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A Comprehensive Review of Fault Location Methods for Distribution Power System

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Abstract

Fault on distribution system does not only affect the reliability of power supply, but also contribute to increasing operational and maintenance cost borne by the utilities. Throughout the years, various methods have been studied and practiced to solve problems related to the fault location in the distribution system. In this paper, the fault location methods are reviewed and summarised according to their categories. The fault location methods discussed in this paper are based on literature studies of outage mapping and field measurement for the distribution system. Furthermore, the component which influences the fault location methods such as unbalanced system, capacitance effects, distributed generation, and distribution topology are related to the explanation of the method. Finally, the field measurements are presented as in comparison which will clarify the effectiveness and the establishment of each method.

Keywords*: Fault location, Power system, Outage Management System*

1. Introduction

Power distribution systems, whether located in rural or urban landscapes are prone to faults incidents. The probable causes of fault incidents are either weather scenario, animal contact, equipment malfunction or in some cases can be due to poor vegetation management. Although, the disturbance can be found all over of the power system, but almost 80% of fault related interruption experienced by customers are due to fault incidents on the distribution system [1]. The occurrence distribution outage due to the fault will affect the utilities' reliability index. So, in order to full fill the reliability index criterion, utilities have to devise fault location method which ensures power is restored to users in short duration of time.

The classical method of fault location process in power system employed by utilities is a step by step process. First, the affected area of disturbance is identified through customer phone calls. This enables utilities to generally localise the disturbance location and its affected customer. After having sufficient geographical and statistical data, the maintenance teams are dispatched to affected substation. They will conduct visual inspections together with measurement to estimate the cause of the disturbance. After identifying the cause of the disturbance, if it is due to fault occurrence, methods such as capacitive discharge and pulse echo meter will be used to obtain the estimated location of fault [2].

Basically, the classical method of fault location requires more time for restoring the power. Besides, the classical method also contributes to higher operation and maintenance cost for the utilities. In order to overcome this problem, modern methods of fault location have been researched and developed. These modern methods of fault location not only able to reduce the power system restoration duration, but also able to provide more accurate fault location compared to the obsolete method.

2. Distribution System Configuration

In the study of distribution fault location, it is important to know and understand the distribution network characteristic as the following:

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(a) Distribution system will either form of a ring network topology or radial network topology.
(b) The interconnection of Distributed Generation (DG) e.g. Renewable energy source.
(c) Unlike transmission system, distribution system contains branches, laterals and load taps to cater based on customer requirements.
(d) There is un-transposed, overhead and underground cable placement in the distribution system.
(f) The cable size and length varies along the distribution system and long distribution lines are subjected to capacitance effect.
(g) Unbalanced system due single phase and three phase load connection.

These aspects of distribution network characteristics as mentioned above may influence the accuracy and effectiveness of the developed distribution fault location method.

3. Type of Faults and Faults Level

Faults in a distribution system can be either single phase to ground, double phase to ground, phase to phase, three phase to ground or three-phase faults. Each of these faults can be distinguished by their characteristic e.g. Single phase to the ground fault will give a spike in the current values of the particular phase during the fault occurrence. Some of the fault location methods will require the identification of fault type in prior before estimation of the fault location. Another aspect which can be related to fault type is the fault level. Fault level can be divided into two different kinds which are low impedance and high impedance fault. Low and high impedance fault are distinguished by the fault current values resulted from the arching between the phase to the surface of contact. Unlike low impedance, high impedance faults are difficult to be detected [3]. It requires customised approaches that can extract information of these high impedance faults from the available data.

4. Fault Location Methods for Distribution System

Figure 1 shows the overview of fault location methods for distribution networks. The details of fault location methods described below are reviewed in the next subsection.

