Journal of Engineering and Applied Sciences 14 (6): 1729-1742, 2019
ISSN: 1816-949X

Multiple Fault Detection and Diagnosis in Electric Power Transmission Lines

Afaneen Anwar and Rana Ali Abttan
Department of Electrical and Electronic Engineering, University of Technology, Baghdad, Iraq

Abstract: One of the most difficult problems in solving faulted networks involves two or more faults which occur simultaneously in power systems. Abnormal conditions in short circuit and open conductor faults been analyzed. The main objectives of multiple fault detection and diagnosis are to satisfy the power supply continuity, maintains system, stability, decrease repair times and high reliability degree. This study presents an approach for detection and diagnosis of multiple faults in transmission lines. Voltage and current measurement method is adapted in the fault detection and classification, reactance based method in the fault location for different types of fault and places were to an estimate of the distance the fault on the transmission line from the point measurement by analyzing the data available after the beginning of disturbance. All programs were written in MATLAB environment. The programs were test on IEEE-14 bus bar network. The results clarified that the voltage and current measurement method and impedance method is very effective for multiple fault detection, classification and location.

Key words: Multiple fault, multiple fault analysis, fault detection, fault classification, fault location, environment

INTRODUCTION

Electric power system is a main pillar in the nation's progress. Power transmission lines represents lifeblood in electric power system and the function is to supply electric energy to customers as reliable and economical as possible. Power transmission lines are routinely subjected to unexpected disturbances by environmental impacts such as lighting, short circuit, faulty equipment's, human errors, overload, …, etc. Such fault result in mechanical damage and also affect the power supply continuity, hence its reliability. A fault on transmission lines is an abnormal circuit condition that result in energy dissipated. Multiple fault of particular interest is frequently occurring in a power system which mixed of the series and parallel faults. Multiple faults may consist of two different types of fault at the same location or at different locations. The parallel faults are: three phase fault through three phase fault impedance, line to line fault, line to ground and double line to ground through fault impedance. The series faults are: one open phase and two open phases (Grainger and Stevenson, 1994).

Detecting multiple faults and disconnecting the faulted transmission as quickly as possible are the main important roles of protection system, after estimating the location of the fault with acceptable accuracy comes into view.

A multiple fault detection and diagnosis scheme is a process aimed at verifying, if a fault event did occur, analysis of certain parameters to determine the type of the fault, phase (s) affected by the fault, the faulted line section and also estimate the distance to the fault with the highest accuracy possible. Generally, electric power fault diagnosis comprises of the following phases.

Detection of multiple fault event: It is the classical task in any protection scheme. The undesired change is detected in system parameters that degrade of performance by monitoring current and voltage signals of the phases.

Multiple fault type/phase (s) classification: Multiple fault type classification is an essential protective relaying feature due to its significant effect on the enhancement of relaying scheme operation. Fault classification is the ability to correctly identify the type of fault on buses or transmission lines irrespective of where the fault is located along the line.

MATERIALS AND METHODS

Multiple fault location in kilometer: Multiple fault location on transmission lines is performed by computes an estimate of distance of the fault on the transmission line from the point of measurement. The point of measurement is often taken at one end of the line.

Multiple fault detection and diagnosis helps utility engineers clearly have to be able to quickly detect and repair the faulty lines. However, to do so they first must reliably identify and analyze these faults. Several investigations have examined the fault detection and diagnosis in power transmission line.

Corresponding Author: Afaneen Anwar, Department of Electrical and Electronic Engineering, University of Technology, Baghdad, Iraq

Han (1982) describes two methods to analyze any combination of simultaneous balanced and unbalanced faults in a power system. The first method can be used to calculate the symmetrical components and phase components for any bus voltage and branch current of a faulted power system. Using the second method, an equivalent network connected to the positive sequence network can be obtained.

