presented. Also, line capacitive current component was considered so that the technique could be used for rural and underground system and overhead distribution systems.

Many modified impedance based methods have been proposed to locate the fault in power distribution systems with distributed generations (DGs). This is due to DGs can change the characteristics of distribution systems, which makes the existing fault location methods to be inefficient. In [22,23], a novel fault location method based on positive-sequence apparent impedance was proposed. Comparison of the proposed method with other existing fault location techniques shows that its error from the actual fault in power distribution systems with DGs is lower than the existing methods.

The presence of DGs in distribution systems can also affect the fault location using impedance based method. In [24], it was reported that inverter-based DGs have less effect in impedance based fault location methods than synchronous DGs since they inject less short-circuit current to the fault. Also, it was shown that upstream DGs have stronger effect on impedance based fault location methods than downstream DGs.

Another work on impedance based method to locate all possible fault locations using a single fault location equation was presented in [25]. The proposed method was tested on a modified IEEE 34-bus distribution system with two fixed speed wind turbines. The test results show that the proposed method is robust in identifying the exact fault location under the effects of fault resistance, fault distance and load uncertainty.

The comparison between 10 fault location methods is summarized in Table 3, which shows the performance of some of the most studied impedance based methods in [26–35] and presented in [36]. The fundamental working principles of each method, such as fault distance equation, modeling of lines and the load models are compared. From the test results, the method with the best global performance was proposed in [31]. The lowest error of fault distance for single-phase fault was obtained by Choi [35]. The common results from all of the proposed methods show good performance in locating single phase faults. However, the comparison result in [36] focuses more on the accuracy of the fault distance and avoided discussing multiple possible fault locations. Recently, work in [37] presents an overview of impedance based techniques, which mentioned that two-ended method yields more accurate results than one-ended data. It is more expensive than one-ended approach because measurements are taken at both ends of the line. In addition to the cost, communication links may be required to transmit the measurement value to a control centre.

Table 4 shows conventional fault location techniques that have been studied in the past, which include travelling wave and impedance based methods. The main advantage of impedance based method is that it is more economical to be implemented since it requires only the measurement data. The accuracy of impedance based method is dependent on the accuracy of line parameters, line characteristic and the accuracy of load value. However, the accuracy can be affected by several conditions such as system non-homogeneity, multiple laterals, measurement error in line parameters, inaccurate relay measurements and effect of fault resistance [38].

Table 4
Conventional fault location techniques in the past.

Conventional fault location techniques	Year				
	2011	2012	2014	2015	2016
Travelling wave method	[7]	[8]	[9]	[10]	[11]
Impedance based method	[17]	[24]	–	[25]	[37]

3.4. Synchronise voltage and current measurement

A fault location method for distribution systems to multi-source unbalanced systems using synchronise voltage and current measurement was reported in [39]. The method uses synchronized voltage and current measurements at the interconnection of DG units, where the Thevenin equivalents of positive-sequence, negative-sequence and zero-sequence for each source type were employed. Tests on a 60-bus distribution system for all fault types with different fault resistances on each section of the system show good results. The method was also able to adapt to changes in the system network.

4. Artificial intelligent techniques

Due to the complexity of distribution systems and various uncertainty factors that are difficult to address using conventional techniques, a knowledge based technique is applied for locating faults. In general, the technique requires information such as feeder measurement, substation and feeder switch status, information provided by fault detection devices installed along the feeders and atmospheric conditions. This information can be analyzed using artificial intelligence methods. Some of artificial intelligence methods that have been employed in fault location in distribution systems are:

- Artificial Neural Network (ANN)
- Support Vector Machine (SVM)
- Fuzzy Logic
- Genetic Algorithm (GA)
- Matching approach

4.1. Artificial Neural Network

Artificial Neural Network (ANN) is one of the intelligent techniques used for locating faults in distribution systems. ANN recognizes difficult patterns of information, which makes it possible to locate faults. However, they need a training process to locate fault with a set of data input and the expected outcome. A general concept of ANN is shown in Fig. 7, where voltage phase (V) and angle (ϕ) are the training

Table 3
Comparison between 10 fault location methods [36].

