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Recent Developments in Fault Location Methods for Distribution Networks

Abstract. *Reliability and quality of electrical power supply are always affected by the occurrence of faults in the distribution networks. However, the reliability and quality indices of power supply could be improved by locating the fault in minimum time. This task could only be achieved by using automated fault location methods. Various fault location methods have been developed with the main objective to expedite the locating time of the fault and thereby reducing the interruption duration. Considering the important needs of automated fault location methods, the aim of this paper is to review the most recent fault location methods in the literature specifically for distribution networks. The reported papers are from journals and proceedings from year 2005 to 2011. The working principle, strength and limitation of each method are discussed in this paper to highlight possible research opportunities in this area.*

Streszczenie. *W artykule przedstawiono przegląd metod wykrywania i lokalizacji awarii w energetycznych sieciach przesyłowych. Materiał obejmuje publikacje z lat 2005-2011. Opisano wady i zalety każdej z metod ze wskazaniem na potencjalne pola badań. (**Przegląd nowych metod lokalizacji awarii w energetycznych sieciach przesyłowych**)*

Keywords: Fault location method, Distribution networks, Fault detection.
Słowa kluczowe: metoda lokalizacji awarii, sieci przesyłowe, wykrywanie awarii.

Introduction

The deregulation and privatization of the power industry in the early 80's have driven awareness of power quality and reliability. In this competitive business environment, power utility companies are obliged to provide high quality power supply in order to fulfill customers' satisfaction as well as regulator's requirements. Thus, the quality and reliability of power supply in a distribution system has become a major concern to all power utilities. One of the challenges of power utilities in maintaining the reliability and quality of power supply are in short-circuits faults. Since faults cannot totally be eliminated (due to unavoidable factors such as adverse weather conditions, insulation breakdown caused by aging, animal contact and human mistakes), the only way is to minimize its impacts.

A fault in any location in the network has the potential to cause temporary interruption such as voltage drop, temporary losses of supply, or even a blackout in the whole network. The duration of such interruption is measured in terms of Customer Minute Loss (CML). Apparently, very often interruption in distribution networks is caused by faults. For instance, according to a report by the Office of Gas and Electricity Markets (OFGEM) in UK [1], over 75% of CML were caused by faults in distribution networks.

Thus, it is very crucial to locate faults fast to minimize CML. Furthermore, reliability indices such as System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency (SAIFI) can be also improved.

In the past, a fault in the distribution system is located through conventional approaches, such as upon receiving a complaint from a customer, a technical staff is deployed to find the fault by patrolling the suspected faulted feeder. Meanwhile, for an underground cable system, switching operations were widely practiced to identify the faulted section. Thus, the locating process is time consuming and might expose additional stress to the equipment during the switching on/off of a section. Due to these problems, many automated fault location methods have been introduced by researches to expedite the process of locating faults.

Considering the importance of fault location, this paper attempts to present and discuss recent developments in fault location methods for distribution networks. The reviewed technical papers are selected from journals and proceedings published between the year 2005 to year 2011. In this review, the fault methods for distribution networks are categorized as follows:

1. Impedance based methods and Other Fundamental Frequency Methods.
2. High Frequency Components and Travelling Wave Based Methods.
3. Knowledge-Based Methods which can be further divided into:
   a) Artificial Neural Networks.
   b) Matching Approach.
   c) Hybrid methods.

By having this review, researchers who are interested in this subject area can benefit from the latest development of fault location methods. Therefore, improvement in fault location methods could be further conducted. This paper is organized as follows; in the following section i.e. section II, we will present methods that are based on Impedance-based and other fundamental frequency methods. Section III deals with High Frequency Components and Travelling Wave based methods. Then, Section IV will present knowledge-based methods and a final conclusion is presented in Section V.

Impedance Based Method and Other Fundamental Frequency Methods

In general, impedance based methods are using impedance as seen from a monitored node to estimate the location of fault from measurement of voltage or current at the monitored substation. Based on Ohms Law, voltage and current from the monitoring node can be used to determine fault as illustrated in Fig 1.