Huang *et al.* (1999) proposed a technique for detection and localization of different kinds of power system disturbances. Takagi *et al.* (1982) proposed a fault locator which has been developed that calculates the reactance of a faulty line with a micro-processor using the one terminal voltage and current data measurements of the transmission line. Girgis and Johnes (1989) presented a Hybrid-Expert system for fault detection, classification and fault selection location algorithms. Krishnanand *et al.* (2015) proposed scheme is evaluated for current differential protection of a transmission line fed from both ends for a variety of faults for help of the new formulation to provide fault detection, classification and location with significant accuracy. Othman *et al.* (2004) proposed selection in the wavelet domain and supervised neural network-fault classifier is developed. An output signal of the speed deviations of each generator of the multi-area multi machines system is taken as the input for the wavelet analysis. The “oscillation signature” for each of the 4 machines in a ‘no fault condition’, ‘fault’ with the PSS and without the PSS is recorded at various fault locations for fault detection using multi resolution analysis (MU) different resolutions allowing a detailed analysis of its energy wavelet transforms.

Singh *et al.* (2011) presents a technique to detect and classify the different shunt faults on a transmission lines for quick and reliable operation of protection schemes. Discrimination among different types of faults on the transmission lines is achieved by application of evolutionary programming tools. Silva *et al.* (2006) proposed a novel method for transmission line fault detection and classification using oscillographic data. The fault detection and its clearing time are determined based on a set of rules obtained from the current waveform analysis in time and wavelet domains. The method is able to single out faults from other power-quality disturbances such as voltage sags and oscillatory transients which are common in power systems operation. Gopakumar *et al.* (2015) proposed a novel support vector machine-based fault localization methodology to precisely identify and localize all types of transmission line faults occurring at any location in the power grid based on Phasor Measurement Unit (PMU) measurements.

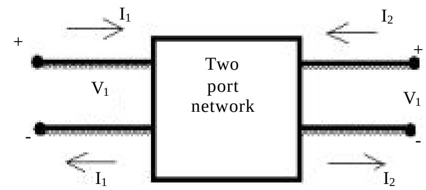

Fig. 1: Two-port network

Table 1: Two-port network parameters

Designation (parameters)	Equations	
Z (impedance)	$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$	(1)
Y (admittance)	$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$	(2)
H (hybrid)	$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$	(3)
G (inverse hybrid)	$\begin{bmatrix} I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix}$	(4)

Multiple fault analysis by two port network: Two- port network is best in analysis because it relies on simplifying large and complex networks into small, streamlined networks.

The concept of a two-port network has two pairs of terminals and the current of each pair of terminal isolated from the other pair. The direction of the current flow of each pair from one side towards the other shown on the network of Fig. 1 (Guillemin, 1935).

Maintain non-overlapping currents (I1, I2) are developed by (1:1) to the ends of the network to prevent interference also between networks group and maintain the currents to facilitate the analysis of these networks. Passive two-port networks are commonly specified in terms of the network parameters defined in Table 1 (Atabekov, 1960).

The two-port impedance parameters above are the two-port Thevenin equivalent impedances. In general, the two-port Thevenin equivalent impedance is given by Eq. 5:

$$Z^{Thevenin} = \begin{bmatrix} U_{i-j}^{i-j} & U_{m-n}^{i-j} \\ U_{i-j}^{m-n} & U_{m-n}^{m-n} \end{bmatrix} = \begin{bmatrix} Z_{i-j}^{i-j} & Z_{m-n}^{i-j} \\ Z_{i-j}^{m-n} & Z_{m-n}^{m-n} \end{bmatrix} \quad (5)$$

where, Eq. 6 and 7:

$$U_{i-j}^{m-n} = E_i^{m-n} - E_j^{m-n} \quad (6)$$

$$Z_{i-j}^{m-n} = Z_{im} - Z_{in} - Z_{jm} + Z_{jn} \quad (7)$$

The term E_i^{m-n} represents the voltage at node i when 1 pu current is injected between nodes m and n and the term E_j^{m-n} represents the voltage at node j when 1 pu current is injected between nodes m and n. The term $(U_{i-j}^{m-n} = E_i^{m-n} - E_j^{m-n})$ is the voltage difference between nodes i and j when 1 pu current is injected between nodes m and

n. The Z terms in Eq. 5-7 represent the respective bus impedance matrix elements. In general, the bus impedance matrix element represents the voltage measured at node i when 1 pu current is injected at node m. Note that if nodes j and n are 0, representing the reference bus, we have the result shown in Eq. 8:

$$U_{i-0}^{m-0} = E_i^{m-0} = Z_{im} \quad (8)$$

To obtain the two-port Y-equivalent sequence networks from the two-port $Z^{Thevenin}$ sequence equivalents. Several methods are available for obtaining the two-port Y-equivalent sequence networks. We can use the two-port Y-equivalent sequence networks to calculate the fault currents at intermediate points along a transmission line (Tziouvaras, 2008).

