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EVOLVING TRENDS FOR ENHANCING THE ACCURACY OF FAULT LOCATION IN POWER DISTRIBUTION NETWORKS

[1]Surender Kumar Yellagoud, [2]Prof. T. Purnachandra Rao, [3]Dr. G. N.Sreenivas

[1]Research Scholar, Jawaharlal Nehru Technological University, Hyderabad, India
[2]Professor, Formerly in National Institute of Technology, Warangal, India
[3]Professor, Jawaharlal Nehru Technological University, Hyderabad, India

Abstract: **Fault location has been the subject of considerable interest to electric power utility engineers and researchers for many years. Quantum of research done has been more on locating faults on transmission lines. This is more justified, for the impact of transmission line faults on the power systems is greater, than that of distribution lines. However, fault location on distribution lines is gaining attention in many utilities, especially operating in deregulated power markets attempting to increase availability of power supply to the customers. So, there is a need for more accurate and efficient methods for fault location, which lead to high-quality of customer service and reduced overall cost. Fast and accurate identification of the faulted section in distribution networks leads to least inconvenience to the connected customers. The research work on this issue has an interesting emergence over the years. It would not be an exaggeration, if one states that still to this day there is a greater scope for improving the accuracy. This paper reviews the work and presents a comprehensive content demonstrating the evolution of various tools and techniques, which are ruling the research domain of fault location over a time-stretch of 10 years to this day.**

Keywords: **Power distribution networks, fault location, artificial intelligence, fuzzy logic, genetic algorithm, impedance-based algorithm.**

I. INTRODUCTION

A. Background

The electric utility industry grew by leaps and bounds since its inception towards the last lap of 19^{th} century, within a short time-stretch of just over a century. The generating stations have increased very rapidly, and the corresponding transmission and distribution networks have proportionately grown into greater and greater magnitudes and complexities. In the same pace and race, the degree of deregulation directives introduced world over levies more and more stringent requirements on power reliability and quality, with no proportionate hike in the cost of the energy. Talk of the day is continuity of quality power supply, and reliability plays a vital role in the power system market today. Consequently, the impinging demands on the high standards of principal and auxiliary equipments/devices (both hardware and software) involved in protection and controls are gaining greater and greater importance. Among the array of varied potentialities of these devices, the functionality of fault location stands out very important. Transmission and distribution lines are highly prone to faults that are caused by lightning, storms, snow, rain, insulation breakdown, etc., and short circuits due to birds, animals and other external objects. In almost all these cases, these fault events result in some form of permanent mechanical damage, which require repair before restoring service to affected customers. The repair and restoration can be expedited if and only the location of the fault is identified or informed or can be estimated with reasonable accuracy. For sure, the transmission and distribution networks today extend over wider geographical horizons, manual methods of either patrolling over road or air, communication help from customers or public, and any other semi-automated means or methods cannot very well be devised or relied upon, for the levels of reliability and power quality envisaged are high and

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becoming higher day after day. And, the automated means and methods are imperative and the accuracy decides their viability. The devices which shoulder this responsibility today are termed as 'Fault locators'. Fault locators provide estimates for both permanent and transient faults. Generally, the damage done by transient faults is minor. Fault locators assist in identifying these locations for early repairs to prevent their recurrence and consequent major damages.

B. Basic Types Of Fault Location Methodologies

Fault location can be carried out by foot, road and air patrols, and obviously such means are laborious and time consuming. These manual methods of fault location consisted of visual inspection as is mentioned in [2]; such means do not meet the requirements of the day on fault location. Automatic fault location is based on determining the physical location of a fault by processing the voltage and current waveform values. Automatic fault location can be classified into the following main techniques: 1. Fundamental frequency approach, 2. Traveling wave method, 3. High frequency method, 4. Knowledge based techniques Direct, simple and economical way of calculating the fault location is by using the fundamental frequency voltages and currents at the line terminal(s), together with the line parameters, to calculate the apparent impedance of the faulted line segment, which is a measure of the distance to fault point. Based on the utilization of input signals of a two terminal line, the method is classified taking into account the data, whether from one or both ends, and also whether complete measurements (voltage and current) or incomplete measurements (voltage or current) from a particular line end are utilized. Similarly, different availability of the fault-locator input signals could be distinguished in application to three-terminal and multi-terminal lines. Various fault-location methods, with acceptable accuracy for most of the practical applications, have been developed using one-end impedance techniques. A major advantage for these techniques is that communication means are not needed and simple implementation into digital protective relays or digital fault recorders is possible. However, the fault-location algorithms will be more accurate, if more information about the system is available. Therefore, if communication channels are at the disposal, then the two-terminal fault-location methods may be used. Only low-speed communications are necessary for this application.