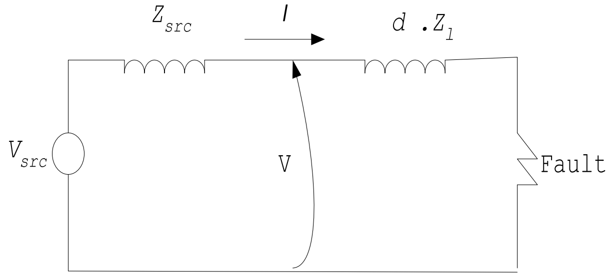

Fig.1. Impedance Based Fault Location Method

The simple formulation of fault location solution with absolute values is:

$$d = \frac{V}{I \times Z_l} \quad (1)$$

where: V = voltage during the fault, Volt, I = current during the fault, Ampere, Z_l = line impedance, ohms per length unit, d = distance to the fault, length unit such as miles

There are various impedance based methods following the basis into (1). Some of the best methods, namely proposed by Das, Choi et.al, Warrington, Novosel et.al, Srinivasan and St-Jacques were compared in [2] to study their performance. In addition, this paper also compares the fundamental working principle of each method such as fault distance equation, modeling of lines and the used load models. From test results, the method proposed by Das and Choi et.al showed lowest error of fault distance for phase to phase fault and two phases to ground fault, but highest error is obtained in single phase fault. On the other hand, the methods proposed by Warrington, Novosel et.al, Srinivasan and St-Jacques show good results for different fault resistance values. The common result from all of the proposed methods showed good performance in locating single phase faults. However, this paper is focusing more on the accuracy of fault distance and does not discuss the multiple possible fault locations.

An extended formulation impedance based method is proposed in [3] to calculate the distance of fault location on distribution systems. Different from other methods, the load variation effect is included in the formulation of the impedance based method. The method has been tested using a network that has multiple laterals, nonsymmetrical lines, highly unbalanced operation and time varying load. Although the test results show promising results, so far the method has not being used in practice. Similar impedance based method as in [3] is further improved by considering line's capacitance [4]. Thus, this method is claimed to be more accurate to locate faults in underground distribution feeders, which has a significant distributed shunt capacity. This method only focuses on single line to ground fault and three phase faults. The proposed method involves iterative procedures in locating fault.

A non-iterative or reduced iterative procedure of fault location is proposed in [5]. This paper introduced two types of algorithms for reducing iterative procedures. Two algorithms are applied for non-radial distribution systems and radial distribution systems. For radial distribution systems, used in analysis of short-circuit and for non-radial distribution systems using bus impedance matrix. The method used is based on the fundamental frequency phasor to develop the bus impedance matrix utilizing the existing voltage and current at the substation.

In most impedance based methods that use a single measurement, multiple fault location is a common problem. This occurs due to multiple electrical distances as seen from the measured node. For a network with high number of branches, the number of possible fault locations could be high. Therefore, in recent developments of fault location based on impedance, the ability to reduce the number of fault locations or to rank the multiple locations according to the most possible location was became one of the main objective [6-8].

Multiple fault locations is addressed in [6] by proposing a new conceptual approach. In this method, the faulted location is identified based on the behavior of the three phase measurement for each lateral, provided that there is difference in the load or line parameters. The effectiveness of the method is shown by using reactance-based method to analyze faults in IEEE 34 distribution test system. However, the method may produce inaccurate fault distance since load current is neglected. Similar methods to identify most possible fault locations as proposed in [6] is also adopted in [7]. In this paper the pre-fault current in the faulted feeder is considered. By doing this, the accuracy of fault distance is claimed to be more accurate. In this method, the multiple possibilities of fault locations is solved using calculated fault current in the healthy phases. Type of fault is determined by monitoring the magnitude of fault current at the substation or by calculating the magnitudes of fault currents. However, both methods [6,7] are more applicable for unbalanced systems.