It is necessary not to interfere between the currents and voltages of the relay networks in the multiple faults. This is done by placing the phase shift on the connection of sequence network (Atabekov, 1960; Tziouvaras, 2008). The multiple faults problems to be solved can be generalized by three forms:

- A series fault at i and a series fault at j
- A shunt fault at i and a shunt fault at j
- A shunt fault at i and a series fault at j
- A series fault at i and a shunt fault at j

Actually, we can view this as only three different fault configurations, since, situations 3 and 4 require exactly the same computation scheme.

RESULTS AND DISCUSSION

A series fault-a series fault (Z type faults): A series-series connection of two-port sequence networks to study the following fault types:

- Multiple single line to ground faults at i and j
- A single line to ground fault and two line open fault at i and j, respectively
- Two line open fault and a single line to ground fault at i and j, respectively
- Multiple Two line open fault at i and j, respectively

Figure 2 shows the series-series (Z-type faults) two-port sequence network interconnection. We use Eq. 9 to calculate port i and port j positive-sequence voltages:

$$\begin{bmatrix} V_{i(1)} \\ V_{j(1)} \end{bmatrix} = \begin{bmatrix} E_{i(1)} \\ E_{j(1)} \end{bmatrix} - \begin{bmatrix} Z_{ii(1)} & Z_{ij(1)} \\ Z_{ji(1)} & Z_{jj(1)} \end{bmatrix} \begin{bmatrix} I_{i(1)} \\ I_{j(1)} \end{bmatrix} \quad (9)$$

From Fig. 2, we can also write Eq. 9 and 10 where, k = 0, 1 and 2:

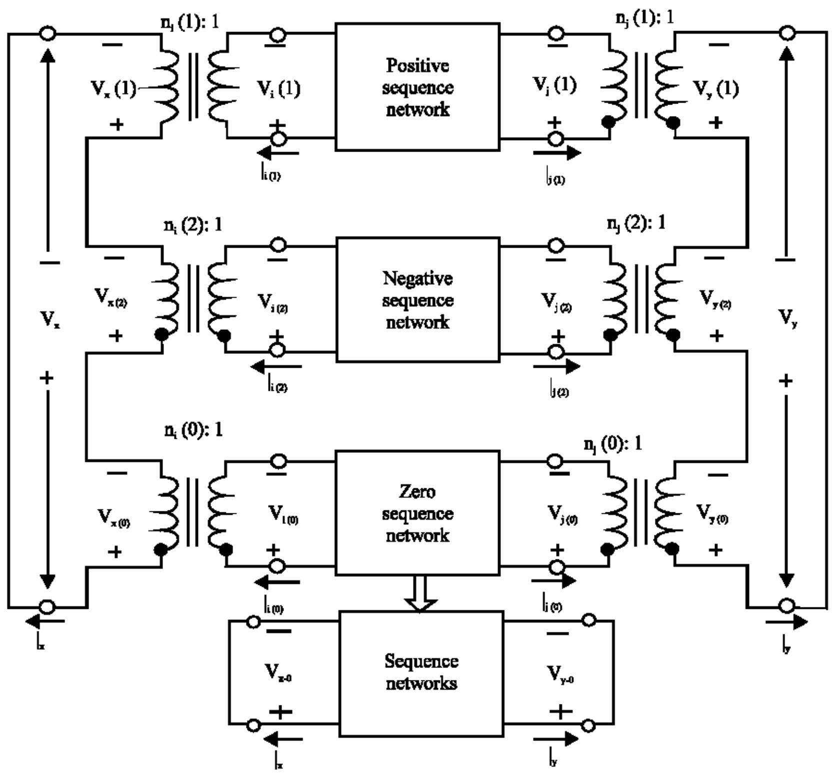

Fig. 2: Sequence network connection for multiple Z-type faults

$$n_{i(k)} = V_{x(k)}/V_{i(k)} = I_{x(k)}/I_{i(k)} \quad (10)$$

$$n_{j(k)} = V_{y(k)}/V_{j(k)} = I_{y(k)}/I_{j(k)} \quad (11)$$

$$\begin{bmatrix} V_{x(1)} \\ V_{y(1)} \end{bmatrix} = \begin{bmatrix} n_{i(1)}.E_{i(1)} \\ n_{j(1)}.E_{j(1)} \end{bmatrix} - \begin{bmatrix} Z_{ii(1)} & \dfrac{n_{i(1)}.Z_{ij(1)}}{n_{j(1)}} \\ \dfrac{n_{j(1)}.Z_{ji(1)}}{n_{i(1)}} & Z_{jj(1)} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (12)$$