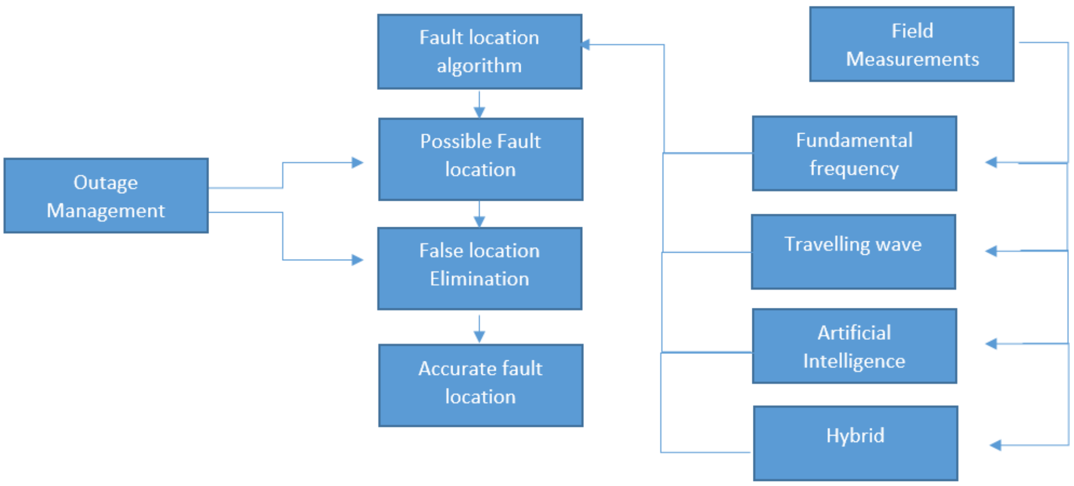

Figure 1. The overview of fault location methods for distribution networks

4.1. Outage Management

Outage management is a system used by utilities for locating zones or areas affected by fault incidents. The system integrates various components such as phone calls, metering communication and smart distribution equipment to triangulate the possible fault location area

[4]. Besides, outage management also serves as a conceivable method to eliminate false fault location when some fault location algorithm results to multiple assumptions of fault location.

The AMI or Advance Metering Infrastructure which normally used for meter reading in the distribution system can serve an alternative purpose as outage mapping. The author of this paper [5] proposed a method which by deploying an intelligent transceiver to sense the failed smart meters. The intelligent transceiver will conduct polling to verify the status of the connected smart meters and transponders. These polling data mask with location address which enables the process of identification of the de-energized section of the distribution system. Another AMI based outage mapping method is by utilising the AMI data. The method described by the author in [6] is by exploiting the communication topology of the smart meter in AMI. When smart meters fail to deliver their data, the communication ping is first established with other groups of smart meters. This to ensure that the supposed smart meters are not experiencing communication problems. The method used in [6] estimates the affected location by using meter digital location.

Besides smart meters, fault indicator (FI) is another alternative equipment which can be used for fault location. FI are built to detect the fault current in the distribution system. When the fault indicator is triggered, the status of the device will be updated to the utilities. The author in [7] proposed a method which utilises fault indicator for locating faults on medium and low voltage. The proposed method for medium voltage is by allocating FI at each beginning of lateral. The iterative approach suggested by the author in [7] enable FI to be employed in the distribution system which contains distribution generation. Meanwhile, smart meters and phone call are used to identify fault location on low voltage. Although, the proposed method shows promising results, but FI are costly, so the installation in the distribution system is usually limited.

The Interactive Voice Response (IVR) is a system which allows interaction between the customer and the utilities through speech and keypad recognition. By integrating IVR into outage mapping, utilities will able to provide up to date information regarding the network status in term of affected areas to the maintenance team. Besides, the IVR based outage mapping method also enables utilities to deliver their customer with an approximate power restoration time [8].

SCADA or commonly known as Supervisory control and data acquisition used by utilities to control and monitor the status of equipment in power system. This feature allows the usage of SCADA for outage mapping in a distribution system. To optimise the outage mapping with SCADA, a dedicated system must be employed, which takes into account factors such as events and forecast. Combining the SCADA's real time data with those factors enables a better outage management system [9]. Due to the heterogeneous nature of the distribution system, some of the outage mapping methods are combined into a single system called hybrids. The advantages of integrating several outage mapping systems can contribute to low maintenance cost for utilities and reduce the downtime [10].

Need to be reminded that, outage management method of identifying the distribution fault location is based on obtaining the general location affected fault. So, in order to procure the exact location of the fault, the outage measurement methods need to be combined with the field measurement method. The advantages of combining these methods contribute to a lower computational burden, especially iterative based algorithm. Besides, combine methods allow utilities to save cost in term of placement of extra devices which specially procured for fault location.