The complexity of the distribution network (typical and configuration cables, lateral, load distributed, feeder configuration) encourage the improvement of impedance based methods using measurement from Intelligent Electronic Devices (IEDs) [8]. The IEDs are installed at the primary substation to monitor voltage and current signal and recording transient data. The IEDs are able to store, updated and modified database including topology, type of cable, feeder geometry, spacer, twisted and underground. This information is used in estimating fault locations. For multiple locations, a ranking procedure is proposed by considering the status of breaker and fuse operation. Since IEDs and GPS are installed at the primary substation as a tool measurement, so, this technique is costly. Another impedance based method is proposed in [9]. In this work, a simple equation of fault location is proposed to locate a fault. In the equation, voltage and current magnitude measured in a relay is utilized in the equation.

In [10], the proposed impedance based method to determine fault location is by comparing between the voltage and current at the time of pre-fault and during the fault. The devices and feeder architecture are installed on the system for storing the database. To analyze fault location, current pattern is compared with conditions at pre-fault, during faults and post fault. Mathematical algorithms and Fast Fourier Transform is used to calculate the existence of the fault location.

Another impedance based method in [11] has been proposed which is a method based on Newton-Raphson formulation, boundary conditions to get sequence network in a three-phase network which can be used to decide fault distance and fault resistance with utilized voltage and current measurements at substation. Time iteration stage is needed to know a fault section in the network.

In general, it can be seen that the accuracy of impedance based method type are dependent on the accuracy of line parameters, line characteristic and the accuracy of load value. The effectiveness of this method is also affected by the complexity of the network such as unbalanced systems, multiple laterals and fault resistance. For multiple fault locations estimation, status of protection devices was commonly used to identify the actual location. However, for a distribution system that is not equipped with on-line status of protection devices, multiple estimations would be unsolvable.

Travelling Wave Based Technique and High Frequency Components

Travelling wave technique is based on the reflection and transmission of the generated travelling waves along the faulty power networks. This concept can be illustrated as shown in Fig.2.

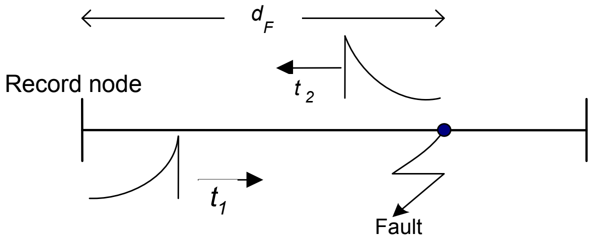

Fig.2. Fault location using travelling wave working principle

The fault distance (d_F) can be calculated using the following expression:

$$d_F = \frac{v \times (t_2 - t_1)}{2} \quad (2)$$

where: v = the velocity of the traveling wave, t_1= time when waveform started to travel, t_2= time when waveform arrived at the record node

The travelling wave based fault locator can be used on single-ended line and spread recorders in along distribution networks. The pattern of the fault-generated travelling wave and the travelling time of the waveform are often used to determine the location of the fault.

In paper [12] it was proposed to compare between information based on starting instants of the voltage transient and travelling wave with both of the methods. GPS is integrated with Event Detection Block (EDB) to detect a logic signal as a transient occurs and triggers. On the other hand, travelling wave is applied to identify the location of laterals. This paper focuses only on phase-to-ground and three phase short circuits.

Wavelet approach is applied in [13] which proposed fault line which was determined by taking advantage Continuous Wavelet Transform (CWT). CWT-based algorithms combined with the measurement system using GPS to obtain the starting instant of the transient and the relevant waveform implemented on the Medium Voltage (MV) distribution networks model by using simulation on the Electro Magnetic Transient Program (EMTP).

Paper [14] proposed the development of algorithms that have been presented in [13]. Continuous wavelet transform mixed with mother wavelets inferred from the fault-originated transient waveforms. Bus test distribution system of the IEEE-34 is used to show the performance algorithm. This paper claims that mother wavelet is used to overcome the limitations in terms of developing the original algorithm. Effectiveness of the algorithm is shown by simulation tool.

