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FAULT LOCATION TECHNIQUES FOR ELECTRICAL DISTRIBUTION NETWORKS: A LITERATURE SURVEY

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ABSTRACT
This paper presents a descriptive state-of-the-art of fault location techniques for electrical distribution networks, and is intended as a guide for those interested in the problem or intending to do additional research in the area. A set of 109 references carried out in this field have been organized, analyzed and classified by areas, then a comparative statistical overview is presented to reflect the state of the art development over the last 15 years.

KEY WORDS
Fault location, power distribution faults, reviews.

1. Introduction

Fault location is an important problem for safe and economical operation of power systems. In transmission power systems the development of techniques for estimating the location of fault line has been identified as an essential requirement for power companies. However, until recently, relatively little work has been done in the development of fault location techniques for distribution networks; this stems from the fact that hitherto, fault locators on such systems have been considered useful but not essential, but nowadays this issue is a subject of main interest in distribution companies due to tendency in regulation and pricing of the distribution business to promote efficiency and to improve power quality. Then the importance of accurate fault location in distribution networks has increased.

There are not so many work reviews or bibliography discussions focused on the fault location problem in distribution systems. For example, Willis [1] presented a resume of some of the classical techniques that have been used through the years to locate cable faults in distribution systems. A general but useful reference is a report of the CIRED working group [4], there the problem of fault location is presented as one of the main issues in a fault management system. Tang, *et al.* [6] review the fault indicator applications both in transmission and distribution systems; principles, merits and demerits of fault location techniques are discussed. S. Jamali [8] and M. Saha [10] presented a review of selected fault location techniques proposed for distributions systems, but mainly based in impedance techniques.

This paper intends to provide an overall literature survey on fault location techniques in distribution systems by describing the research situation and evolution over the last 15 years. First, the principal issues related to this subject are described, next a general classification is performed and a historical evolution is presented. The main publications carried out in this field have been analyzed and classified by areas, a statistical analysis and a brief discussion is performed to reflect the state of the art development. For this purpose only the bibliography with a direct contribution to fault location in distribution systems was selected, without considering transmission systems approaches.

The last section of the paper presents an organized set of 109 references, which are sorted according to the classification of fault location techniques proposed in the following sections.

2. Fault location in distribution networks

In electrical distribution networks, fault management is one of the main functions to reduce outage times, one of the main issues is the fault location for repair and inspection purposes, this is not a protective relaying problem since the protection scheme is an on-line applications and the speed of operation is the main issue, whereas the fault location techniques are off-line applications and accuracy is the main concern. It should be pointed out that in this paper only the case of fault location is considered, the cases of fault detection (protection scheme) and fault classification (identification scheme) are also two important issues in distribution systems, but they are outside of the scope of this paper.

Fault location in distribution systems differs considerably from the approaches applied for transmission systems. In fact the significant differences in networks structure, dimensions and grounding principles must be considered when a fault location method is used in distributions systems. Fig. 1 shows that many of these characteristics have not been totally considered in the bibliography, for example Fig. 1a shows that most of the fault location approaches for distribution systems (70%)

are developed for solidly grounded systems, Fig. 1b shows that the case of a feeder having multilaterals has