Analyzed aspect	Warrington [26]	Srinivasan et al. [27]	Girgis et al. [28]	Zhu et al. [29]	Agarwal et al. [30]	Das [31]	Novosel [32]	Yang [33]	Saha el al. [34]	Choi et al. [35]
Line model	Short	Long	Short	Short	Short	Long	Short	Short	Short	Short
Non homogeneity	No	No	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Unbalanced System	No	No	No	Yes	Yes	Yes	No	No	No	Yes
Laterals	No	No	Yes	Yes	Yes	Yes	No	No	No	No
Load taps	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	No

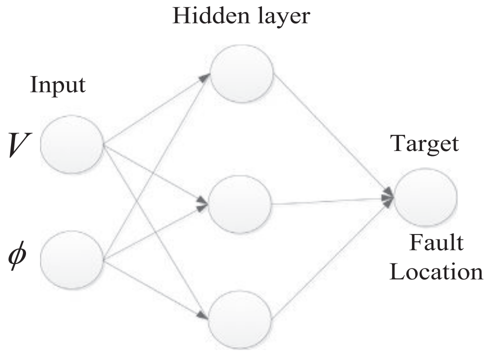


Fig. 7. Artificial neural network.

input from the measurement node and the target output is the fault location.

In [40], ANN uses two approaches of finding fault distance in transmission lines using one- and two-end measurements. It uses cascade correlation for fault detection and was concluded that both approaches perform equally good in identifying fault location. Also, it is noted that cascade correlation uses less amount of epochs and less number of hidden layers compared to multilayer perceptron (MLP).

In, [41] a method to detect high impedance fault for nonlinear arcing was proposed. The method evaluates lower order harmonics of voltage and current. Later, ANN-based method without considering the fault inception angle was proposed in [42]. The method considers fault resistance and is independent of the fault inception angle. It utilizes the fundamental components of pre-fault and post-fault positive sequence components of voltage and current as input for estimating the fault location. The method considers MLP with back propagation training algorithm and Levenberg-Marquardt optimization method.

A neural network was used to assist the operator in fault section estimation control centre in [43]. The work was based on the operation information of circuit breakers and protection equipment. For the diagnosis, the protection of transformers, bus bars and transmission lines were modelled with two types of ANN; the multilayer perceptron and general regression neural networks. The test results managed to cope with changes in system network in real bulk power systems without training the networks again.

ANN has also been applied to locate and detect high impedance faults (HIF) in distribution systems with DGs [44]. This is due to HIFs are difficult to be detected and located using traditional digital relaying. In the work, the input data are the current phase components and local measured voltage while the output data are the classification and location of the fault. The tests conducted on a distribution system with DG show that higher efficiency and robustness of the method were achieved compared to usual detection method.

Javadian [45] uses multilayer perceptron (MLP) neural network to identify fault types and locations. The method was implemented on a distribution system considering DGs. The fault current at three phases was used as input to neural network. MLP with back propagation is the most commonly used method in ANN. However, due to slow convergence speed of the back propagation algorithm and more calculations in MLP network, Lavenberg-Marquardt was proposed to increase the convergence speed. Also, MLP model suffers from slow learning rate and there is a need to guess the number of hidden layers and neurons in each hidden layer.

An approach using maximum loading point neural network was reported in [46], which includes DGs in a distribution system for fault type and location identification. Several approaches using MLP neural networks were proposed to determine the fault type in distribution systems with DGs. In [47], through normalizing the main source of the fault current after determining the fault type, the neural network was used to find the exact location of the fault. The method managed to achieve a good accuracy. This shows that MLP neural network can be a good application to locate a fault in distribution system with DGs.

In [48], a method using feed-forward ANN was used to classify and locate faults in a distribution network. The method uses fault voltage and current samples to locate fault. The proposed method was tested for various fault types, fault locations, fault resistances and fault inception angles. A maximum percentage error of 3% was obtained in the analyzed test cases.

ANN was tested in an IEEE 34-bus distribution feeder to estimate the fault distance to the substation [49]. The input data consists of three-phase voltages, currents and active power of the feeder measured at the substation in pre-fault and fault condition. The fault location, fault resistance and loads were changed in each operating pattern. It was found that the trained ANN managed to estimate the fault distance to the substation successfully. The proposed method was also effective when the input data was included with measurement error.

A back propagation network was implemented in [50] to identify the type of the fault. The frequency bands and energy distribution at different moments are extracted by Hilbert-Huang transform from asymmetric ground fault. The method uses zero sequence current as the input feature of the network. It was found that the proposed method has improved the accuracy of different fault identification, fault distance, grounding resistance and fault time.