Travelling wave based on high frequency method also available. In general, high frequency voltage and current transient signals are injected to determine fault location. In [15], high frequency components are used to detect fault location by injecting sinusoidal signals. It causes feedback which can be obtained by further analyzing each branch starting from the first sequence until the last by separating each layer on different branch. Actual fault is obtained by repeated searching process with the second frequency. Two sinusoidal signals with different frequencies are injected into faulted and calculated with feature extraction schemes. From the table resulting from the simulated line with seven branches, it gives a more accurate distance. Another paper [16] proposed an algorithm of automatically localizing the fault point based on the signal injection method. Feeder Terminal Unit (FTU) and SCADA have been utilized to generate the information of injected current and the information of zero sequence faults. This information was used to obtain the information vector *S* of injected signal. Further, the fault judgment matrix and the flow of automatic algorithm were proposed to detect faulted section. High frequency component also have been utilized in [17] to detect arching fault in distribution network. The proposed method is based on the frequency spectrum analysis to automatically identify the state transformation of duffing oscillator. By utilized the applications of FIR filter bank and duffing oscillator the location of fault can be detected.

Knowledge Based Technique

Due to the complexity of distribution systems and various uncertainty factors such as length of cables and unknown fault resistance that are difficult to address using impedance-based and travelling wave techniques, a knowledge-based technique for locating faults has been explored. In general, the technique requires information such as substation and feeder switch status, feeder measurement, atmospheric conditions, and information provided by fault detection devices installed along the feeders. This information is analyzed using artificial intelligence methods to locate a fault.

Artificial Neural Network

Artificial Neural Network (ANN) is one of the well-known and reliable methods in solving many engineering problems related to classification and optimization. Its ability to recognize complex patterns has made it possible to use also in locating a fault. A general concept of ANN is shown in Fig 3, where the training input can be from measurement data such as voltage, current, status of circuit breaker and feeder. The target output is the location of fault.

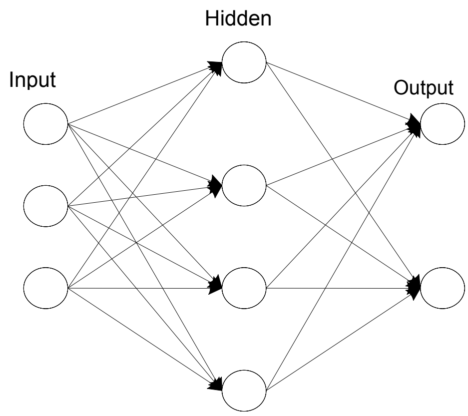

Fig.3. Artificial Neural Network

Previously, many fault location was using ANN for transmission line system, such as in [18]. In this work, parallel process of a novel Complex Least Error Squares (CLES) and Adaptive Linear Neural Networks (ADALINE) were used to locate fault. Most recent work using ANN to locate fault for distribution are proposed in [19, 20]. Paper [19] proposed a Feed-forward Multilayer perceptrons to locate a low current fault on distribution systems. Different types of fault and location are simulated on the studied network for training data. This method has been tested on IEEE 34 node. Although this method can be implemented with low cost, ANN produces multiple fault locations. In [20], ANN using standard back propagation approach was used to locate fault in a distribution network connected with distributed generators (DGs). In this method, the training data is based on the injected current of each DG during the fault. Thus, the accuracy of the method is highly dependent to the number of DGs in the system. Fault type is based on normalized three phase current at a substation.

The main drawback of the ANN method is that it is highly dependent on amount and quality of the trained data to produce a well-trained ANN algorithm. A limited amount of information, or inaccurate information, will affect the performance of the algorithm in correctly identifying the fault location. This problem happens for distribution systems with limited information resulting from an insufficient number of monitoring devices. Other problems with this method are that it has slow convergence in the training process, and that appropriate parameters such as hidden units, layers, learning rate and momentum values, have to be determined. In addition, the ANN algorithm needs to be re-trained whenever there are changes in the system.