To calculate the negative sequence network at port i and port j, we write Eq. 13:

$$\begin{bmatrix} V_{x(2)} \\ V_{y(2)} \end{bmatrix} = - \begin{bmatrix} Z_{ii(2)} & \dfrac{n_{i(2)}.Z_{ij(2)}}{n_{j(2)}} \\ \dfrac{n_{j(2)}.Z_{ji(2)}}{n_{i(2)}} & Z_{jj(2)} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (13)$$

To calculate the zero sequence network at port i and port j, we write Eq. 14:

$$\begin{bmatrix} V_{x(0)} \\ V_{y(0)} \end{bmatrix} = - \begin{bmatrix} Z_{ii(0)} & \dfrac{n_{i(0)}.Z_{ij(0)}}{n_{j(0)}} \\ \dfrac{n_{j(2)}.Z_{ji(0)}}{n_{i(0)}} & Z_{jj(0)} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (14)$$

But from Fig. 2, we observe that, for a series-series connection (Eq. 15 and 16):

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} V_{x(1)} \\ V_{y(1)} \end{bmatrix} + \begin{bmatrix} V_{x(2)} \\ V_{y(2)} \end{bmatrix} + \begin{bmatrix} V_{x(0)} \\ V_{y(0)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} I_{x(1)} \\ I_{y(1)} \end{bmatrix} = \begin{bmatrix} I_{x(2)} \\ I_{y(2)} \end{bmatrix} = \begin{bmatrix} I_{x(0)} \\ I_{y(0)} \end{bmatrix} \quad (16)$$

Performing the addition indicated by Eq. 15 and making the substitution Eq. 12-14, we get the result in Eq. 17:

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} n_{i(1)}.E_{i(1)} \\ n_{j(1)}.E_{j(1)} \end{bmatrix} - \begin{bmatrix} Z_{ii} & Z_{ij} \\ Z_{ji} & Z_{jj} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (17)$$

Where:

$$Z_{ii} = Z_{ii(1)} + Z_{ii(2)} + Z_{ii(0)} \quad (18)$$

$$Z_{ij} = \frac{n_{i(1)}}{n_{j(1)}} Z_{ij(1)} + \frac{n_{i(2)}}{n_{j(2)}} Z_{ij(2)} + Z_{ij(0)} \quad (19)$$

$$Z_{ij} = \frac{n_{j(1)}}{n_{i(1)}} Z_{ij(1)} + \frac{n_{j(2)}}{n_{i(2)}} Z_{ij(2)} + Z_{ji(0)} \quad (20)$$

$$Z_{jj} = Z_{jj(1)} + Z_{jj(2)} + Z_{jj(0)} \quad (21)$$

A shunt fault-a shunt fault (parallel type): A parallel-parallel connection of two-port networks is required to represent the following multiple fault conditions:

- Multiple double line to ground faults at i and j
- A double line to ground fault and one line open fault at i and j, respectively
- One line open fault and a double line to ground fault at i and j, respectively
- One line open fault and one line open fault at i and j, respectively

The sequence network connection with parallel-parallel termination is shown in Fig. 3 where the ideal transformations are phase shifters with voltage and current relations.

For parallel-parallel sequence network connections, we work with the two-port admittance parameters (Y-parameters). We calculate the Y-parameters by inverting the two-port sequence network impedance parameters (Z-parameters). We use Eq. 22 to calculate port i and port j positive-sequence currents:

$$\begin{bmatrix} I_{i(1)} \\ I_{j(1)} \end{bmatrix} = \begin{bmatrix} I_{Si(1)} \\ I_{Sj(1)} \end{bmatrix} - \begin{bmatrix} Y_{ii(1)} & Y_{ij(1)} \\ Y_{ji(1)} & Y_{jj(1)} \end{bmatrix} \begin{bmatrix} V_{i(1)} \\ V_{j(1)} \end{bmatrix} \quad (22)$$

