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Optimal Current Meter Placement for Accurate Fault Location Purpose using Dynamic Time Warping

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Abstract

This paper presents a fault location technique for transmission lines with minimum current measurement. This algorithm investigates proper current ratios for fault location problem based on thevenin theory in faulty power networks and calculation of short circuit currents in each branch. These current ratios are extracted regarding lowest sensitivity on thevenin impedance variations of the network structure. Proposed algorithm compares current ratios from offline calculations with corresponding values achieved from measurements with a look-up table system. Best solution based on Dynamic Time Warping (DTW) algorithm is introduced as an output (location of the fault) which includes the line and the distance. Among many current ratios to form look-up table system, the minimum number of them will be extracted by a multi-objective optimization technique using Bees Algorithm (BA). This extraction is based on lowest possible number of buses for instruments installation and required current measurements, estimation accuracy and sensitivity degree from thevenin impedances changes. Accuracy of proposed algorithm is evaluated in a widely used multi-machine network of Western Systems Coordinating Council (WSCC).

Keywords: Fault Location, Current Measurement placement, Dynamic Time Warping, Optimization, Bees Algorithm.

1. Introduction

Transmission networks are subject to faults and short circuits in all voltage levels. Recognition and determination of fault locations in transmission lines has a close relationship with rapid restore of power network and its efficiency [1]. Many methods had been proposed for precise protection with minimum possible cost in fault location. Due to non-idealities of measurement instruments and their effectiveness from network faulty conditions, elimination of dependency on current and voltage values of the system leads to accuracy of fault location algorithm. Therefore, in spite of accuracy of the techniques which use both current and voltage parameters of the network, expansion of new method independent of mentioned parameters are in concern.

The fault location strategies independent of currents [2-6] is among the techniques to reduce the size of information needed for network fault analysis. Recent advances in synchronous measurement based on GPS technology attracted many researches in fault location to use this equipment. Fault location methods based on Phasor Measurement Units (PMU) are among leading strategies in the field of distance protection of transmission lines [7-9]. Precise fault location and estimation of exact value of fundamental frequency components of voltage and current with elimination of measurement noises were presented at [7-9] offering a novel algorithm discrete time Fourier transform. Brahma [9] calculated fault location with synchronous measurement of voltages and currents with PMU in terminals of a multi-terminal network along with estimation of network thevenin model in each terminal and formation of bus impedance matrix. Current independent techniques are presented at [10-12] utilizing PMU measurement strategy.

In all mentioned methods, the formation of thevenin admittance matrix of equivalent faulty network and consequently, solving short circuit equation and determination of fault location is impossible without having network thevenin equivalent in generators and transfer (coupling points of the network with neighboring networks) busses. Knowing network thevenin model, voltage measurement in all busses as network independent variables makes the whole network observable. Therefore, the simplest approach to cover all system parameters is PMU installation in all busses and their processing in dispatching center [13]. In fact, many PMUs are needed to achieve all system information. This approach is not cost effective at all and therefore, measurements should be limited to minimum possible umbers of busses for monitoring to reduce the total cost [14]. Therefore, determination of appropriate number of PMU installations is a significant concern, which is related to the efficiency of the scheme. In fact, there is a tradeoff between the monitoring capability and cost efficiency. Thus, the proper number of monitors and their locations must be optimally determined [15-18]. The complete state of the power system (voltages and currents of the entire system) can be estimated from a relatively small number of synchronized, partial and asymmetric measurements of phasor voltage and current at the selected bus bar.

The basis of the spread monitoring system is based on evaluating a few numbers of the voltages and currents in some busses and estimating the parameters of the other busses. Determination of the bus numbers and the location of monitors is known as observability analysis which can be performed by well documented procedures based on topological or numerical methods [19]. The advantage of this method in solving the observability problem with low required input data. It needs only the Existence Matrix as an input, and it can get from this matrix all the required data in order to solve the problem. According to Eldery et al. [6], the observability constraints guarantee that all the state variables are measured (or calculated) by at least one monitor, and the constraints are obtained from Kirchhoff's Laws. A PMU placed at a given bus can provide the voltage phasor at the bus and the phasor currents of several or all lines incidents to that bus [20-22]. Therefore, given the widespread availability of PMUs in a power system, the state of the system can be directly obtained at a higher rate without estimation. Note that such an approach also carries the risk of bad data.

System observability considers not only the capability to monitor whole system with minimum measurement devices, but also their reliability. The reliability issue can be explained in cases which some plausible inconsistencies in measured data are possible. Observability can be affected by plausible system configuration changes. The changes that are mainly due to loss of transmission equipment would be considered as contingency. Note that, a contingency analysis must be applied to the reliability assessment for system observability checking. This analysis involves possible contingencies that are likely to occur in order to detect the potential harmful ones (i.e., contingencies that lead to a state of emergency in the system). The single line outage is considered as high probability events. Problems associated with contingencies have recently received greater attention [23-26].

In spite of system state estimation, these techniques did not consider determination of fault location and values estimation in faulty conditions. Only limited numbers of researches are dedicated to PMU location in order to achieve fault location with minimum possible cost and places of installation [27-30]. These techniques are based on possible topologies of power network and one-bus-spaced deployment strategy. In this scheme, PMU is installed in one side of transmission line, which is investigated for fault analysis. Advantage of the mentioned strategy is that there is no need to have the information of sub-networks connected to the main network such as load, generator and combined network. This requires allocation of more measurement units. Therefore, offering and strategy to eliminate dependency of the calculation of thevenin model of sub-network along with least PMU is pleasurable.

In dynamic study of the system, network structure is always changing. This leads to changes of the system equations and analysis results may have essential difference with previous results. Assuming single line outage of observable network, the observability of the new network will be influenced. In other words, calculation of voltages and currents values of unmonitored points with information of monitored points is impossible by network model change in short circuit condition.

In this paper, a fault location strategy with least current measurement units will be presented. The algorithm is based on the ratios of lines currents in occurrence of short circuits. Search for proper ratios is carried out by offline short circuit calculation to form a look-up table. Introduction of the proposed algorithm and of problem formulation are presented in section 2-1. Recognition algorithm structure is based on comparison of the current ratios in short circuit calculation with online network measurement values. Dynamic Time Warping (DTW) method as similarity detection toll is mentioned at subsection 2-2. Current ratios optimal search is offered in section

2-3 based on constraints that complete recognition process with high accuracy and minimum number of measurement points. Forming a look-up table is investigated in section 2-4. Proposed optimization strategy is introduced in 2-5 using Bees Algorithm. Finally, simulation results of proposed algorithm and its implementation on common multi-machine network of Western Systems Coordinating Council (WSCC) are shown in section 3.