In the traveling-wave method the voltage and current waves, traveling at the speed of light from the fault towards the line terminals, are utilized for fault detection and location. Though these methods were found to be very accurate, they were proved as considerably complex and quite expensive requiring high sampling frequency and hence costly communication equipment involved [3]. Being expensive, the method is not that widely used. The basic idea of these methods is based on the interrelation between the incident and reflecting waves travelling along the line. The principle of the fault-location techniques is purely on the consecutive recognition of the fault, triggered by traveling high-frequency voltage/current signal at the locator. The first and few consecutive signals are good enough for locating the fault position. The technique is free from errors caused by power frequency signals, the power swings and CT saturation, and also to fault impedance, fault inception angle, source impedance, etc. [4].

The high frequency method is based on high frequency components of currents and voltages generated by faults, which travel between the fault and the line terminals. This technique is an expensive and complex one, since use of specially tuned filters for measuring high-frequency components is required, and hence not widely used. The basic principle of the technique based on high-frequency components of currents and voltages generated by faults. When a fault occurs along a transmission line, the voltage and current transients will travel towards the line terminals. These transients will continue to bounce back and forth between the fault point and the two terminals for the faulted line until the post-fault steady state is reached.

Application of knowledge based techniques to Fault Location in transmission and distribution networks has been gaining ground over the recent years much more than ever more, as is noticed from recent research work. Another name stands as synonym for these techniques is Artificial Intelligence. AI is a subject related to computer science that explores ways and means to mimic the thought and action of human beings. Besides taking rational decisions artificial intelligence knows how to handle and populate the missing data, adapt to existing situations and upgrade itself in the long run deriving benefits from the accumulated experience. AI techniques can very well be grouped into five areas, which are becoming popular in today's power system automation: Expert systems, artificial neural networks, Fuzzy logic, Hybrid combinations and Genetic algorithm.

C. Uniqueness of Fault Location in Distribution Networks

Fault location in distribution networks is becoming a subject of greater interest to utility engineers and researchers today much more than ever before. Accurate Fault location helps utility engineers greatly to quicken repair and restoration of

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faulty part and reduce outage periods and maintenance costs. Hence, more and more efficient methods for fault location are immediate exigencies today to remain competitive with respect to high quality of service.

Fault location on distribution lines has unique complications when compared with that of transmission lines. In transmission lines, a fault locator is installed on every line separately. In this case, the algorithm for fault location is merely a mathematical calculation for a single quantity called, "distance to fault" using the digital data of voltage and current. But, with the distribution lines, which are usually not homogeneous, having branches and load taps all along the line, fault location is comparatively complex [5]. Distribution systems are basically the medium voltage networks, which supply electrical energy to final step-down distribution transformers. Though these networks also supply directly to large customers, but major chunk of the consumers are connected on the secondary of distribution transformers.

The distribution networks are supplied from step-down (from high to medium voltage) transforming substations. These networks are made up with line sections having length varying from a few hundred metres to kilometres. Based on targeted load distribution and subsequent network additions the feeder configuration is heterogeneous with different conductor cross-sections and therefore the related parameters. Since it is uneconomical to dedicate a device to every feeder, the fault locating devices are mostly centrally located, so that they monitor the quantities at the substation. Obviously, the estimation of fault location becomes more complicated, specifically due to some specific reasons, viz. non-availability of current in a faulted line, compensation inaccuracy of pre-fault load current in faulted line, multi-terminal nature of networks, inadequate compensation of load variations, etc.

II. CLASSICAL (IMPEDANCE-BASED) ALGORITHMS

Since in distribution networks fault devices are centrally located, which lead to errors for reasons cited in the previous section, some algorithms are developed to minimize the errors. These algorithms have following fundamental steps/stages in common.