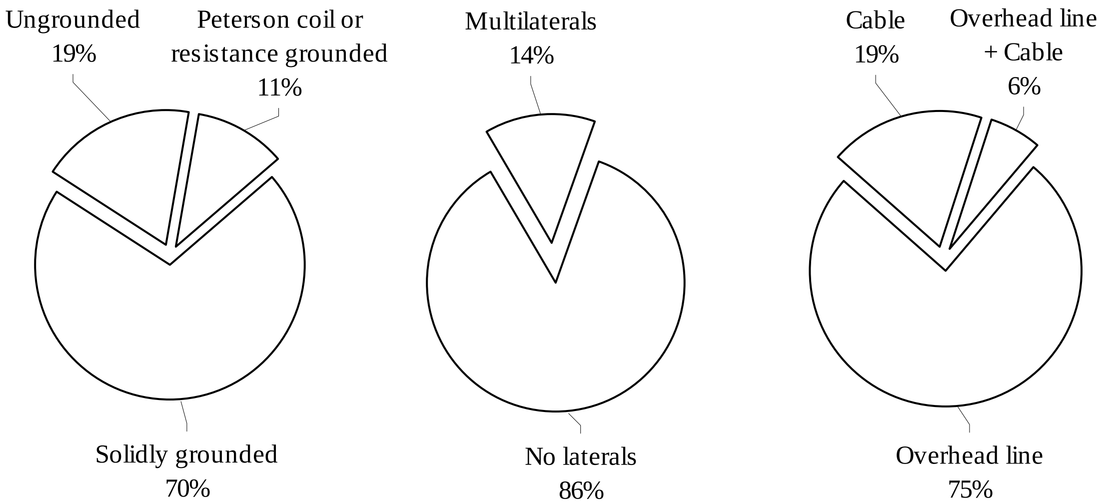

Fig. 1. Percentage distribution of fault location publications according to characteristics of distribution systems.
(a) Grounding principle (b) Network structure (c) Types of distribution lines

not been fully resolved, because only 14% of the specialized literature consider this case, Fig. 1c shows that most of the approaches only consider overhead line and only 6% of the proposed techniques include overhead lines and cables simultaneously.

3. Fault location techniques for distribution networks

In the mainstream literature, fault location techniques which particularly focus on distribution systems were first proposed around 1990, such as Fig. 2 shows.

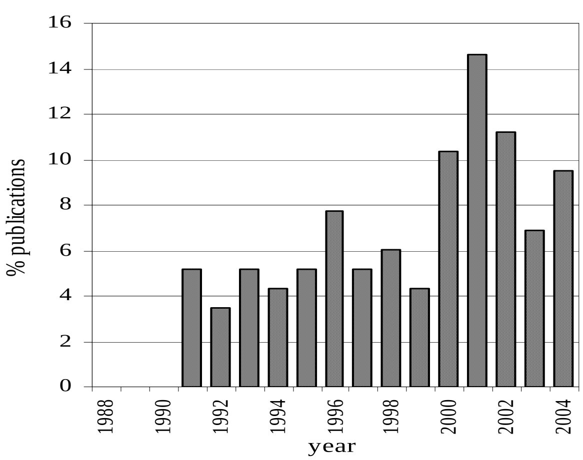

Fig. 2. Evolution of fault location techniques in distribution systems according to research articles appeared on bibliography

In recent years the subject has received increasing attention as indicated in the number of research articles which have appeared recently.

Various fault location techniques have been proposed in the literature. However, a survey of previous work has revealed that most of the fault location methods were developed for transmission systems and are not suitable for radial distribution networks.

Traditionally the short circuit faults in power distribution lines were located by trial and error method, i.e. by dividing the line into sections and trying to close the energizing circuit breaker, this is both time consuming and also exposes additional stresses on the equipment. A fault can thus be located in several “iterations”, its main drawback is the crew time required to localize the faulted section and the fault. Crew productivity can be improved through the use of faulted circuit indicators (FCI), a single or multiphase device designed to sense fault current and provide an indication that the fault current has passed through the power conductor(s) at the point where the FCI sensor is installed [13].

Nowadays there has been considerable research effort into development of new fault location techniques for distribution systems, these techniques can be classified under two principal categories such as Fig. 3 shows.

Fig. 4 shows an increasing research in recent years on signal analysis approaches. In particular, with the rapid developments of microprocessor technology, there have been active research activities in using high frequency components.

The next section of this paper presents an analysis of someone of the main publications on fault location techniques in distribution systems, according to the classification showed at Fig. 3.