2. Problem Formulation and Proposed Algorithm

2.1. Problem formulation

Pre fault and during fault models of transmission line are shown in Fig.1. Thevenin theorem is one of the short circuit calculation methods. Effect of short circuit is shown with thevenin motive force and buses voltage and lines currents represent resultant changes of short circuit.

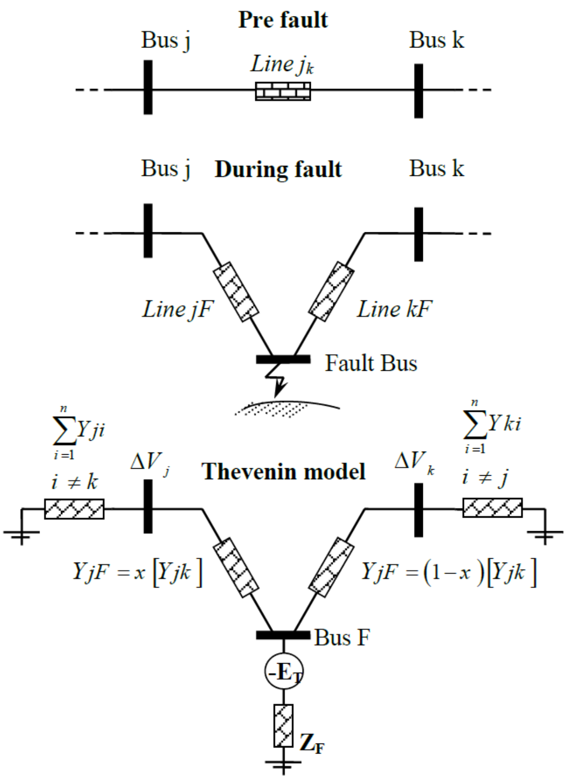


Fig.1. Part of an n-bus network: pre fault, during fault and thevenin model of faulty network

$$\Delta V = V_{\text{During-Fault}} - V_{\text{Pre-Fault}} = V^{f} - V^{\circ} \tag{1}$$

Fault occurrence in each location of the transmission lines of power network leads to following equations.

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ I_F \end{bmatrix} = \begin{bmatrix} Y'_{11} & Y'_{12} & \cdots & Y'_{1n} & Y'_{1F} \\ Y'_{21} & Y'_{22} & \cdots & Y'_{2n} & Y'_{2F} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Y'_{n1} & Y'_{n2} & \cdots & Y'_{nn} & Y'_{nF} \\ Y'_{F1} & Y'_{F2} & \cdots & Y'_{Fn} & Y'_{FF} \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \vdots \\ \Delta V_n \\ \Delta V_F \end{bmatrix} \tag{2}$$

Buses voltage changes can be related to network currents changes ($\Delta i = i^{f} - i^{\circ}$) with circuit calculations. Therefore, branches currents of thevenin network will be achieved based on fault current in appointed location.

$$\begin{bmatrix} \Delta I_{branch1} \\ \Delta I_{branch2} \\ \vdots \\ \Delta I_{branchN} \end{bmatrix} = \begin{bmatrix} f_1(I_{Fault}) \\ f_2(I_{Fault}) \\ \vdots \\ f_n(I_{Fault}) \end{bmatrix} \tag{3}$$

Each branch's current with respected to expanded model of transmission line, can be considered to two variables consists of sending and receiving sides currents. Therefore, i[th] branch's current involves two local and remote busses.

$$\Delta I_{\text{branch i}} : \begin{cases} \Delta I_{LR} & \boxed{\text{Current from local to remot bus}} \\ \Delta I_{RL} & \boxed{\text{Current from remot to local bus}} \end{cases} \tag{4}$$

Finally, currents ratios can be considered independent of fault current and only dependent to faulty line and fault location. Based on mentioned current ratios, branches current ratios and matrix M_k^l can be presented to specific fault location (k% of line length) in l^{th} branch (from N branches) exclusively.

$$\frac{\Delta I_{\text{branch i}}}{\Delta I_{\text{branch j}}} = \frac{f_i(I_{Fault})}{f_j(I_{Fault})} = f_{ij}(x) \tag{5}$$

$$M_k^l = \begin{bmatrix} \frac{\Delta I_{branch1}}{\Delta I_{branch1}} & \frac{\Delta I_{branch1}}{\Delta I_{branch2}} & \frac{\Delta I_{branch1}}{\Delta I_{branch3}} & \cdots & \frac{\Delta I_{branch1}}{\Delta I_{branchN}} \\ \frac{\Delta I_{branch2}}{\Delta I_{branch1}} & \frac{\Delta I_{branch2}}{\Delta I_{branch2}} & \frac{\Delta I_{branch2}}{\Delta I_{branch3}} & \cdots & \frac{\Delta I_{branch2}}{\Delta I_{branchN}} \\ \frac{\Delta I_{branch3}}{\Delta I_{branch1}} & \frac{\Delta I_{branch3}}{\Delta I_{branch2}} & \frac{\Delta I_{branch3}}{\Delta I_{branch3}} & \ddots & \frac{\Delta I_{branch3}}{\Delta I_{branchN}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{\Delta I_{branchN}}{\Delta I_{branch1}} & \frac{\Delta I_{branchN}}{\Delta I_{branch2}} & \frac{\Delta I_{branchN}}{\Delta I_{branch3}} & \cdots & \frac{\Delta I_{branchN}}{\Delta I_{branchN}} \end{bmatrix}_{N \times N} \tag{6}$$

Current ratios of (5) are substituted in (6) and therefore, matrix C_k^l is achieved as (7).

In mentioned thevenin model, current changes of loads and other elements are neglected due to high fault current assumption. Therefore, these values will be subjected to some variations in real model. Also, as the diagonal elements of above matrix are equal to 1, the process related to these elements is not considered any more. Note that some of these ratios may result to zero, infinity or irrational values due to probable null values of numerator or denominator of the ratios. These elements are also considered as zero in the modified matrix. In addition, due to diagonal reversal symmetry between components of upper and lower triangles, only components of upper triangle are considered. For more clarification, knowing component $\frac{\Delta I_{11}}{\Delta I_{12}}$ from C_k^l matrix, the parameter $\frac{\Delta I_{12}}{\Delta I_{11}}$ is achieved without further calculations. Therefore, above matrix can be modified as (8).