Matching Approach

Another recent type of knowledge-based technique is matching approach between measured data and simulated data. Commonly, voltage magnitude and current magnitude measured at one or multiple locations are used to determine the location of a fault. A fault location technique using voltage sag data was proposed in various papers [22-35]. The underlying principal of this approach is based on the severity pattern of the voltage sag that can be clearly differentiated according to the location of fault. A close fault to the monitored node causes more severe sag as compares to fault occurs far from the monitored node as shown in the Fig 4 below [21]:

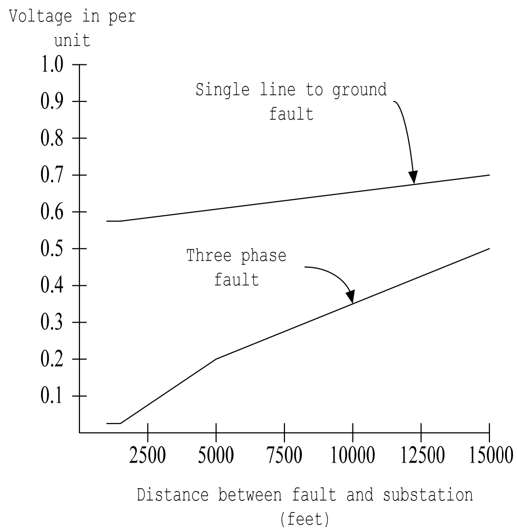

Fig.4. Voltage sag magnitude profile along a feeder due to Three Phase and Single Phase

The earliest reported work of fault location using voltage sag was in [22, 23]. The work proposed a faulted section estimation using database approach for 11 kV distribution network. Simulated voltage sag is generated by simulating a fault at various locations. When actual fault occurs, the measured voltage sag is compared with the generated voltage sag database. The corresponding, voltage sag in the database will lead to the most likely faulted section. Since these methods require measurement of voltage sag at the primary substation, it can be considered economical for implementation.

Latter, the methods in [22, 23] were improved by locating the distance of the fault from a sending node of the identified faulted section [24]. The fault location searching time could be reduced further mainly if long line cables are involved. The fault distance is calculated by considering a linear representation of voltage sag profile between two adjacent nodes. This assumption however is valid only for a short line cable. Thus, further improvement was conducted in [25] to address the non linearity of voltage sag profile by grouping the line into long line and short line. A more accurate fault distance could be achieved by this consideration. Considering the limitation of the previous method [25], paper [26] presents the improvement work of the method. The uncertainty of fault resistance by constructing the voltage sag equations based on different fault resistance values has been considered. Further, the proposed method in [26] was tested to obtain the overall method performance, which was presented and discussed thoroughly in [27]. The computation aspects of the method in [26] was presented in [28], which focusing mainly the algorithm of the method.

Most recent research on fault location based on matching is presented in [29]. The basic principle of the method is using Three-Dimension (3D) Voltage Vector Database Matching method. The method can locate faults in several neighboring substations by utilized data from one monitoring node. The type of fault can also be identified using this method.

Similar concept of voltage sag applied to locate faults was also reported in [30]. This method has been adopted for locating faults on primary distribution feeders. This method required multiple meters in the system. It has been tested on 13.8 kV overhead line with 238-node. Ranking process and possibilities of fault location nodes are considered the phases embroiled in the fault. Similar methods have been proposed in [31], however, with a different test system of 13.8 kV with 134 nodes overhead line. Differing from other methods, the method in [32] is based on the difference in phase angle between the positive sequence component of the current during fault and pre-fault is used to estimate the fault direction. This direction is important for directional over-current relay operation.

In [33], a methodology to develop a comprehensive database for fault location purposes is proposed. In the development, ATP and MatLab were used to produce voltage sag data. In the process of the database development, the status of protective devices was also included. The database is useful for knowledge based type methods of fault location. Paper [34] proposed a fault location software for distribution networks. The software is developed in Matlab and using N-ary-tree structure to address the complexity of distribution networks. Different from previous discussed methods, a statistical methodology to locate a fault in distribution network is proposed in [35]. The approach is based on the statistical modeling and extraction of information from databases associated in fault recording.