1. **Pre-fault steady state condition:** Calculation of positive- and zero-sequence impedance in all nodes of the network using the existing feeder topology and load profile.
2. **Fault condition:** Calculation of specific fault-loop parameters for every fault type and the place of measurements (either at transformer or faulty-feeder), which enables to find fault position.
3. **Final estimation of fault location:** by elimination of unlikely fault locations using consistent logic or procedure or a technique.

The final stage is paramount, more particularly for fault location on distribution lines. It is highly imperative to employ an advanced tool or technique to arrive at an accurate estimation. The current research trends are more inclined towards artificial intelligence tools and techniques.

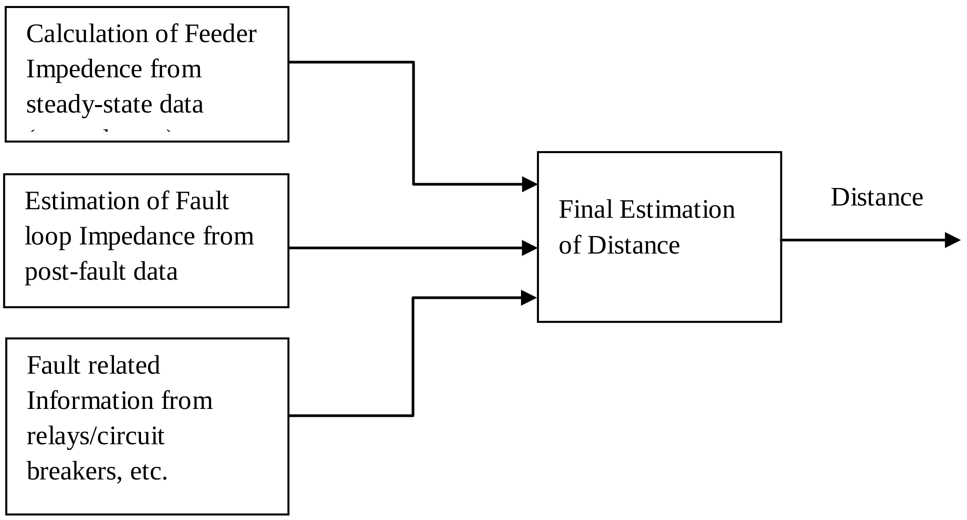

Fig.1 Block diagram of the Apparent-impedance based algorithm

Fig.1 presents the Block diagram of the Apparent-impedance based algorithm. Accuracy of these algorithms can be enhanced with the accuracy of system data. These methods involve calculation of apparent impedance and fundamental quantities. If dynamic load variations are duly compensated, accuracy can be improved.

A typical radial distribution system is made up of main feeder, laterals and loads. Laterals are basically feeder branches, which may or may not be of three phase configuration. Fig.2 depicts such a system. There are numerous ways, in which an impedance based procedure can be executed. However, a popular one is briefly presented here. This is using the concept of prevailing power flow pathways and their equivalent systems. For every power-flow path, there is an equivalent radial system, and therefore no. of equivalent systems equals no. of laterals. Assuming that there are no load variations during the first cycle upon the inception of fault, lines and loads, which are falling out of the power flow pathway under consideration, are represented by constant impedances. But, before this, it is necessary to run a power-flow algorithm [20], to record voltages and currents during pre-fault conditions. Knowing this power-flow data, equivalent impedances, and therefore the equivalent systems for each power-flow path can modeled. Then, the fault-location algorithm is executed for each equivalent system, and accordingly multiple no. of fault locations corresponding to all prevailing power-flow paths can be estimated. The number of fault locations estimated equals the total number of equivalent systems. This is unique with the issue of fault location in distribution systems, where-in the multiple fault locations estimated have to be properly diagnosed thereafter using various tools and techniques to arrive at a final correct and accurate one.