Following matrix sets are defined based on fault occurrence probability in each line and distance.

$$\begin{matrix} \left[C_{1\%}^{branch1}\right] & \left[C_{2\%}^{branch1}\right] & \left[C_{3\%}^{branch1}\right] & \cdots & \left[C_{99\%}^{branch1}\right] \\ \left[C_{1\%}^{branch2}\right] & \left[C_{2\%}^{branch2}\right] & \left[C_{3\%}^{branch2}\right] & \cdots & \left[C_{99\%}^{branch2}\right] \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \left[C_{1\%}^{branchN}\right] & \left[C_{2\%}^{branchN}\right] & \left[C_{3\%}^{branchN}\right] & \cdots & \left[C_{99\%}^{branchN}\right] \end{matrix} \quad (9)$$

It is obvious that each component of matrices in (9) indicates a specific ratio of branches currents in different faults, distances and line number. These values are achieved based on offline short circuit calculations of the power system.

Network current ratios, which are the difference between the pre-fault and during-fault currents, are influenced by network structure and its involved parameters. Although dependency of the values to network topology and fault recognition from variations of these values is a positive point, thevenin equivalent in generator and transfer buses is a negative point regarding to currents and their ratios.

$$C_k^l = \begin{bmatrix}
\frac{\Delta I_{11}}{\Delta I_{11}} & \frac{\Delta I_{11}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{1N}} & \frac{\Delta I_{11}}{\Delta I_{21}} & \frac{\Delta I_{11}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{N1}} & \frac{\Delta I_{11}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{NN}} \\
\frac{\Delta I_{12}}{\Delta I_{11}} & \frac{\Delta I_{12}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{1N}} & \frac{\Delta I_{12}}{\Delta I_{21}} & \frac{\Delta I_{12}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{N1}} & \frac{\Delta I_{12}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\Delta I_{1N}}{\Delta I_{11}} & \frac{\Delta I_{1N}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{1N}} & \frac{\Delta I_{1N}}{\Delta I_{21}} & \frac{\Delta I_{1N}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{N1}} & \frac{\Delta I_{1N}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{NN}} \\
\frac{\Delta I_{21}}{\Delta I_{11}} & \frac{\Delta I_{21}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{1N}} & \frac{\Delta I_{21}}{\Delta I_{21}} & \frac{\Delta I_{21}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{N1}} & \frac{\Delta I_{21}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{NN}} \\
\frac{\Delta I_{22}}{\Delta I_{11}} & \frac{\Delta I_{22}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{1N}} & \frac{\Delta I_{22}}{\Delta I_{21}} & \frac{\Delta I_{22}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{N1}} & \frac{\Delta I_{22}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\Delta I_{2N}}{\Delta I_{11}} & \frac{\Delta I_{2N}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{2N}}{\Delta I_{1N}} & \frac{\Delta I_{2N}}{\Delta I_{21}} & \frac{\Delta I_{2N}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{2N}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{2N}}{\Delta I_{N1}} & \frac{\Delta I_{2N}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{2N}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\Delta I_{N1}}{\Delta I_{11}} & \frac{\Delta I_{N1}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{N1}}{\Delta I_{1N}} & \frac{\Delta I_{N1}}{\Delta I_{21}} & \frac{\Delta I_{N1}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{N1}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{N1}}{\Delta I_{N1}} & \frac{\Delta I_{N1}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{N1}}{\Delta I_{NN}} \\
\frac{\Delta I_{N2}}{\Delta I_{11}} & \frac{\Delta I_{N2}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{N2}}{\Delta I_{1N}} & \frac{\Delta I_{N2}}{\Delta I_{21}} & \frac{\Delta I_{N2}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{N2}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{N2}}{\Delta I_{N1}} & \frac{\Delta I_{N2}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{N2}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\frac{\Delta I_{NN}}{\Delta I_{11}} & \frac{\Delta I_{NN}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{NN}}{\Delta I_{1N}} & \frac{\Delta I_{NN}}{\Delta I_{21}} & \frac{\Delta I_{NN}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{NN}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{NN}}{\Delta I_{N1}} & \frac{\Delta I_{NN}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{NN}}{\Delta I_{NN}}
\end{bmatrix}_{N^2 \times N^2} \quad (7)$$

$$C_k^l = \begin{bmatrix}
0 & \frac{\Delta I_{11}}{\Delta I_{12}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{1N}} & \frac{\Delta I_{11}}{\Delta I_{21}} & \frac{\Delta I_{11}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{N1}} & \frac{\Delta I_{11}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{11}}{\Delta I_{NN}} \\
0 & 0 & \cdots & \frac{\Delta I_{12}}{\Delta I_{1N}} & \frac{\Delta I_{12}}{\Delta I_{21}} & \frac{\Delta I_{12}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{N1}} & \frac{\Delta I_{12}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{12}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & \frac{\Delta I_{1N}}{\Delta I_{21}} & \frac{\Delta I_{1N}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{N1}} & \frac{\Delta I_{1N}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{1N}}{\Delta I_{NN}} \\
0 & 0 & \cdots & 0 & 0 & \frac{\Delta I_{21}}{\Delta I_{22}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{N1}} & \frac{\Delta I_{21}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{21}}{\Delta I_{NN}} \\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & \frac{\Delta I_{22}}{\Delta I_{2N}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{N1}} & \frac{\Delta I_{22}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{22}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & \frac{\Delta I_{2N}}{\Delta I_{N1}} & \frac{\Delta I_{2N}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{2N}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 & \frac{\Delta I_{N1}}{\Delta I_{N2}} & \cdots & \frac{\Delta I_{N1}}{\Delta I_{NN}} \\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & \frac{\Delta I_{N2}}{\Delta I_{NN}} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & 0 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0
\end{bmatrix}_{N^2 \times N^2} \quad (8)$$

$$where \left\{ \text{in } \frac{\Delta I_{ij}}{\Delta I_{kl}} : \text{if } \Delta I_{ij}=0 \text{ or } \Delta I_{kl}=0 \rightarrow C_k^l(ij,kl)=0 \right.$$

The proposed algorithm's principle is based on the best selection of the proper ratios that are most capable of fault location recognition from matrices of (9). Identification of fault location is carried out based on comparison of faulty network, forming candidate current ratios and extraction of a case with most similarity from intended matrices. In fact, proposed algorithm provides the most similar matrix from offered sets of (9) as a matrix related to fault location (using limited measurements of the network model) with a technique based on signal processing and similarity measure extraction methods.