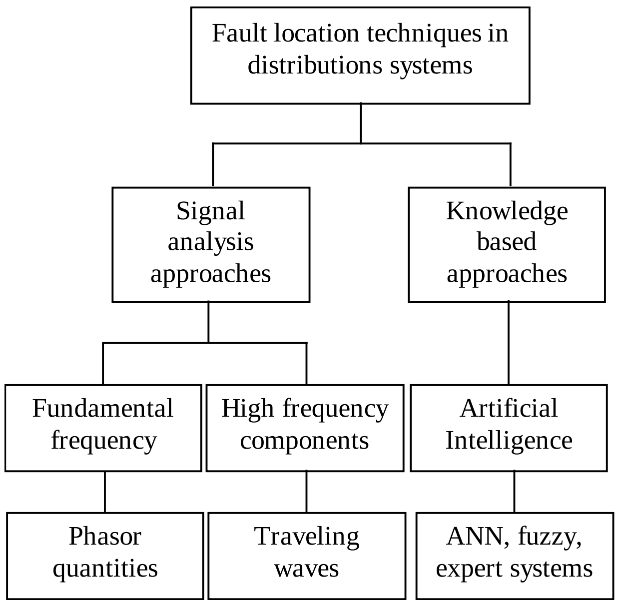

Fig. 3. A general classification of fault location techniques for electrical distribution networks.

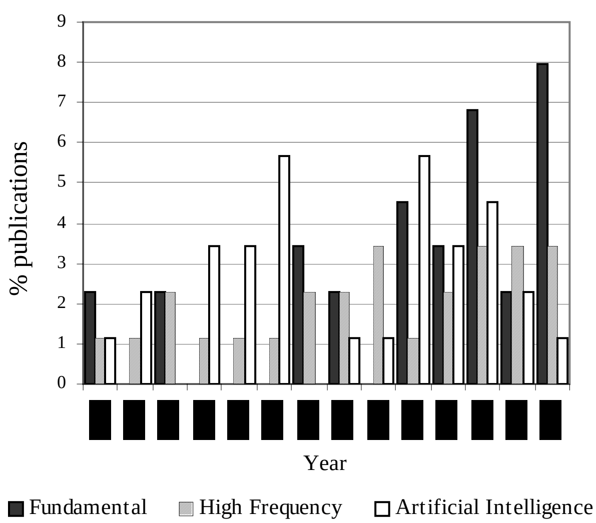

Fig. 4. Evolution of fault location techniques in distribution systems in the mainstream literature.

3.1 Signal Analysis Approaches

Fault location techniques using signal analysis approaches are based on an analysis of the currents and voltages measured. These methods can be divided into two categories: methods that use the fundamental frequency and methods that use high frequency components. The methods in this category can be further classified depending on available measurements into two sub categories: single ended and double ended methods. Single ended techniques have been developed using one terminal measurements, usually based on the information provided by digital fault recorders (DFR) at the head of the feeder. Its major advantage is that communications are not needed. When communication channels are available, the double ended techniques give more reliable and accurate results.

The fact that a feeder has many branches adds a big difficulty in locating the fault since estimating the fault location based in the voltage and current signals yields more than one location.

3.1.1 Fault location using fundamental frequency

The fault location techniques in distribution systems based on fundamental frequency are those that use the power frequency phasors to estimate the fault distance.

In 1991, Lehtonen *et al.* [16] discussed the theoretical basis and implementation of fault location method for radially operated electrical distribution networks based on phasor analysis. The parameters that affect fault location accuracy such as effects of load current, fault resistance, variation of network impedances, measurement precision, load current compensation are discussed.

In 1993, A. Girgis *et al.* [18] presented a single-ended fault location technique for rural distributions feeders based on phasor quantities obtained using a recursive optimal estimation algorithm, then the distance to fault is estimated using a method based on the apparent impedance approach and the updated voltages and currents vectors. The approach is extended in [20], [22].

In 1997 R.K. Aggarwal, *et al.* [21],[23] presented a single-ended fault location technique for overhead distribution systems, based on the concept of superimposed components (the difference between the total post-fault and pre-fault quantities) of voltages and currents, the principal advantage of this methodology is that the fault locator is highly insensitive to variations in local and remote source impedances and to the presence of taps with variable loads.

In 1998, Hanninen, *et al.* [24], analyzed the problem of fault location in high impedance earthed distributions systems (unearthed or compensated neutral), based on the change of neutral voltage and zero sequence currents, measured at the high voltage/medium voltage substation and also at the distribution line locations, the method is able to detect faults up to 160 kohms. A Similar approach is proposed by Nikander *et al.* [25].

In 2000, Pettissalo *et al.* [30], developed a reactance based fault location for three fault and two phase fault. The key of the technique is the compensation of the load currents superposed on the fault current, that leads to improvement in accuracy. The algorithm was implemented in protective relays and integrated as a part of a DMS system.