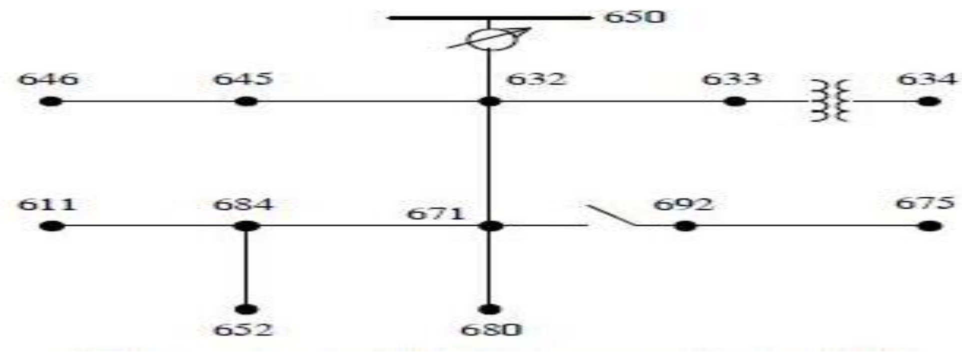

Fig. 2 A typical distribution system

Classical Impedance-based algorithms have evolved over time, and they still remain as popular fault location method till to this day. The researchers are still in progress to upgrade and uplift the accuracy offered by these algorithms, and they stand competitive and extend scope for further development. To cite one such is the work [7], where line shunt admittance (LSA) effect is considered to improve the accuracy of the existing impedance-based methods. The results of this work demonstrated that even in overhead power distribution lines this effect should not be neglected since it can significantly increase the error in the existing methods. This paper [6] presents a new impedance-based method that gives all possible fault locations by using an elaborate feeder model and fault event reports, supported with data from other intelligent electronic devices deployed in the field. This method provides automated fault location within a minute after the inception of fault. Another paper [21] single-end fault location algorithm used a distributed parameter model, with which more accurate results could be obtained due to the distributed nature of line losses and capacitive effects

III. MODERN (KNOWLEDGE-BASED) ALGORITHMS

A. Artificial Neural Network(ANN) Algorithms:

Artificial Neural Network (ANN) is one of the fast emerging versatile methods offering more accurate (classifying and optimizing) solutions for many engineering problems involving complex patterns. These networks have immense potential to track highly complex patterns, which enabled them to pinpoint a fault on electrical power lines. In Fig.3 the basic concept of an ANN is given, wherein collected data of voltages, currents, etc. in the feeders can be used as input to the train the neural network to track their patterns with the output, i.e. location of the related type of fault created.

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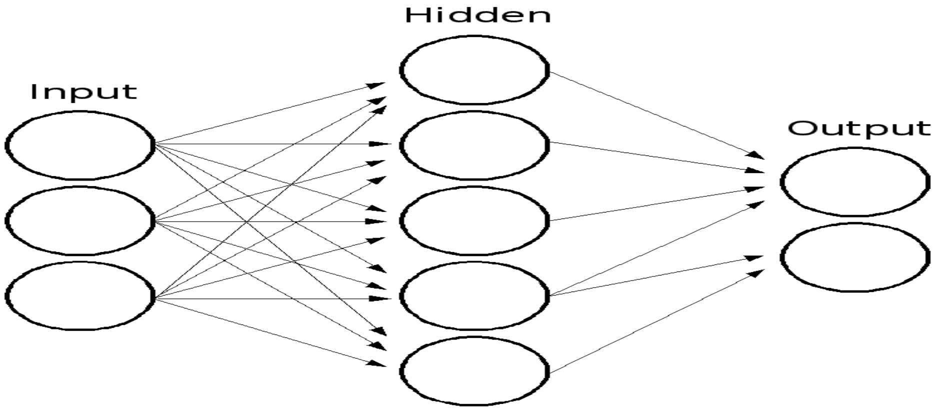

Fig.3. Artificial Neural Network

An ANN is a set of elementary neurons that are connected together in different architectures organized in layers (input, hidden and output layers) that are biologically inspired. A model of a neuron is given in fig.4. below:

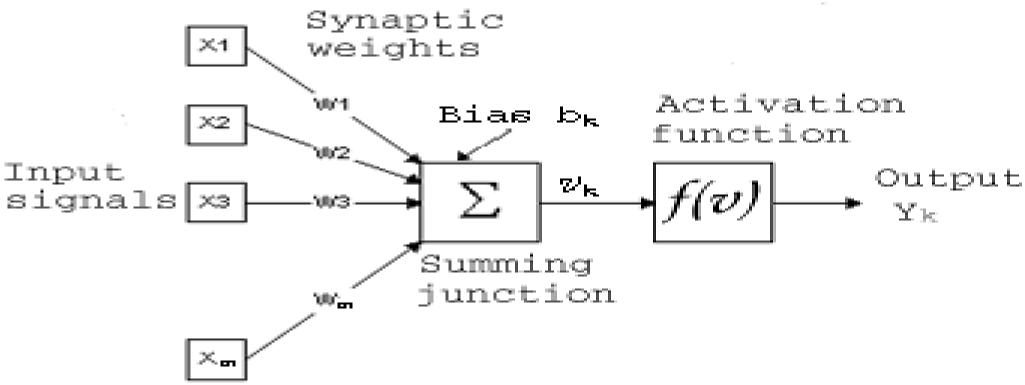

Fig.4 Model of a neuron

A neuron is a non-linear processing unit that relates the given set of inputs with the desired output. A weight (synapse) is attached to every neuron. Neural networks learn a response based on given inputs and a required output by adjusting the node weights and biases accordingly. The main issue in the design of a neural network is the adjustments of the weights aiming to achieve the desired target. This process of adjusting weights is termed as learning or training. Broadly, there are two types of learning: one is supervised learning and the other is unsupervised learning. In supervised learning the adjustments of the weights are done with the objective of narrowing down the error between the presented inputs and the output values. This type is a form of 'teaching' where the teacher exhibits his knowledge of the required input–output relations. In unsupervised learning, as the name implies the teacher is absent and there are no predetermined relations between inputs and output. Here the learning is based on a set of examples with known conditions. In this process of learning these set of examples are selected based on a similarity criteria. This network is a self-organizing system that undergoes learning through a competition, i.e. the output neurons compete with each other for activation, and only single neuron is on at any time (a winner-takes-all competition rule) [9]. The type of ANN structure decides the learning strategy. For example feed-forward multi-layer networks undergo supervised learning. The ANN structures have evolved over the times in dealing with complex engineering issues, and many competitive structures are available today to meet the accuracy demands of the times.

ANN structures was extensively applied for fault location on transmission lines, one such is [8]. Complex Least Error Squares (CLES) and Adaptive Linear Neural Networks (ADALINE) were applied for fault location. The ANNs were used for distributions networks too, and some recent ones were found in [9, 10]. Feed-forward Multilayer perceptrons were used in [9] for fault location on distribution lines. One of the main drawbacks of the ANNs is that their accuracy is highly sensitive to the quantum and quality of the data used to train an ANN algorithm. The results are at stake with limited data

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generated from less number of measuring/monitoring devices. Another drawback is, sluggish convergence in the training process, and therefore requires additional parameters like, hidden layers, learning rate, momentum values, etc. More so, ANN algorithms demand re-training for every change in the networks.

B. Hybrid Type Algorithms:

As the name implies these algorithms are the hybrid combinations of two or more methods or techniques. Each method complements the other, and the resultant combination is comparatively more accurate than either considered independently. Many such combinations have come up between classical impedance-based method and any of the knowledge-based methods. Impedance-based methods, when applied to distribution lines have the drawback of multiple fault locations, and therefore many algorithms took recourse to complementing knowledge-based procedures.

In these papers, [17], [18] and [19], the hybrid combinations of classical approach and knowledge-based methods were worked-out. Here, the data containing voltage sags and the respective currents is extracted, which demonstrates the performance of the system as a consequence of fault, and which is necessary for later diagnosis. The extracted voltage and current data used in this hybrid approach includes both, before and during the fault. Though many algorithms use steady state information from the fault, however there are some, like neural networks, SVM (support vector machines), etc., which rely on the transient state information. As the outputs of these knowledge-based applications, there is data for setting the algorithmic methods, and also a set of possible fault locations. Also, with the steady state data drawn from the fault registers, and using parameters such as the fault resistance, well-known algorithms can be applied to fixed the location of fault. As a result of the application of the algorithmic methods, a set of possible fault locations is obtained. Finally, and having the results of the two methods, it is necessary to make the intersection of the two possible fault sets obtained, in order to have the final possible fault location(Fig.5)