It is apparent that finding proper candidate current ratios among many C_k^l matrices is the task. This issue is based on selection of the ratios with least sensitivity to network's thevenin impedance variations. The selection algorithm of current ratios is presented at Fig.2. Based on proposed flowchart, current ratios of C_k^l matrices are investigated for random values of thevenin impedance between 80 to 120 percent of base value for different occurred faults in distances of 1 to 99 percent. Regarding to variance of each current ratio corresponding to $C_{(i,j)}$ in mentioned random values, variance matrix is calculated. The corresponding components of $M_{(i,j)}$ are considered infinity if one of their used currents is zero. After variance calculation for all non-zero matrices C_k^l, following variance matrix is achieved.

In this matrix, the least value components are corresponding to current ratios with least sensitivity to thevenin impedance changes of the network. According to high number of non-infinite components of variance matrix, only the components with all minimum, maximum and average variances below 1% are considered. After sorting of proper values, the candidate current ratios with their variance are achieved. It is obvious that why variance values corresponding to zero components of C_k^l are considered as infinity. They are exited in sorting process. Finally, following vector matrices with lower dimensions (with the length of variance matrix) are achieved as reference current ratios in different fault conditions instead of $N^2 \times N^2$ matrices of (9).

Consequently, the fault location algorithm is established based on limited current measurements corresponding to candidate current ratios. To determine the location of the fault, the values of required currents are collected from limited measurements to form the candidate current ratios matrix. These values create a test matrix corresponding to length and ratios of current ratio matrix.

$$[\text{CurrentRatio}]^{\text{Test}} \quad (12)$$

Proposed algorithm extracts most similar matrix from sets of (11) to the measurement matrix of (12) based on signal processing technique and a similarity measure strategy. Extracted matrix from (12) gives the fault spot characteristics (line number and fault distance) as the output of recognition algorithm.

$$
VarMatrix=\begin{bmatrix}
\infty & \cdots & \frac{Var\left(\frac{\Delta I_{11}}{\Delta I_{1N}}\right)}{Mean\left(\frac{\Delta I_{11}}{\Delta I_{1N}}\right)} & \frac{Var\left(\frac{\Delta I_{11}}{\Delta I_{21}}\right)}{Mean\left(\frac{\Delta I_{11}}{\Delta I_{21}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{11}}{\Delta I_{2N}}\right)}{Mean\left(\frac{\Delta I_{11}}{\Delta I_{2N}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{11}}{\Delta I_{N1}}\right)}{Mean\left(\frac{\Delta I_{11}}{\Delta I_{N1}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{11}}{\Delta I_{NN}}\right)}{Mean\left(\frac{\Delta I_{11}}{\Delta I_{NN}}\right)} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\infty & \cdots & \infty & \frac{Var\left(\frac{\Delta I_{1N}}{\Delta I_{21}}\right)}{Mean\left(\frac{\Delta I_{1N}}{\Delta I_{21}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{1N}}{\Delta I_{2N}}\right)}{Mean\left(\frac{\Delta I_{1N}}{\Delta I_{2N}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{1N}}{\Delta I_{N1}}\right)}{Mean\left(\frac{\Delta I_{1N}}{\Delta I_{N1}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{1N}}{\Delta I_{NN}}\right)}{Mean\left(\frac{\Delta I_{1N}}{\Delta I_{NN}}\right)} \\
\infty & \cdots & \infty & \infty & \cdots & \frac{Var\left(\frac{\Delta I_{21}}{\Delta I_{2N}}\right)}{Mean\left(\frac{\Delta I_{21}}{\Delta I_{2N}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{21}}{\Delta I_{N2}}\right)}{Mean\left(\frac{\Delta I_{21}}{\Delta I_{N2}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{21}}{\Delta I_{NN}}\right)}{Mean\left(\frac{\Delta I_{21}}{\Delta I_{NN}}\right)} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\infty & \cdots & \infty & \infty & \cdots & \infty & \cdots & \frac{Var\left(\frac{\Delta I_{2N}}{\Delta I_{N2}}\right)}{Mean\left(\frac{\Delta I_{2N}}{\Delta I_{N2}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{2N}}{\Delta I_{NN}}\right)}{Mean\left(\frac{\Delta I_{2N}}{\Delta I_{NN}}\right)} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\infty & \cdots & \infty & \infty & \cdots & \infty & \cdots & \frac{Var\left(\frac{\Delta I_{N1}}{\Delta I_{N2}}\right)}{Mean\left(\frac{\Delta I_{N1}}{\Delta I_{N2}}\right)} & \cdots & \frac{Var\left(\frac{\Delta I_{N1}}{\Delta I_{NN}}\right)}{Mean\left(\frac{\Delta I_{N1}}{\Delta I_{NN}}\right)} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots & \ddots & \vdots \\
\infty & \cdots & \infty & \infty & \cdots & \infty & \cdots & \infty & \cdots & \infty
\end{bmatrix}_{N^2\times N^2}
$$

$$
where\left\{\text{in } Var\left(\frac{\Delta I_{ij}}{\Delta I_{kl}}\right)\text{:if } \Delta \mathrm{I}_{ij}=0 \text{ or } \Delta \mathrm{I}_{kl}=0 \rightarrow \frac{Var\left(\frac{\Delta I_{ij}}{\Delta I_{kl}}\right)}{Mean\left(\frac{\Delta I_{ij}}{\Delta I_{kl}}\right)}=\infty\right. \quad (10)
$$

$$
\begin{matrix}
\left[\text{CurrentRatio}_{1\%}^{branch1}\right]^{\text{Ref}} & \left[\text{CurrentRatio}_{2\%}^{branch1}\right]^{\text{Ref}} & \cdots & \left[\text{CurrentRatio}_{99\%}^{branch1}\right]^{\text{Ref}} \\
\left[\text{CurrentRatio}_{1\%}^{branch2}\right]^{\text{Ref}} & \left[\text{CurrentRatio}_{2\%}^{branch2}\right]^{\text{Ref}} & \cdots & \left[\text{CurrentRatio}_{99\%}^{branch2}\right]^{\text{Ref}} \\
\vdots & \vdots & \ddots & \vdots \\
\left[\text{CurrentRatio}_{1\%}^{branchN}\right]^{\text{Ref}} & \left[\text{CurrentRatio}_{2\%}^{branchN}\right]^{\text{Ref}} & \cdots & \left[\text{CurrentRatio}_{99\%}^{branchN}\right]^{\text{Ref}}
\end{matrix} \quad (11)
$$