4.2. Field Measurements

Most of the measurements in the distribution system can be obtained from the substation, feeder and user end metering. Type of measurement which these devices record is either numerical data or signal waves. Basically, before the selection of a fault location method, it is necessary to identify the type of measurement which can be obtained from a distribution system. For example, fault location methods based on travelling wave method require signal wave from a measuring device with high sampling rate. This method describes the process of how the signal wave which is obtained from the measurements are used for fault location. Besides that, some distribution fault location methods require measurement taken from the various locations. Naturally, the location of the measurement is either single ended, double ended or sparse measurements. By addressing the correlation between measurement, methods of fault location and algorithm enable researchers and utilities to choose the optimal distribution fault location method.

4.2.1. Fundamental Frequency Component Methods

Impedance algorithm is one of the most used fault location algorithms in the power system. The algorithm requires the measured fundamental frequency, RMS (Root Mean Square) or phase voltage and current which can be obtained from digital or analogue devices placed at the substation. Fault location by impedance algorithm is a computational process which involves an iteration process. But, the method proposed by [11] uses the Clarke transformation of the measured three-phase voltage and current which eliminates the needs of the long iterative process.

One of the requirements for impedance algorithm is to identify the type of fault before the application of the algorithm. But, the proposed method by [12], uses a single impedance equation which can be used for fault location disregarding the fault types. Nowadays, distribution systems do not only rely on the transmission for power supply, with the integration of distributed generation such as photovoltaic, wind and etc. The impedance algorithm developed by [13] takes into account the integration of distributed generation in the network and able to provide an accurate fault location method.

Impedance algorithm is quite sensitive to capacitance effect. The algorithm discussed in [14] devices an impedance based fault location algorithm which considered the capacitance effect in the distribution line. The proposed method can even be used to locate faults for both overhead and underground electrical power distribution. According to the author in [14], the fault location algorithm is impermeable against laterals taps, intermediate load, time varying load profile and under unbalanced operation. Meanwhile, in [15] the impedance algorithm with accounts of the capacitance effect used measurements obtained from substation side only. Although the impedance algorithm discussed in [15] shows a better result of fault location incidents, the impedance algorithm unable to locate fault incidents in laterals.

The common factor which affects the impedance algorithm is multiple estimations of the fault incident location. The algorithm described by [16] was able to solve the multiple estimations by examining the fault current in the healthy phase. Although this algorithm is able to locate faults incidents accurately for multiple estimations, it is unable to locate three phase fault multiple estimations.

In the earlier practice of impedance algorithm, for transmission power system, the only symmetrical component was considered. But, the application of the impedance algorithm on distribution system possesses difficulty due to the unbalanced condition of the network. The proposed algorithms discussed in [11–13, 15, 16] all consider the effects of the unbalanced condition.

The short period under-voltages are termed as "voltage sags" or "voltage dips". Voltage sags are deterioration of the supply voltage magnitude followed by voltage recovery after a brief timeframe. In the IEEE Standard 1159-1995, the term "sag" is characterised as a reduction in root mean square voltage to values between 0.1 to 0.9 p.u., for spans of 0.5 cycles to 1 min [17]. In a faulted network, the point of the fault will experience the lowest magnitude of RMS voltage while the neighbouring point, depending on the distance from fault location, will also experience sags, but the magnitude will be much higher compared to the sags at the point of fault. Voltage sags algorithm uses these characteristics to estimate fault location.

Among the research of voltage sags based fault location algorithms are the method which able to assume the fault location on the feeder based on matching the voltage sags database of the feeder [18]. The voltage sags algorithm proposed in [19], is based on matching the calculated and collected data of the voltage sags and together with the phase angle of the current. The voltage sags algorithm is used to identify faults node. To pinpoint the exact fault location, the apparent impedance calculation is used to narrow down the distance of the fault from the node.

The paper written by [20] discusses the impact of voltage sags based fault location with DG penetration. The studies in this paper also show that the presence of DG also may provide false fault current which may impact the reliability of voltage sags method. Adding, the availability of DG will cause the distribution system to be viewed as the multisource system. Hence, the estimation of fault distance from the single source will be a not valid assumption when DG is present in the system.