Genetic Algorithm

Genetic algorithms (GA) are one of the knowledge-based techniques that have been applied to locate a fault. However, there are very few papers on this topic and the most recent paper is in [36].

The advantageous of GA is that it searches all the possible fault locations through selection, crossover, and mutation operations. Thus, there is a high chance to locate faults correctly. In [36], a continuous GA (CGA) is used to estimate the fault section in a distribution network. However, in this work the objective function is determined using hebb's rule. By using this rule, a simple objective function in terms of linear algebraic equations is used. The objective function is created based on the relays/circuit breakers status.

The flow chart in Fig 5 shows the general step for GA implementation to locate a fault.

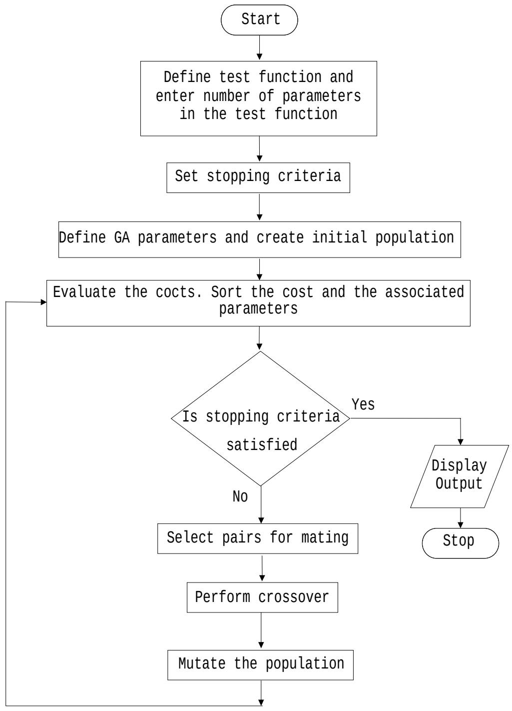

Fig.5. General flowchart of fault location using genetic algorithm [36]

Hybrid Method

Commonly this type of fault location method combines more than one method. By doing this, the strength of each method in locating fault could be combined and thus more accurate locations could be expected. Some of the most current methods are like in [37,38].

The limitation of impedance based methods in producing one possible fault location encourages the use of knowledge based methods such as learning algorithm for multivariable data analysis (LAMDA) together with impedance based methods [37]. In this paper, LAMDA is trained using voltage and current data generated from fault simulation studies to identify faulted zone. An impedance based method, which is Ratan-Das's method, is used to determine the fault distance. As describe in the Fig 6.

Another hybrid method have been proposed in [38]. Impedance-based method, wavelet based and Artificial Neural Network have been amalgamated to detect fault location, fault section, fault type and fault resistance. Wavelet transforms was adopted for detection and for classification process. The results are forwarded for processing to determine fault location with the use of impedance-based methods. Further, current and voltage signal is used to determine fault section by ANN.

In [39] the proposed Artificial Neural Network (ANN) mixed with Support Vector Mechine to detect Fault Location in Distribution Systems. Voltage and current grouping is used to detect the type of fault and to detect Short Circuit Current (SSC) level by using SVM. After this process, testing is used feed forward neural networks to determine the location of actual location of fault.

Other hybrid method is proposed in [40], Impedance based method, k-nearest neighbours (k-NN) and Support Vector Machines (SVMs) method have been combined to locate fault zone. To locate fault zones the use of voltage, current, measured at power substation as input. Fault zones consist of a few sections and are designed by considering complexity of the distribution systems. In this paper fault locator is composed of two main stages:

1. Training is designed to get assosiated object (as an input) and output (fault zone).
2. Testing is aimed to find the best class (fault zone).

For classification the technique used was k-Nearest Neighbours (k-NN). This paper identifies four types of faults, namely single phase, phase to phase, double phase to ground and three phase.