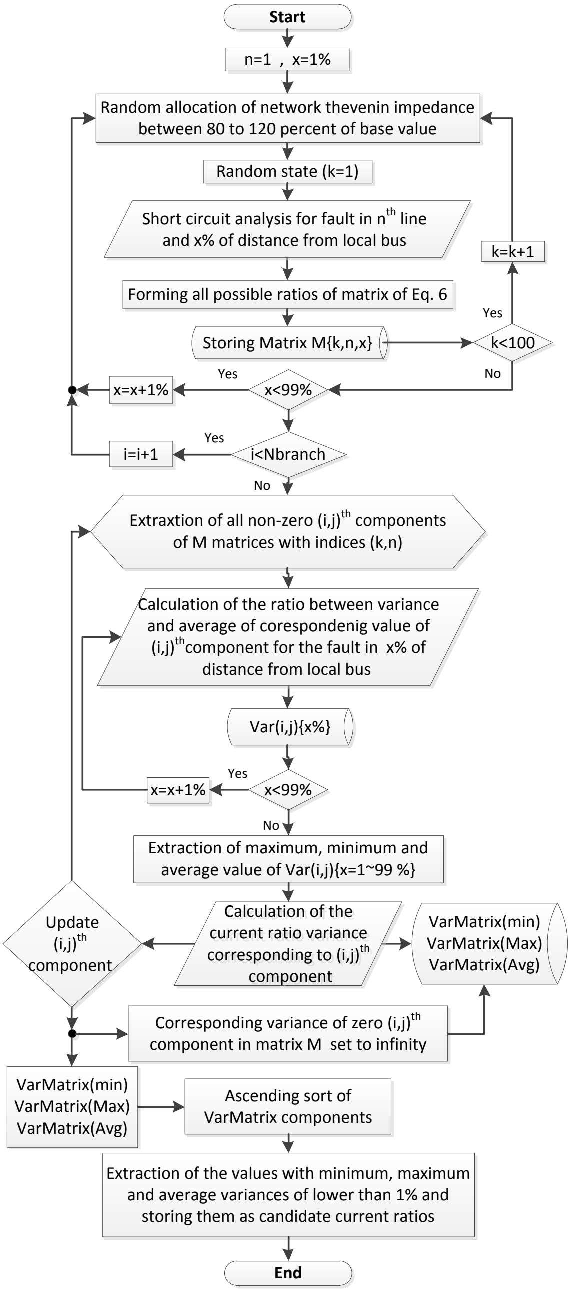


Fig.2. Selection algorithm of current ratios

2.2. Searching similarities between test and reference data

In many signal-processing applications, a proper measure to compare two signals plays an important role in successful performance of algorithm. Similarity measure and similarity search methods are widely used in broad range of applications such as pattern recognition, data analysis, prediction and forecasting regarding to financial and business activities, share market information and etc. also, these functions are commonly used in listing, disorder diagnoses, classification, clustering and discovering rules [31].

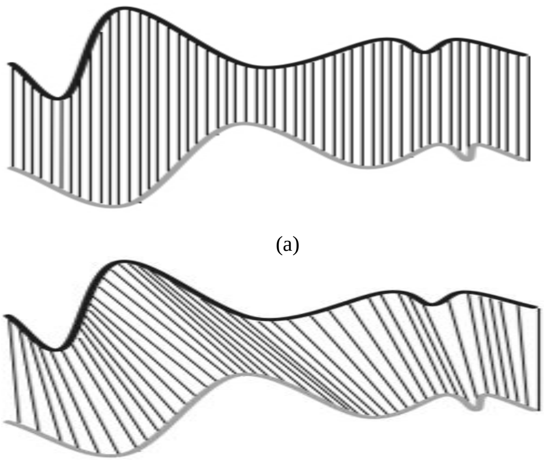
Similarity measures are type of rating functions which maps a numerical value to a sequence pair or time series. In determination of similarity measure, it is proper to use and algorithm considering different similarity aspects. In pattern recognitions of a signal, application of proper similarity measures in order to compare extracted characteristics of that signal which can recognize available similar specimens play a key role in classifier performance improvement.

Similarity measures are used in implementation and evaluation of an algorithm in most signal processing applications. For instance, proximity between simulation data and real data are investigated with a measure. Determination of correlation between presented model for test signal and real signal is one of these applications. In addition, algorithm performance is evaluated by a similarity/distance measure such as cosine or Euclidian distances in noise reduction problems [32].

Generally, any proposed method to solve a signal processing problem such as noise reduction, classification, pattern recognition, quantization, clustering, coding and compression should be evaluated by a similarity measure.

Most algorithms used to compare signals and sequences utilize the Euclidean distance or some variation thereof. Recently DTW (dynamic time warping) has been recognized as the most robust distance function to measure the similarity between two series. Euclidean distance can be an extremely brittle distance measurement. A more robust form of similarity measure is Dynamic Time Warping (DTW). Although it has well documented advantages as a distance measure, it is computationally very expensive. The DTW measure calculates the similarity between two vectors based on their best nonlinear alignment version, hence being insensitive to the relative shift and relative stretch of one vector with respect to the other. The ability of DTW to handle sequences of different lengths is a great advantage, and therefore the simple lower bound that requires different-length sequences to be reinterpolated to equal length is of limited utility.

In Euclidean approach a simple point-to-point comparison and calculation is performed between two sequences. Fig. 3.a shows an example of distance between two sequences. By allowing flexibility in the time axis, Dynamic Time Warping achieves a more intuitive alignment between the two series (Fig 3.b). The definition and calculation of the DTW distance measure is detailed in [33, 34].



(a)

(b)

Fig.3. Comparison of Euclidean distance (a) and Dynamic Time Warping (b)

2.3. Extraction of optimal current ratios

Obtained candidate current ratios from the algorithm of Fig 2 consist of many currents due to network topology characteristics. Selection of all these ratios in a relatively long vector increases the complexity of calculations and the number of busses for current measurement installations. For instance, some of the candidate current ratios of IEEE 9-BUS test system with least sensitivity order to thevenin impedance values are sorted as follows:

$$\left[\overset{\text{Condidate}}{\text{CurrentRatio}}\right]=\Big[\frac{\Delta I_{11}}{\Delta I_{14}}\ \frac{\Delta I_{22}}{\Delta I_{28}}\ \frac{\Delta I_{33}}{\Delta I_{36}}\ \frac{\Delta I_{11}}{\Delta I_{41}}\ \frac{\Delta I_{14}}{\Delta I_{41}}\ \frac{\Delta I_{22}}{\Delta I_{82}}\ \frac{\Delta I_{28}}{\Delta I_{82}}\ \frac{\Delta I_{33}}{\Delta I_{63}}\ \frac{\Delta I_{36}}{\Delta I_{63}}\ \frac{\Delta I_{55}}{\Delta I_{99}}\ \frac{\Delta I_{77}}{\Delta I_{99}}\ \frac{\Delta I_{55}}{\Delta I_{82}}\ \frac{\Delta I_{77}}{\Delta I_{82}}\ \frac{\Delta I_{55}}{\Delta I_{63}}\ \frac{\Delta I_{55}}{\Delta I_{77}}\ \frac{\Delta I_{49}}{\Delta I_{94}}\ \frac{\Delta I_{76}}{\Delta I_{87}}\ \frac{\Delta I_{45}}{\Delta I_{54}}\ \frac{\Delta I_{78}}{\Delta I_{87}}\ \frac{\Delta I_{67}}{\Delta I_{87}}\ \cdots\Big] \quad (13)$$

Extraction of optimal current ratios is carried out based on an objective function with following cost functions.