A combination of wavelet transform and modular multilayer feed forward neural network was presented in [51], which identified the fault type and the location. Test results show that the method identified the faulty phase and fault type within one cycle time from the inception of the fault. Fault distance was identified with a maximum error percentage of 0.688%. Thus, the results confirm the reliability and suitability of the proposed method under different fault situations.

The main advantage of ANN is its simplicity in implementation. The disadvantage of the method is that it is highly dependent on the amount and quality of the trained data in producing a well-trained ANN algorithm. A limited amount of information will therefore affect the performance of the method. This problem happens for distribution systems with limited information resulting from an insufficient number of monitoring devices. Other disadvantage of ANN is that the training process has slow convergence. Also, the parameters such as hidden layers, neurons and learning rate are identified using trial and error case. In addition, the ANN algorithm needs to be re-trained whenever the system undergoes changes.

4.2. Support Vector Machine

Another recent type using knowledge based method is support vector machine (SVM) [52]. SVM is widely used in classification and regression techniques, which is gaining popularity among various intelligent techniques due to its performance. The number of support

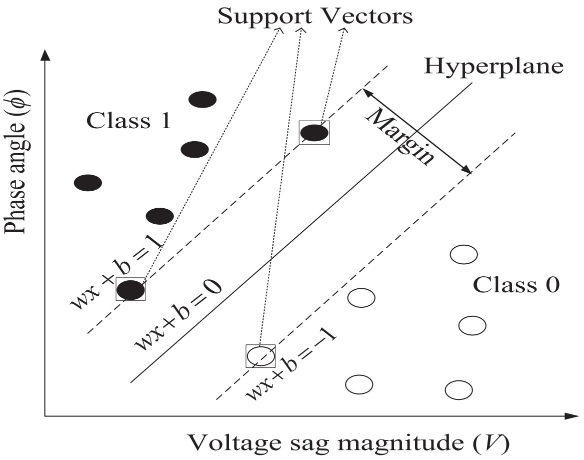


Fig. 8. Linear classification using SVM.

vectors for SVM is determined by SVM algorithm whereas in neural network, the number of hidden layers is determined by trial and error method. This facility makes SVM a better classification algorithm than ANN. Also, SVM does not require any training effort like neural network for good performance.

The concept of SVM classification is shown in Fig. 8 for classification between two classes (Class 1 and Class 0). The points are marked using training set of the voltage phase and angle data for fault classification. Support vectors are the elements of the training sets, which identify the dividing hyper plane. The black circles represent class 1 and the empty circles represent class 0. The input for class 1 and 0 are from measurement node (V and ϕ) and the target output is the type of fault by identifying the optimal hyper plane. The objective is to identify the hyper plane for classification of 1 and 0 classes. The hyper plane separates all samples and also maximizes the margin between the two types. The margin is defined as the sum of the minimum distance between training data set and the separating hyper plane. For non-linear patterns, SVM uses kernel function to transform the original data to map into high dimensional feature space.

Suppose the training samples are $\{x_i, y_i\}$ where i=1 to l, $x_i \in R^n$ represents independent variables and $y_i \in (-1, +1)$. A hyper plane can be expressed by

$$f(x) \Rightarrow wx + b = 0 \tag{3}$$

where w is vector of coefficients and b is a constant. The perpendicular distance from hyperplane to origin is $|b|/\|w\|$. If the output is $y_i = +1$ then the training samples satisfy the following constraint,

$$y(wx + b) \geq 1 \tag{4}$$

The optimal hyper plane is identified when the margin is the maximum. The maximum margin leads to constraint optimization problem, which can be solved using Lagrange function. If Lagrange is not equal to 0, then it denotes the support vectors. The optimization problem is given by

$$\text{Maximize: } \sum_{i=1}^{l} \alpha_i - \frac{1}{2} \sum_{i=1}^{l} \sum_{j=1}^{l} \alpha_i \alpha_j y_i y_j (\phi(x_i)\phi(x_j))$$

$$\text{subject to } \sum_{i=1}^{l} \alpha_i y_i = 0 \text{ and } 0 \leq \alpha_i \leq C \text{ for i } = 1, 2, \ldots, l \tag{5}$$

where $\phi(x_i)\phi(x_j)$ is the kernel function and is represented as $K(x_i x_j)$.