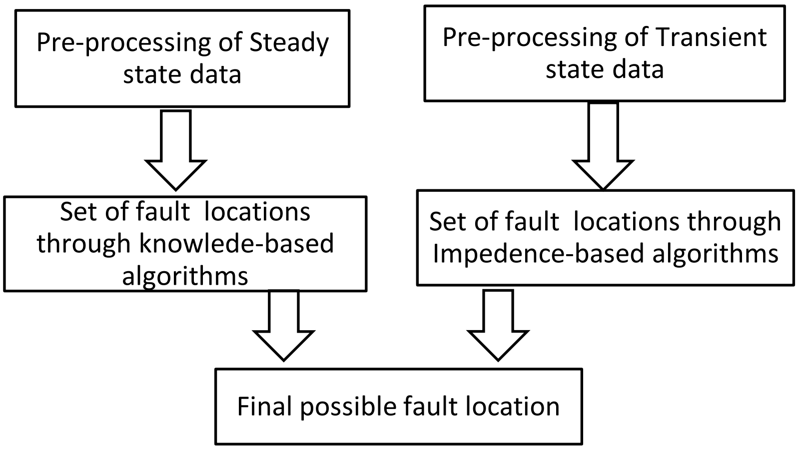

Fig.5. A hybrid type algorithm

In these papers [12, 13, 14, 15, 16], due to the drawback of impedance-based methods in producing one possible fault location, the knowledge-based methods were used. The learning algorithm for multivariable data analysis (LAMDA) together with impedance-based methods is employed in [12]. Here the faulted area is fixed by training LAMDA with the voltage and current data produced from fault simulation. And the fault location is fixed using an impedance-based method. In [13] Impedance-based method, wavelet- based approach and Neural network method, all these three methods are combined to ascertain fault location, fault section, fault type and fault resistance. Wavelet transforms was adopted for Fault detection and classification was done by Wavelet technique. Fault location function was carried out by impedance-based method, and fault section by ANN.

In an another hybrid combination [14], Artificial Neural Network and Support Vector Machine dealt with the Fault Location issue in Distribution networks, SVM shouldered fault detection and fault classification, ANN the fault location. In one more hybrid method [15], Impedance based method, k-nearest neighbors (k-NN) and Support Vector Machines (SVMs) were 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 associated 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 Neighbors (k-NN). This paper identifies four types of faults, namely single phase, phase to phase, double phase to ground and three phases. 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).

C. Genetic Algorithms:

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 general flowchart for fault location using genetic algorithm is given in Fig.6

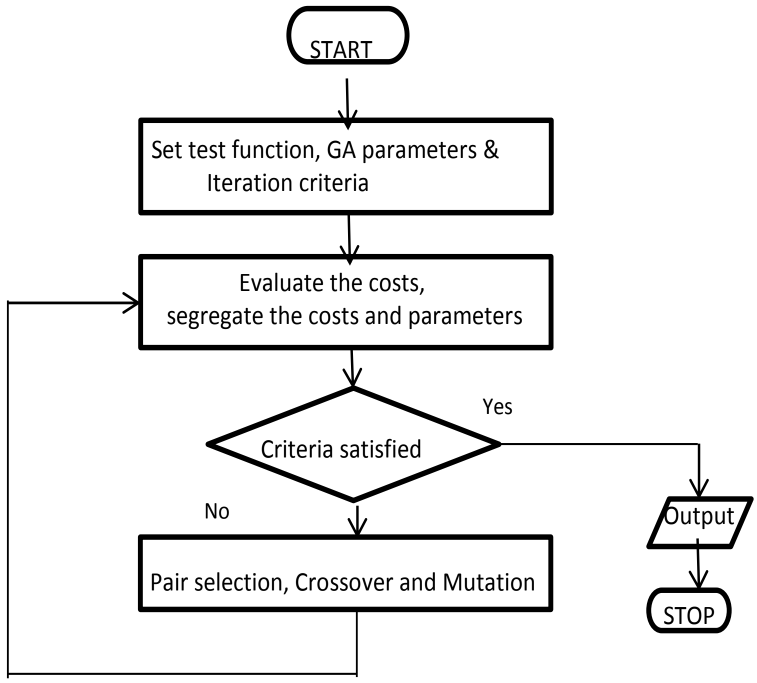

Fig.6. Flowchart for fault location using GA

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D. EM Algorithm

Electromagnetism-like Mechanism Algorithm [22] is one of the new evolving efficient optimization algorithms gaining its applicability in the area of fault location challenges confronted by the power engineers today. The pioneering work on the development of this algorithm was first carried out by Dr. Birbil. Here in this electromagnetism-like mechanism, the imitation of the process of electrical attraction and repulsion phenomena between the oppositely charged particles is employed, wherein particles of population under consideration are directed toward the best direction, enabling the calculation of most optimized solution. The basic steps in EM Algorithm are given the Fig.7.