2.3.1. Fault location estimation with least error

Selecting some of the ratios in Eq.14 and forming new vectors (which is referred as rewritten vector) based on Equations 10 & 11 depends on the best estimation and similarity of the test and reference vectors. Estimation performance and extraction of the most similar vectors of rewritten versions of equations 10 and 11 depends on correct recognition of the faulty line and proper identification of the fault distance.

Fitness of any desired current ratios string is given by examining all the possible scenarios for the occurrence of errors in the network. Implementation of this section is accomplished by assuming fault occurrence in all parts of the network and finding similarities between Test and Ref vectors in each case. The Cost function which is representative of this objective function is formed based on total numbers of wrong faulty lines estimation ($C_{\text{Wrong Faulty Lines Estimation}}$) and maximum error of fault distance estimation ($C_{\text{Max Fault Location Error}}$) in all possible fault conditions.

Assigning weighting coefficient

Determination of proper weighting coefficient for each of the above values should be designed so as that their importance is modelled correctly. In this way, weighting coefficient of total numbers of wrong faulty lines estimation is considered 1 and weighting factor of 0.01 is considered for maximum error of fault distance estimation at all conditions. Therefore, sum of above two terms assigning mentioned weighting coefficients gives following cost function of fault location estimation for any desired string of current ratios.

$$C_{\text{Estimation Error}} = C_{\text{Wrong Faulty Lines Estimation}} + \frac{1}{100}\times C_{\text{Max Fault Location Error}} \quad (14)$$

2.3.2. Measurement cost

In candidate current ratios of (13), for $\frac{\Delta I_{11}}{\Delta I_{14}}$ only bus1 is required for current measurement installation while the ratio $\frac{\Delta I_{55}}{\Delta I_{99}}$ needs current measurement installations on buses 5 and 9. The same scenario is valid for other ratios. Therefore, optimal selection of candidate ratios of (13) is introduced as a determinant term in cost function for least required buses as well as proper fault location recognition.

$$C_{\text{Number of Monitoring Bus}} \quad (15)$$

Also, number of used currents in candidate current ratios and the number of these ratios are other effective factors of measurement cost.

$$C_{\text{Number of Current Measurement}} \quad (16)$$

Selection of any of mentioned ratios of (13) should have the most desirable answer and cover minimum sensitivity on network thevenin changes at the same time. For instance, considering following string as an acceptable rewritten current ratio vector among the ratios of (13):

$$[\text{CurrentRatio}]_{\text{Rewrited}} = \begin{bmatrix} \frac{\Delta I_{22}}{\Delta I_{28}} & \frac{\Delta I_{22}}{\Delta I_{82}} & \frac{\Delta I_{36}}{\Delta I_{63}} & \frac{\Delta I_{77}}{\Delta I_{82}} & \frac{\Delta I_{45}}{\Delta I_{54}} \\ 2 & 6 & 9 & 13 & 18 \end{bmatrix} \quad (17)$$

Where, the second row indicates the sensitivity level ranks of candidate current ratios against network thevenin changes. Therefore, worth case of sensitivity is selected as another effective factor on the fitness of the candidate current ratio string. Regarding to (13), worth dependency case occurred in 18[th] current ratio out of candidate ones based on algorithm of Fig 2. Finally, cost function is defined considering variance of 18[th] current ratio as:

$$C_{\text{Max Current Ratio Variance}} \quad (18)$$

Assigning weighting coefficient

Same as above sub-section, proper weighting coefficients are assigned to each cost functions to model their importance on final objective in order to achieve desired answers in optimization process. Priority and importance level of cost functions are offered in (15), (16), (18). Therefore, their weighting coefficients are assigned by values of w_{m_1}, w_{m_2}, w_{m_3} in (19). Note that $w_{m_1} > w_{m_2} > w_{m_3}$.

$$C_{Measurement} = w_{m_1} \times C_{\sum Monitoring\ Bus} + w_{m_2} \times C_{Number\ of\ Current\ Measurement} + w_{m_3} \times C_{Max\ Current\ Ratio\ Variance} \quad (19)$$

2.3.3. Conclusive cost function

To achieve a certain purpose, it is necessary to evaluate several measures concurrently and rate different options according to the measures. This process is called multi-objective decision. In this problems, the strategy of weighted sum of functions are used to convert a multi-purpose function to a single-purpose one. As described in section 2-3-4, analytical-random process is used in weighting coefficient determination. Cost functions of fault location estimation with least error and limited measurements are added together with weighting coefficients of W_1 and W_2 in conclusive cost function.

$$C_{\text{Total}} = W_1 \times C_{\text{Estimation Error}} + W_2 \times C_{\text{Measurement}} \quad (20)$$

In this method, each of mentioned weightings ($Wm_1, Wm_2, Wm_3, W_1, W_2$) are determined in a preset range. Each range is defined based on nature of the costs and general knowledge about their importance.

$$\begin{cases} 0.4 < Wm_1 < 0.8 \\ 0.1 < Wm_2 < 0.3 \quad \text{where} \quad Wm_1 + Wm_2 + Wm_3 = 1 \\ 0.1 < Wm_3 < 0.3 \end{cases} \quad (21)$$
$$\begin{cases} 0.6 < W_1 < 0.8 \\ 0.2 < W_2 < 0.4 \end{cases} \quad \text{where} \quad W_1 + W_2 = 1$$

2.4. Preparation of database for test vectors formation

Proposed fault location algorithm requires a network database with different faults on various time intervals to optimize its search with a smart search method based on recognition of correct $[CurrentRatio]^{Ref}$ matrix from measurement matrix of $[CurrentRatio]^{Test}$. Therefore, test network modelling is carried out with DigSILENT software for different faults in a comprehensive database. This software provides required information for fault locating algorithm (final candidate currents in optimal current ratios). The process of most similarity search extracts the best matrix from reference database (taken from load flow information in offline mode) and provides as a match location with measurement data.