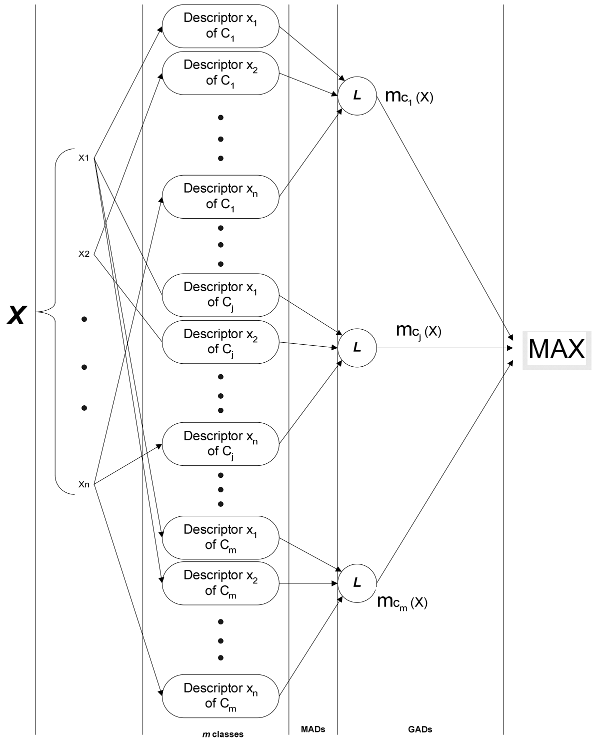

Fig.6. Basic LAMDA recognition methodology [37]

In paper [41] a travelling wave based technique was proposed together with artificial neural network to determine high impedance faults. Training pattern of artificial neural network is available from output of Discrete Wavelet Transform (DWT) as a filter of current signals. Phase current signals have been simulated at five of power distribution feeders which were modeled by Matlab. These distribution systems consist of 35.7 km of overhead line and 8.6 km of underground line. Wavelet analysis and Artificial Neural Networks (ANNs) have been combined in [42] to detect high impedance fault location. EMTP/ATP software was applied to simulate test system (20kV underground power distribution systems).

This paper [43] proposed a method to determine fault location and types of fault in distribution systems utilizing Adaptive Neuro Fuzzy Inference System (ANFIS). Data inputs used post-fault on three-phase RMS current. The expected result is the output data of the type of interference and fault point is indicated by geometrical coordinates (X, Y).

Conclusion

This paper has presented overview of several recent fault location methods proposed from 2005 to 2011 for distribution systems. From the solution point of view, this paper classified fault location method into six categories as in the following table, together with the related reference.

Table 1. The parameters of the sensor

No	Year						
	2005	2006	2007	2008	2009	2010	2011
1	[8]	-	[9]	[2] [11]	[3] [4] [6]	[5] [7] [10]	-
2	-	[13]	[12] [15]	[14] [16]	-	[17]	-
3	-	-	[19]	[18]	[20]	-	-
4	[22]	[33] [35]	[32] [34]	-	[30] [31]	[23] [24] [26]	[25] [27] [28] [29]
5	-	-	-	-	-	-	[36]
6	[39] [41]	-	[37]	[38]	[40] [42] [43]	-	-

Where:

1: Impedance based methods and other fundamental frequency

2:High frequency components and travelling wave based methods.

3: Artificial Neural Network

4: Matching between measured data and simulated data.

5: Genetic Algorithm

6: Hybrid method

From the reviewed articles, it can be observed that there is no single method that has capability to solve all problems since each of them is developed based on specific conditions/assumptions. Each method may suit particular problem i.e. depending on the complexity of the network and also availability of the monitoring technology. For instance, fault location based on intelligent approach may be suitable to be used for a network that equipped with various monitoring equipments. On the other hand, impedance based method is more suitable for single measurement. Hence, it can be concluded that to use particular fault location method effectively, it is working principle basis must be understood.

This exercise also reveals research areas that can be conducted in the future to improve the existing methods. For instance, so far all the discussed methods didn't consider renewable energy interconnection in distribution system such as mini hydro, photovoltaic farms and wind forms. Hence, such improvement could be one of the future works for fault location method.

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