In certain case, fault location based on voltage sags algorithm requires the knowledge of fault types. The paper by [21] proposed a method to identify the fault type through the Power Quality (PQ) devices voltage sag waveform. But, normally most substations are equipped with relays which available to identify the fault type. So, the method proposed by the author in [21] can be an alternative way to identify the fault type which can assist in fault location.

4.2.2. Travelling Wave Based Methods

Fault incident on distribution network causes the surge to travel along the interconnected distribution network. Rendering those surges into high-frequency component enables identification of fault location. Application of this method on distribution systems provides a better solution for the fault location if discontinuities of the distribution network are not taken into account. This method can be used to identify the short duration of faults in the distribution network. The algorithm in [22] uses the wavelet decomposition of high-frequency voltage and current transient signals. The signals are obtained from the transducer placed at substation end. The fault path is identified by using the equivalent wavelet coefficient. The distance of the fault from the substation is acquired through computational of power frequency components. The method described in [23] is by using the cross-correlation function of the reflected wave and incident wave to obtain the location of the fault. The measurement of high-frequency transient signal is attained through the placement of fault recorders. The proposed method compares the positioning of the fault recorder through single ended measurements and double ended measurements. It shows that double end measurement able to provide better fault location compared to single ended. This is due to the interconnected nature of the distribution system which introduced discontinuity. Double end measurement proposed by [23], required synchronous measurement by using GPS time stamp which increases the cost of implementation. The algorithm in [24] is by comparing the decomposed high-frequency voltage wavelet coefficient from voltage transducer with the database in order to estimate the fault location. The method is immune to post voltage phase angle and network loading as it relies on the accusations of the high-frequency component.

4.2.3. Intelligence Based Methods

Neural network algorithm is part of the artificial intelligence-based method. Abilities solving complex computational problems and pattern recognition make the Neural Network algorithm one of the most proposed methods for distribution fault location. The Neural network algorithm used by [23][25] is based on two input vectors in the ‘input layer’, one ‘hidden layers’ made of five neurones, also, one ‘output layer’. The two input vectors are eigenvalue and eigenvector data which are obtained through Clarke-Concordia transformation of the fault and pre-fault currents. The proposed method by [25] shows immunity against total harmonic distortion, requires less input (only current components are used) and able to match and locate faults.

The monolithic Neural network algorithm performs well on a limited information space. However, when the complexity of the parameters increases and the algorithm performance decreases rapidly [26]. Modular Neural Network algorithm, on the other hand, able to resolve the complexity issue effortlessly which makes it the optimal selection for the distribution fault location application. The article in [27] uses Modular Neural Network algorithm to locate fault incident on the distribution system. Nonhomogeneous features of the radial distribution feeder and lateral sources are considered in the application of the algorithm

Neural network algorithm structure can be divided into Multilayer Perceptron (MLP) and Radial Basis Function Network (RBFN) [28]. The MLP Neural network algorithm proposed by [29] able to locate faults distance for a ring distribution with distributed generation. The proposed method in [29] analyses the type of fault by comparing the fundamental current from the distributed generation. Meanwhile, in [30] RBFN algorithm is used to estimate the distance from each injected source and able to locate the exact location of the fault on the line. Meanwhile, in [31], both RBFN and MLP neural network is used to identify the type and location fault in the distribution network. The phase currents from source end are first converted into components by using Clark Transformation. The eigenvector is applied with RBFN algorithm for classifying faults meanwhile the MLP algorithm uses eigenvalue comparison to identify the fault location which is based on its trained data. This method works well with multiple branched networks and able to identify the high impedance fault.

Beside neural network algorithms, there are other types biologically inspired computing method which has been developed for the distribution fault location [32]. Among them is the Particle Swarm algorithm which uses an iterative approach, set of rules and switching function to determine the estimated fault location. The method proposed [33] eliminates the switching function by using the Bacterial Foraging Algorithm.The author simulates the proposed algorithm in a distribution system with distributed generation and shows a high tolerance for distorted fault information.