2.5. Optimization Technique

Selecting each of the current ratios of (13) is done with binary modelling. Presence or absence of each of the current ratios of (13) in (17) is modelled with allocation of one or zero to the corresponding bit with row number of intended current ratio. Therefore, length of the used binary string in optimization process should be equal to length of current ratio vector of (13). Accomplishment of fault location algorithm requires a high-speed optimization algorithm with proper accuracy regarding to rather high length of the achieved binary string. Hence, in order to speed up the proposed method in finding optimum monitoring, the proposed scheme is accomplished by a fast optimization algorithm. In other words, to implement the proposed method it has to be joined with a searching engine.

Various random search methods are invented in recent decade. Genetic algorithm (GA), Evolutionary Programming, Bees Algorithm (BA) and Particle Swarm Optimization (PSO) algorithm are some of these optimization tools.

Among mentioned algorithms, BA is used in this paper due to its robustness, fast convergence, high flexibility and fewer setting parameters.

2.5.1. Algorithm description [35-38]

This algorithm was formed based on the exploratory behaviour of the nature. In this method, each bee tries to achieve best result based on probability rules by direct coordination and sharing information. Possible space to find food resources is randomly travelled by specified numbers of scout bees (n_s) at the beginning of algorithm. Evaluated values by scout bees at the beginning of the algorithm provide the initial values to enter main loop. In the first stage of main loop, random values of food resources are ranked and rated based on the calculated fitness of mentioned cost functions.

Based on the competency level of each bee (depends on the amount of its prepared food), n_b number of bees with best patches are selected among

n_s initial bees. Among n_b bees, n_e elite bees are selected with best food resources and their ranks. These elite bees are divided to two groups of Elite1 and Elite2 in order to local search. Considering the fact that best food resources are most probably in the basket of elite bees, more bees are sent to them. After local search, the best bee is replaced to neighbouring examined bees. New food resources in the neighbouring of the elite population include n_e and n_b- n_e bees are searched by sending new bees.

During this process, if the quality of the collected nectar is an acceptable range, scout bees save them in the hive and advertise that food resource with waggle dance. Waggle dance is vital for communications and covers all the information outside the hive. Hive bees select food resources based on achieved information by waggle dances about their quality. Therefore, more bees visit better food resources, which lead to a global search process of the answer. Sending more bees to a food resource continues until achieving better result.

Seven stages of BA are as follows:

1) Random formation of initial population
2) Fitness calculation of initial population
3) Selecting certain amount of best bees and their location for neighbouring search
4) Sending certain amount of bees to selected locations and their fitness calculation
5) Selection of the best bee in each place for new population formation
6) Allocation of remained bees for random search and their fitness calculation
7) Terminate the process in case of establishment of the answer in proper range. Otherwise, return to stage 3.

Candidate food resources with high finesses are selected for neighboring search at stage 3. Neighboring search is done in stages 4 and 5. Chosen resources are searched with higher accuracy than the other neighboring resources by sending more bees to these resources. This search mechanism and scouting are of the main characteristics of BA. In stage 5, best bee in each location is selected to transfer to next generation. Fourth stage is repeated till reaching proper answer range. BA flowchart is shown in Fig 4. Adjustable parameters of the BA algorithm are shown in table 1.

3. Simulation Results

Proposed algorithm is simulated and evaluated with test network of 9 bus WSCC [39]. Single line diagram of the network is shown in Fig 5. As shown in the Fig., the exposed lines to short circuit are:

$$\begin{aligned}
&Line\ 1 = From\ Bus\ 9\ to\ Bus\ 4\\
&Line\ 2 = From\ Bus\ 8\ to\ Bus\ 9\\
&Line\ 3 = From\ Bus\ 8\ to\ Bus\ 7\\
&Line\ 4 = From\ Bus\ 7\ to\ Bus\ 6\\
&Line\ 5 = From\ Bus\ 6\ to\ Bus\ 5\\
&Line\ 6 = From\ Bus\ 5\ to\ Bus\ 4
\end{aligned} \tag{22}$$

Local and remote assumption of the lines for determination of fault location in (22) (distance percentage from local bus) is shown by the terms “From” and “to” respectively. 9 bus WSCC network is evaluated with proposed current ratios selection algorithm of Fig. 2. Regarding to the number of scanned buses of the network, matrix of VarMatrix is provided with the dimension of $9^2 \times 9^2$. Finally, candidate current ratios with least sensitivity to thevenin impedance changes of WSCC network are extracted as shown in Table.2.

According to the presented quantities of this table, sensitivity level of each mentioned current ratio is also stated. Utilized currents in candidate current ratio is presented by expressing send and receive sides buses (from-to) in two numerator and denominator columns. These current ratios are only the values with average variances below 1%.

According to Table 2, all the candidate current ratios are located in a vector for similarity search of all buses and most of the currents. Therefore, it is necessary to perform optimization process to search most proper currents. Regarding to the length of achieved vector of all ratios of Table 2, the binary string is modelled with length of 46 during optimization process. The binary string ($\overline{\mathrm{X}}$) with 46 elements is defined as current ratio vector or optimization variable.

$$\overline{\mathrm{X}} = \left[x_1, x_2, \ldots, x_{46}\right] \tag{23}$$

$$x(\mathrm{i}) = \begin{cases} 1 & \overset{\text{Condidated}}{\text{CurrentRatio}(\mathrm{i})} \text{ is in } \overset{\text{Rewrited}}{\text{CurrentRatio}(\mathrm{i})} \\ 0 & \overset{\text{Condidated}}{\text{CurrentRatio}(\mathrm{i})} \text{ is not in } \overset{\text{Rewrited}}{\text{CurrentRatio}(\mathrm{i})} \end{cases} \tag{24}$$

Equation (24) determines that if i^{th} candidate current ratio is reselected in rewritten current ratio vector, x_i is equal to 1. Otherwise, it is equal to zero. For instance, if all elements of $\overline{\mathrm{X}}$ are 1, it means that all the ratios are re-selected in rewritten current ratio vector.