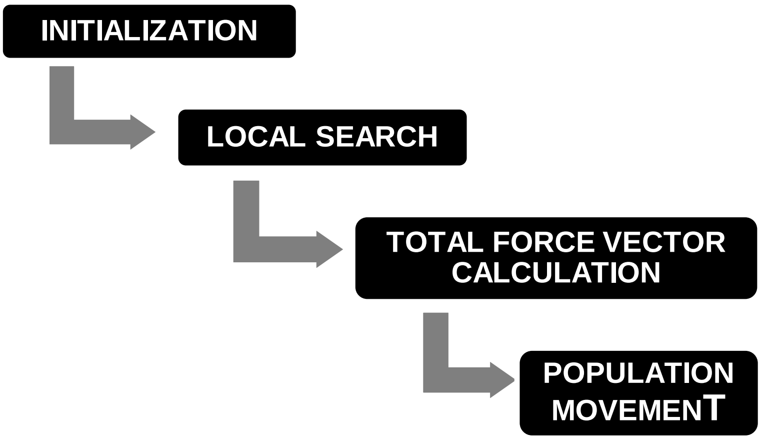

Fig.7: Basic steps in EM Algorithm

***Initialization*:** The first basic step of Initialization consists of, finding all possible solutions, fixing of fitness function for the calculation of objective function, and then the best solution and objective function are saved.

Local Search: Local search is basically a linear and random search to get an update of every independent particle, and therefore an overall update on deviations of whole population.

Total Force Vector Calculation: The total force is the sum total of all the attractive and repulsive forces between the particles of the population. The charge is evaluated by:

$$q_{k,i} = \exp(-m \cdot \frac{f(x_{k,i}) - f(x_{k,j})}{\sum_{i=1}^{n}(f(x_{k,i}) - f(x_{k,best}))})$$

$q_{k,i}$ means the charge of the i^th^ particle in k^th^ iteration.

'm' is the dimension of the particle

'n' is the number of particles.

$f(X_{k,i})$ is the fitness function

$f(X_{k,best})$ is the objective function in k^{th} iteration, when $X_{k,best}$ is the best particle

$F_{k,i}$ is the total vector force equal to summation of vector forces of the particle $X_{k,i}$ with other particles.

Population Movement: The particle X_i of the population will move in the direction of vector force through random incremental displacement. This random incremental displacement, ƛ (varies from 0 to 1), takes the following movement formula:

$$Y_i = X_i + \lambda \frac{F_i}{||F_i||}$$

Once the initialization is done, the best particle and the fitness function is updated using local search, total vector force and population movement. The final updated best particle and its objective function will be the final output (at the end of iterations), which is the final solution of fault location algorithm using EM mechanism.

The accuracy of EM fault location algorithm can be improved using GA in its local search step [22]. There are some more neo-algorithms emerging, which are classed as indirect algorithms, where they use the 0-1 information. In the paper [23], ant colony algorithm is used for fault location in distribution networks. In these papers, [24], [25], Particle swarm optimization algorithm (PSO) and Binary particle swarm optimization (BPSO) algorithm are applied for fault location problem. These algorithms exhibited superior fault tolerance with respect to changing input information.

IV. CONCLUSION

A detailed review of various methods and algorithms applied for the fault location problem in distribution networks over a time-stretch of 10 years to this day (of year 2014) was done. Though all the methods cited in today's fault location literature were not covered in this paper, however, most important and popular of them were dealt in good detail. Several algorithms are swarming into the competitive market today to enhance the accuracy of fault location, especially in the distribution networks, in the context of pacing-up deregulation of electrical power system world. It goes without saying that most of these emerging algorithms are stochastic in nature, more so with distribution networks, because of their complex network configuration (with non-homogenous conductor system and highly ramifying branches) and greatly dynamic load profiles. Upon the study of all these tools and techniques and their impact on the fault location accuracy, it bears the blame of an exaggeration, if one states that a given method/tool/technique/algorithm is most accurate of all. However, in the face of developing monitoring technological resources, the knowledge based methods are gaining more ground in this application. And, it doesn't mean that traditional methods (so called deterministic methods), i.e. the impedance-based methods, which are popularly reckoned under traditional category, have become obsolete. They are still evolving and offering accuracy, which still remain competitive with the modern emerging technologies (which are predominantly knowledge-based in nature).

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