In 2003, P.M. Van Oirsouwf, *et al.* [39] present the real experience of a Dutch distribution company with reactance based methodology for distribution fault location. The system turned out to be able to identify the fault location within the required accuracy of 100 meters for two and three phase faults and 1000 meters for single phase faults. Within 5 minutes after the fault the dispatch center could instruct the emergency repair crew to check the fault location directly, by using this system the company could save an estimated one hour of manual searching time.

In 2004, M.S. Choi, et.al. [41] proposes a algorithm that identifies candidates fault locations using an iterative estimation of load current at each line section. The algorithm determines the actual location by comparing the current waveform pattern with the expected pattern due to operation of the protective devices.

3.1.2 Fault location using high frequency components

The use of non-power frequency components for power system analysis has been contemplated for more than sixty years [47], especially in power system protection, but only in the last years has progress been achieved. A great deal of activity has occurred in the area of traveling wave type protection methods for transmission lines, but has been gradually abandoned due to reliability and maintenance problems [6]. Recently, traveling wave methods have re-emerged as an alternative for fault location. The essential idea behind these methods is based on the correlation between the forward and backward traveling waves along the line. These methods monitor the correlation between these waveforms, which will become quite large in case of fault. The fault transients will be reflected from the fault point and will arrive at the relay terminal yielding a highly correlated signal for a delay time equal to twice the traveling time of the transients to the fault location. This time can then be used to solve the distance from the relay to the fault location. However, for distribution systems, the problem becomes more complex because the topology in radial grid involves many reflections. It has been noted that the traveling wave based method does not perform well for certain type of faults and system conditions, these include for example faults very close to the measurement point and faults that occur close to a zero crossing of the voltage waveform at the fault point.

One of the first reports on the use of high frequency components to determine fault location in distribution systems was proposed in 1992 by A.T. Johns [47],[48]. The technique is inherently tolerant to variations in type of fault, fault resistance, source short circuit level and most importantly the point-on-wave of fault inception, but the main drawback is that the locators need to be inserted at strategic and convenient intervals along the overhead distribution system.

In 1996, Z.Q. Bo, *et al.* [55], [56] presented a distribution single cable fault location based on the fault generated high frequency traveling wave voltage signals. In the scheme, the accuracy of fault location is proportional to digital sampling rate and simulation studies show that an accuracy of up to ± 10 meters in cable fault location could be achieved using a sampling rate of 20 MHz.

In 1998, Z.Q.Bo the research extended and presented the application of transient based fault location techniques to the distribution systems by utilizing GPS [59] and including tapped-off loads [60]. It relies on detecting fault generated high frequency signals and avoids the long-standing problem of identifying multiple reflections from busbars and the fault point, which restrict the use of traveling wave techniques. In [61] the technique is improved to attain the accurate instance of an initial traveling wave applying wavelet transform to extract the transient components from the captured fault signals, the fault location is performed by comparing the differences between instances in time for all locators in the system.

The main drawback of the previous proposals is that they are based on a double-ended method and due to capital and installation costs these schemes are costly compared to the importance of a distribution systems.

A more attractive approach is to develop a fault location method with current or voltage signals measured at one end of the line (single-ended), usually at the substation, in this case fault location relies on the analysis of these signals to detect the reflections that occur between the measuring point and the fault. One of the main problems is the multiple possibilities of fault location for a given recording. One of the first attempts in this line was proposed in 1999 by F. Magnago, *et al.* [63], the analysis is performed using the transient signals recorded at the substation during the fault. The method identifies the faulted lateral first, based on the traveling wave information provided by the high frequency components and using the special properties of wavelet transform coefficients, to differentiate between faults occurring along different laterals of the same main feeder, equal distance away from the main substation. After the initial identification stage, the fault location along the identified lateral is calculated based on a simplified system model and steady phasors using the A. Girgis methodology [18].