Heuristic knowledge of personal experience and weather condition can be mathematically modelled for fault location. In [34] the author formulated a fuzzy set theory algorithm consist of knowledge based vectors to identify the fault location. The estimated location is varied by the set of fuzzy function which states the approximated distance of the fault incidents in the distribution system.

4.2.4. Hybrid Methods

The fault location method that employs more than one method is called a hybrid fault location method. The method described in [35] combines both high-frequency component and intelligence-based method to identify the fault location in underground distribution cable. The fuzzy decision-based algorithm uses the first peak time of Discrete Wavelet Transform (DWT) of positive sequence current as the input for identifying fault location. The paper created by [36] describes a method for fault detection, classification and location. Fault selection and classification are done by using the travelling wave based method. The fundamental frequency based method is used to identify faults on the main distribution line. The Neural network algorithm in this paper is train based on fundamental phasor quantities and fault resistance. The Neural network algorithm used to identify fault location on laterals of the main distribution line. This method described in [37] is based on fault location in an underground cable. The method contains both travelling waves based method and intelligence based methods. The Wavelet Transform (WT) data from travelling wave based method is used for feature extraction. This feature extraction is used to train the Neural network algorithm. The Neural network algorithm developed in this method serves not only as fault location but also as fault classification. The method described in [38] contains both travelling waves based method and intelligence-based method. The intelligence-based method proposed in this paper is based on genetic algorithm and Support Vector Machine (SVM). The genetic algorithm is used for the selection of the decomposed coefficient from the wavelet packet transform (WPT) and Discrete wavelet transform (DWT). Meanwhile, the SVM is trained to various factors such as fault distance, inception angle, fault resistance, fault type. By using more than one fault location method, it is not only able to produce better accuracy, but reduces the computational burden on other types of the method described.

4.2.5. Comparison of the Field Measurement Methods

Based on Table 1, it can be seen that each of the fault location methods has their own unique requirements for the fault location application. The fundamental frequency and intelligence methods require line, loads and network topology, meanwhile the travelling wave method only requires network topology. In terms of measurement requirements, the fundamental frequency method requires voltage and current measurement meanwhile travelling wave requires high-frequency signal waves. The intelligence and hybrid method of fault location required data and required measurements depends on the algorithm. By factoring these requirements, researchers or utilities can suggest the suitable fault location methods for a particular distribution system.

Besides the requirements, each of the fault location methods weakness has to be identified so that it can be addressed during the application of the method. The fundamental frequency method weakness is based on the impedance and voltage sag algorithm. The impedance-based algorithm is prone to multiple estimations meanwhile the voltage sags based algorithm can cause computational burden. But, when compared to the fundamental frequency, travelling wave, intelligence and hybrid methods, fundamental frequency methods are the simplest and cost-effective method for distribution fault location. Travelling wave methods have a higher fault location accuracy compared to fundamental frequency methods. But, the travelling wave algorithms are unable to distinguish reflected wave of the transient signal. The intelligence methods are able to locate the fault on lateral with better accuracy compared to fundamental and travelling wave method. But, the down point of intelligence methods is that it is unable to adapt to the distribution topology changes. The hybrid methods are almost perfect fault location method for distribution, but the complexity of the method impact in term of cost and application.

Table 1. The required parameters of fault location method for the distribution system

	Algorithm	Required Data	Required Measurements
Fundamental frequency	Impedance Voltage sags	Line and load data Network topology	Voltage and current measurements
Travelling wave	Wavelet decomposition Fourier transform	Network topology	High-frequency transient signal
Intelligence	Artificial Neural Network Fuzzy Logic Support Vector Machine Genetic algorithm	Line and load data Network topology Weather Heuristic (Depends on the algorithm)	(Depends on the algorithm)
Hybrid	Combination of 2 or more algorithms	(Depends on the algorithm)	(Depends on the algorithm)

5. Conclusion

Pinpointing fault location in the distribution network is complicated, mainly due to the complexity of the network. But, with recent advancements in technology and the computational process has triggered researchers and utilities to develop the best method to determine the fault location in the distribution network. In short, as long as there is a future expansion of the distribution network together with the advancement in technology, till then new and improved methods of fault location will be discovered.

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