The value of kernel function is equivalent to the inner product of two vectors x_i and x_j in the feature space, $\phi(x_i)$ and $\phi(x_j)$. Kernel function transforms non-linear separable dataset into a new high dimension space where the dataset is made linearly separable. Different types of kernel used for training the SVM are

- Linear Kernel $K(x, y) = x.\ y$ (6)
- Polynomial Kernel $K(x, y) = (\gamma(x.\ y) + \gamma)^{\text{degree}}$ with $\gamma > 0$ (7)
- Radial basis kernel $K(x, y) = \exp(-\gamma\|x.\ y\|^2)$ with $\gamma > 0$ (8)
- Sigmoid kernel $K(x, y) = \tanh(\gamma(x.\ y) + \gamma)$ (9)

where γ is the kernel parameter. By solving the dual Lagrangian, the nonlinear decision function is obtained as $f(x) = \text{sgn}(\sum_{i=1}^{l} \alpha_i y_i k(x, x_i) + b)$ where x is the test vector, b is the constant found from the primal constraints and is computed by $\alpha(y_i(w.\ x_i + b) - 1) = 0$, $i = 1, \ldots.. ,l$ such that α_i is not zero and sgn is a signal function.

An effective method of fault location for transmission lines was proposed in [53]. The method uses the fundamental components of voltage and current at ill phases for fault location. The fault distance was identified using the high frequency range characteristics of voltage and current. In [54], radial basis function (RBF) neural network and SVM are used to identify the fault. The method uses three phase voltage signals to locate the fault. The method utilizes SVM classifier and shows better classification rates than the RBF classifier, especially for oscillatory transients. By decreasing the number of training vectors, the difference between RBF and SVM classifiers grows in favor of SVM. This shows that the SVM network has satisfactory generalization ability and was able to recognize sags and other disturbances correctly, for the wide range of variable parameters.

A comparison was made between RBF neural network and SVM in [55], which shows neural network has a disadvantage of minimizing error function by affecting the learning process. SVM has also been applied for fault classification in transmission lines. In [56], information obtained from the wavelet decomposition of post fault current signals was used as the input to SVM for classification of fault type in transmission lines. The proposed method was tested on a 240 kV, 200 km transmission line under different types of fault and system variables, such as fault resistance, fault distance and fault inception angle. The results show that the proposed technique was accurate and robust for various system parameters and fault conditions.

SVM was used as an intelligent tool in [57] to discriminate between different zonal element faults in transmission systems. The method uses apparent impedance values from distance relay at different fault conditions. The method was successful for different operating conditions and fault resistance values. Another work also uses SVM for a transmission line with series compensated using a fixed capacitor placed at the centre of the line to classify a fault [58]. The samples of each zero sequence current and line current are the input features of SVM, which classify the corresponding fault. The method was tested on a 400 kV transmission line for different fault resistances, fault position, fault inception angles, percentage compensation levels, pre-fault power transfer levels and source impedance values. Test results indicate that the proposed technique is fast, accurate and robust.

A hybrid approach using wavelet transform and SVM was suggested in [59,60] for precise fault location in transmission lines. The voltage and current signals at one end of the transmission system were used in [59] to locate a fault. It works in three stages. Firstly, wavelet transform was employed to extract the high frequency components of voltage and current. Secondly, fault type was identified using support vector classification. Finally, the fault distance was identified using support vector regression analysis. The accuracy of fault type identification is 1% and 0.7% for fault distance. The limitation of the method is that it does not consider the faulty phase in the system. The method in [60] identifies the faulty section and fault distance. The faulty section was identified using the zero sequence current variation before and after closing the switch in ring network. The method also utilizes wavelet transform to extract eigenvalues from zero sequence current. The extracted values are then trained using SVM to identify the fault distance. The proposed method was analyzed only for single phase grounding fault and is not suitable for other types of fault.

In [61], SVM was used to estimate the fault type and the fault distance of long transmission lines. It uses post fault single cycle current waveform to analyze the fault. The features are collected by wavelet packet transform and the redundant features are removed through forward feature selection method. The test data are examined by SVM in which the parameters are optimized by particle swarm optimization method. The simulation results yield maximum fault classification accuracy and minimal fault position error.

The advantage of SVM is that it is faster even for large-sized problem and requires less heuristics. The main features of SVM are the upper bound on the generalization error does not depend on the dimension of the space. Also, the error bound is minimized by maximizing the margin. These differences make SVM more attractive in statistical learning applications than other artificial intelligence methods.

4.3. Fuzzy Logic

In fuzzy set theory, the concept of possibility is used instead of the concept of probability. Possibility is defined by a number between one (completely possible) and zero (totally impossible). Probability is an appropriate measure of uncertainty if statistical information is available. In uncommon situations where no statistics are available, an expert may be able to express degrees of confidence in various hypotheses.