In 2002 P.F. Gale, *et al.* [69] shows that it is possible to locate a fault on a distribution feeder consisting of underground cables, overhead lines and tapped load, using measurement at a single location. The method identifies a probable location of the fault by comparing the relative distance of each peak in the high frequency current signals to the known reflections points in the distribution feeder. The probable fault location is then used within a transient power system simulator that models the actual network. The resulting simulated current waveforms are then cross-correlated against the signal captured on the real network, if the estimated fault location is correct, then high frequency signatures in the simulated waveform will be similar to that of the measured waveforms and then the cross-correlation value will be a high positive value.

3.2 Knowledge-based Approaches

Artificial intelligence techniques, such as expert system, neural network, fuzzy logic and genetic algorithm, have been employed to fault location in distributions systems. The following are some of the contributions in this area.

Initial attempts (1991) at the applications of expert system for fault location in distribution network can be found in H. Yuan-Yih, *et al.* [76], the authors propose an expert system to serve as an operational aid for the dispatchers to locate the faults in distribution systems, the effectiveness of the designed expert system is demonstrated on a distribution system within the service area of the Taipei City District Office of Taiwan Power Company.

In 1994, J.A. Momoh *et al.* [80], [81] proposed an expert system for fault location in underground distribution network, the rules for the system are constructed using knowledge acquired through an exhaustive fault simulation program specially designed to facilitate sensitivity studies.

In 1996, Jarventausta, *et al.* [83] proposed an expert system that combines information obtained from the network database, SCADA and heuristic knowledge of operators to inference possible fault locations. The electrical distance between the feeding point and the fault location is determined by comparing the measured short circuit current and the type of fault with the calculated fault currents of each line section. The possible fault locations are ranked using information on other knowledge and data sources.

The information obtained from the remote control system contains some degree of uncertainty and may be incorrect, conflicting or inadequate. For this reason there are some approaches [79], [84], [86] based on the fuzzy set theory to deal with the uncertainty involved in the process of locating faults in distribution networks.

A more interesting method than the conventional solutions for fault location in distribution system is the use of artificial neural network (ANN), since it does not require the explicit formulation of the solution algorithm, but is able to implicitly employ various dependencies in the training data. In 1995, M. Glinkovsky [82], proposed ANN to locate faults in underground distribution systems. The technique is based on the assumption that during the fault, before it is cleared, the voltages and currents measured by the network units contain information about the location of the fault in the system. These measured quantities uniquely define a fault pattern (or signature) that can be recognized by a specially designed neural network. The challenge in ANN fault location technique is to be able to process the data for a given pattern and reliably extract the information about fault location. A comparison of ANN techniques for fault location was carried out in 1996 by J.A. Momoh [85]. The authors conclude that higher success rates are achievable using the back propagation method and the clustering method when compared with the counter propagation method.

In 2000, G. Eberl, S. Hanninen , *et al.* [87] presented a comparison between an ANN method and differential equation algorithm and wavelet algorithm in transient based earth fault location in unearthed or resonant distribution systems. The results are compared with ANN trained by phase current and voltage samples. The comparison shows that ANN is better than the conventional algorithms in the case of very low fault resistance. In 2001, the authors extended this research, and proposed a neural network approach [89] for transient based earth fault location using ANN trained only with the harmonic components of the neutral voltage transients. The performance is comparable to [87] and solves the problem of very low fault resistance.

Probabilistic methods are other approaches for fault location, for example, in 2000, S. Hanninen, *et al.* [88], proposed a probabilistic method based on the change of the neutral-voltage and zero-sequence currents.

4. Conclusion

The basic aim of this paper is to organize, classify, review and compare various approaches to fault location in distribution systems. A comparative study identifies the relative strengths and weaknesses of the different approaches and reveals that no single technique has all the desirable features for accurate fault location in distribution systems. For example, the application of traditional fault location techniques that use fundamental voltages and currents at line terminals for distribution lines with tapped loads is difficult. Traveling wave based fault locators are perceived to be more reliable if a double-ended method is used. Nevertheless for distribution systems, single-ended fault location should be less expensive and hence preferable.

Research efforts are actually aiming at the development of a novel fault location method, based on a central fault locator installed in the substation with only currents and voltages measurements available. Towards that goal the signals based method and knowledge-based method can complement each another as a way to develop hybrid systems that could overcome the limitations of individual solution strategies.

Hence, there is a technical challenge in research and development for the successful design and implementation of a practical fault location method for distribution systems.

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