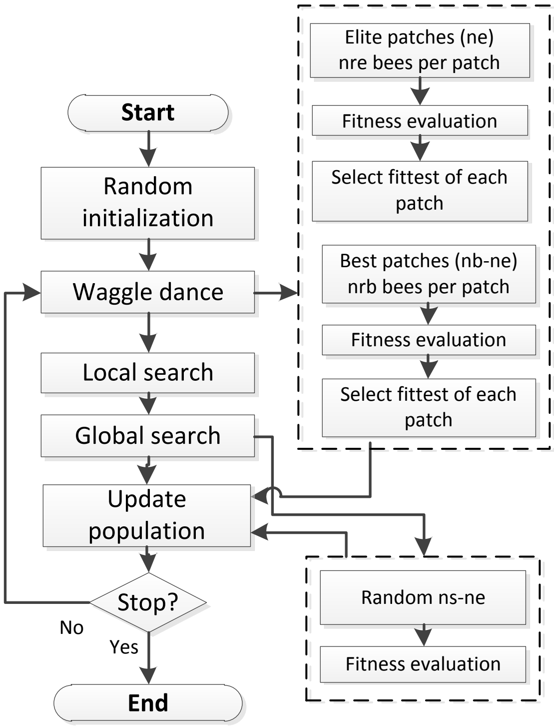


Fig.4. Flowchart of the Bees Algorithm [38]

Table.1
Bees Algorithm parameters

symbol	Description	Amount
n_s	number of scout bees	100
n_e	number of elite sites	5
n_b	number of best sites	15
n_{re}	recruited bees for elite sites	30
n_{rb}	recruited bees for remaining best sites	20
n_{gh}	initial size of neighbourhood	0.01

This program is called full monitoring program, which is not optimal in terms of mention constraints. Optimization procedure is done using Bees Algorithm and candidate current ratios are achieved by optimization algorithm in 700 iterations. Due to the best solution, fault location process is done by measurement installation at bus 9. So, the estimation error is in an acceptable range. Therefore, the measurement cost will be decreased significantly.

$$[\text{CurrentRatio}]_{\text{Rewrited}} = \begin{bmatrix} \frac{\Delta I_{94}}{\Delta I_{99}} & \frac{\Delta I_{98}}{\Delta I_{99}} \\ 33 & 42 \end{bmatrix} \quad (25)$$

$$\text{Monitoring Busses: } [9] \quad (26)$$

Used Currents: $[I_{94} \quad I_{98} \quad I_{99}]$

Using this monitoring system, the total numbers of wrong faulty lines estimation is zero. The maximum error of fault distance estimation in monitoring systems is 3.551%. While, average error of fault distance estimation in suggested monitoring system is 1.1030%, which is relatively low.

Table.2
Candidate current ratios for WSCC network

Order	Numerator: Current from	Numerator: Current to	Denominator: Current from	Denominator: Current to	$\frac{\text{Var}\left(\frac{\Delta I_{ij}}{\Delta I_{kl}}\right)}{\text{Mean}\left(\frac{\Delta I_{ij}}{\Delta I_{kl}}\right)}(\%)$
1	1	1	1	4	0.0000
2	2	2	2	8	0.0000
3	3	3	3	6	0.0000
4	1	1	4	1	0.0000
5	1	4	4	1	0.0000
6	2	2	8	2	0.0000
7	2	8	8	2	0.0000
8	3	3	6	3	0.0000
9	3	6	6	3	0.0000
10	5	5	9	9	0.0499
11	7	7	9	9	0.0718
12	5	5	8	2	0.0872
13	7	7	8	2	0.1044
14	5	5	6	3	0.1520
15	5	5	7	7	0.1627
16	4	9	9	4	0.1778
17	7	6	8	7	0.3023
18	4	5	5	4	0.3106
19	7	8	8	7	0.3133
20	6	7	8	7	0.3719
21	7	8	8	2	0.3880
22	5	4	6	5	0.3972
23	6	7	7	6	0.4062
24	8	9	9	4	0.4188
25	7	6	8	2	0.4354
26	7	7	9	4	0.5015
27	5	4	8	2	0.5065
28	5	5	9	4	0.5194
29	5	6	8	2	0.5348
30	5	4	6	3	0.5966
31	6	5	8	2	0.6206
32	6	7	7	8	0.6217
33	9	4	9	9	0.6275
34	5	6	6	3	0.6525
35	6	7	8	2	0.6589
36	2	2	4	1	0.7252
37	2	8	4	1	0.7252
38	4	9	8	2	0.7676
39	4	5	8	2	0.7822
40	3	3	4	1	0.7958
41	3	6	4	1	0.7958
42	9	8	9	9	0.8375
43	4	9	8	9	0.8477
44	4	5	6	5	0.8822
45	4	9	9	9	0.8917
46	5	4	5	5	0.9501

Therefore, fault distance estimation process with minimum number of sensitive currents to thevenin impedance changes. Following weighting coefficients are utilized in optimization procedure.

$$\begin{cases} Wm_1 = 0.603 \\ Wm_2 = 0.219 \\ Wm_3 = 0.178 \end{cases} \quad \begin{cases} W_1 = 0.667 \\ W_2 = 0.333 \end{cases} \quad (27)$$

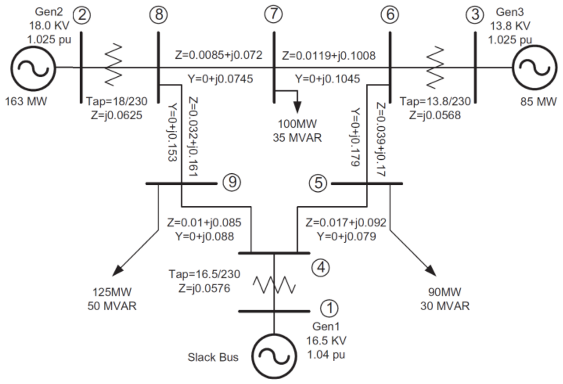


Fig.5. Single line diagram of WSCC 9 bus system

4. Conclusion

An optimal current measurement placement strategy based on observability of the fault location is evaluated in this paper. Thevenin impedance variations are considered in observability process. Short circuit analyses are carried out for a typical network in offline mode for all possible fault conditions. A look-up table is formed based on offline data (calculated based on short circuit analyses) and online data achieved by real time simulation from DigSILENT software. Dynamic Time Warping is utilized to detect similarity between online and offline data. This fault locating algorithm is based on current ratios of branch currents of faulty network. Optimal results are presented to find optimum currents and ratios insensitive to thevenin impedance variations for a 9 bus WSCC network with limited measurement buses. The best solution suggests measurement installation at bus 9 with 3 current measurements in order to achieve lower cost (acceptable average percentage error of 1.1030%). Optimum search procedure of current measurements placement are carried out with 700 iteration using BA.

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