Fuzzy logic-based classification scheme was proposed in [62–64], which identified the type of fault in transmission systems. In [62], higher order statistics were developed to extract the features of fault signal and to categorize the fault using fuzzy logic. Fault identification using line current measurement of all 3 phases was proposed in [63]. Later, the method was developed in [64] for fault type in unbalanced systems.

Fuzzy system and synchronized phasor measurement was used in [65] to identify the fault type and fault location in double circuit transmission lines. The method classifies series, shunt and simultaneous series-shunt faults. Test results show that the fault location error percentage is within 1% for series fault and is up to 5% in case of shunt fault. An approach for fault detection and classification based on fuzzy logic and Programmable Automation and Control technology was presented in [66]. The three phase alternating current, zero sequence and positive sequence current data are generated and processed directly for relaying. The results show that the proposed technique is capable of right tripping action and can give automatic protection in real time. Although fuzzy logic-based scheme is quite satisfactory, the drawback of fuzzy logic is in determining the global minimum using fuzzy membership functions. Also, feature definition and extraction have to be enhanced for classification algorithm.

4.4. Genetic Algorithm

Genetic algorithm (GA) is an intelligent technique that can also be used to locate fault. The method searches the possible fault location through selection, crossover and mutation operations to identify the exact location. The algorithm of GA is shown in Fig. 9. An approach for faulty section estimation using GA was proposed in [67]. In this work, the faulty section estimation is treated as an optimization problem. The objective function is identified using Hebb's rule and used by Continuous Genetic Algorithm (CGA) optimization for faulty section identification. The objective function reduces the time required by CGA to identify the faulty section. The method uses less storage and is faster than Binary GA.

A new method using GA was proposed in [68], which divides the distribution systems into main branch and into individual regions. The independent regions are detected using the fault current and GA was used to find the fault for the main branch and fault independent regions. This method is only suitable for single fault or complex fault location of single power source. A fault location method using GA for transmission lines was proposed in [69]. It uses line parameters at both terminals of the line to identify the fault location. The method was tested with the actual fault recording data obtained from the south grid of China.

Genetic Algorithm and wavelet transform were used in [70] for fault sorting of three-phase transmission lines. The method uses three-phase currents at one end of transmission line for fault detection. The features are extracted using discrete wavelet transform and used as inputs to GA. The proposed method classifies fault with a maximum error percentage of 7%.

The advantages of this method are the simulation speed can be enhanced and the dimension of possible solutions can be reduced. The disadvantage of GA for fault location in distribution systems is the results are not consistent over time because in GA, almost all processes are random. There is a possibility that GA may produce inaccurate results, hence online analysis using this method might not be appropriate.

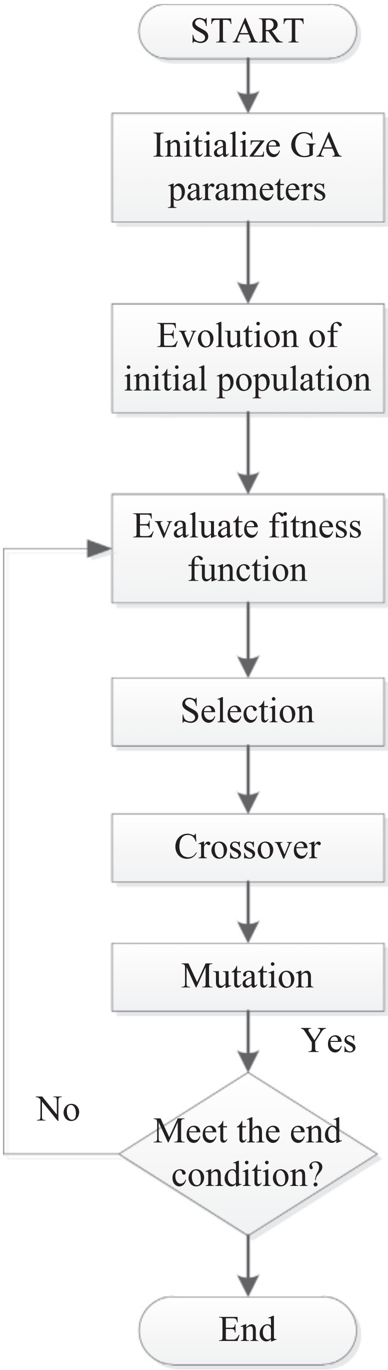


Fig. 9. Flowchart of Genetic algorithm.

4.5. Matching Approach

Matching approach uses database for fault location identification. The method makes a comparison between the measured data and the simulated data. Commonly, voltage sag or current data are recorded to identify the location of the fault. In [71], a method to identify the faulty section was proposed, where a database was created by generating fault at various sections. When a fault occurs, the voltage sag during the actual fault was compared with the one in database to identify the faulty section. The limitation is that the method identifies only the faulty section; hence maintenance crew needs to patrol along the suspected line section to find the exact location of the fault. This process consumes time if the line section is long and will delay the restoration process. Later, the method was further improved in [72] for

Table 5
Comparison of artificial intelligence techniques.

Artificial intelligence techniques	Advantages	Disadvantages
ANN	Simplicity in implementation.Detects the nonlinear relationship between dependent and independent variables.	Dependent on the amount and quality of the trained data in producing a well-trained ANN algorithm. Training process has slow convergence. The parameters such as hidden layers, neurons and learning rate are identified using trial and error.
SVM	It is faster even for large-size problems and requires less heuristics. Upper bound on the generalization error does not depend on the dimension of the space and the error bound is minimized by maximizing the margin.	The limitation is in choosing kernel function and hyper parameters which gives the best generalization performance.
Fuzzy logic	Fuzzy logic handles uncertainties and can also interpret input/output relationship by producing rules.	The drawback is in determining the global minimum using fuzzy membership functions. Feature definition and extraction have to be enhanced for classification algorithm.
Genetic algorithm (GA)	Simulation speed can be enhanced and the dimension of possible solutions can be reduced.	The results of fault location are not consistent over time because in GA, almost all processes are random.
Matching approach	It is a more economical method since it considers only the measurement node voltage sag or the current data.	The method is dependent on the simulated data stored in a database for matching the data with actual fault data. The process of creating database is time consuming since it is created through simulation for fault at all nodes.

finding the fault distance. The fault distance was calculated using a trigonometric equation considering a linear representation of voltage sag between two nodes. An improvement was made in [73] considering voltage sag nonlinear representation between two nodes. A set of two quadratic equations are framed using voltage phase and distance and current phase and distance for fault distance calculation. However, this method is more accurate for lower fault resistance.

A work in [74] proposed an improved faulty section location for LLLGF by considering multiple measurements in a distribution system. The method proposed a new method to identify faulty section and a ranking procedure to prioritize the faulty section. The method was evaluated on an 11 kV network consisting of 5 branches and 43 nodes. The test result shows that correct fault distance was achieved by taking the average of the fault distance from each measurement data.

The advantage of matching approach is that the method is more economical since it considers only the measurement node voltage sag data. The limitation of matching approach is that it is dependent on the simulated data stored in a database for matching the data with actual fault data. The process of creating database is time consuming since it is created through simulation for fault at all nodes.

A comparison on the advantages and disadvantages of artificial intelligent techniques is shown in Table 5. According to the advantages and disadvantages described for each method, it can be noted that artificial intelligent methods have more accuracy and better speed. Among different knowledge-based algorithms, SVM algorithm is widely used than other methods in accordance with the success progress in recent years.

5. Conclusions

This paper reviewed most of the techniques that have been developed since the past and commonly used to locate and detect faults in power distribution systems with distributed generation. The basic principles, advantages, disadvantages and review of past works related to each technique have been studied. The effectiveness of each method described has also been evaluated. In general, fault location methods in distribution systems can be divided into two categories, conventional methods and artificial intelligence methods. The advantages of conventional fault location methods are simple measurement setup and less time is required for computation. However, their disadvantages are they can be inaccurate for too large power system networks and when measurement errors are considered. For artificial intelligence fault location methods, the main advantage is the accuracy is very high even for large power system networks and when measurement errors are considered. However, SVM algorithm of artificial intelligent technique is more widely used in accordance with the success progress in recent years.

In overall, it has been observed that no single method has the capability to solve all the problems since each of them was developed based on specific conditions. Each method suits a problem depending on the complexity of the network and the availability of monitoring devices. Hence, it is concluded that in order for a particular fault location method to be effective, its basic working principles must be comprehensively understood. Also, users have a choice to select methods that best suit their needs and infra-structure. Therefore, researches on fault location and detection techniques in distribution systems are actively on-going in the world.

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