Where I_s the independent source term viewed from the i and j ports. From Fig. 3, we can also write Eq. 23 and 24 where k = 0, 1 and 2:

$$n_{i(k)} = V_{x(k)}/V_{i(k)} = I_{x(k)}/I_{i(k)} \quad (23)$$

$$n_{j(k)} = V_{y(k)}/V_{j(k)} = I_{y(k)}/I_{j(k)} \quad (24)$$

Multiplying Eq. 2 by ($n_{i(1)}$ 0/0 $n_{i(1)}$), results in Eq. 25:

$$\begin{bmatrix} I_{x(1)} \\ I_{y(1)} \end{bmatrix} = \begin{bmatrix} n_{i(1)}.I_{Si(1)} \\ n_{j(1)}.I_{Sj(1)} \end{bmatrix} - \begin{bmatrix} Y_{ii(1)} & \dfrac{n_{i(1)}.Y_{ij(1)}}{n_{j(1)}} \\ \dfrac{n_{j(1)}.Y_{ji(1)}}{n_{i(1)}} & Y_{jj(1)} \end{bmatrix} \begin{bmatrix} I_x \\ I_y \end{bmatrix} \quad (25)$$

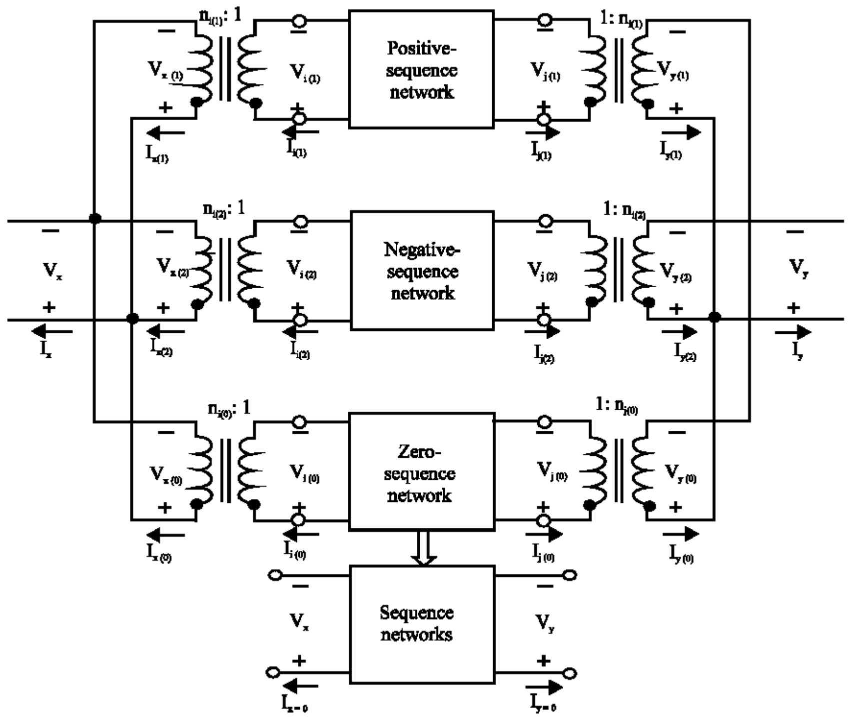

Fig. 3: Sequence network connection for multiple Y-type faults

To calculate the negative sequence network at port i and port j, we write Eq. 26:

$$\begin{bmatrix} I_{x(2)} \\ I_{y(2)} \end{bmatrix} = -\begin{bmatrix} Y_{ii(2)} & \dfrac{n_{i(2)}.Y_{ij(2)}}{n_{j(2)}} \\ \dfrac{n_{j(2)}.Y_{ji(2)}}{n_{i(2)}} & Y_{jj(2)} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (26)$$

To calculate the zero sequence network at port i and port j, we write Eq. 27:

$$\begin{bmatrix} I_{x(0)} \\ I_{y(0)} \end{bmatrix} = -\begin{bmatrix} Y_{ii(0)} & \dfrac{n_{i(0)}.Y_{ij(0)}}{n_{j(0)}} \\ \dfrac{n_{j(2)}.Y_{ji(0)}}{n_{i(0)}} & Y_{jj(0)} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (27)$$

which transformers, since, $n_{i(0)} n_{j(0)} = 1$, we get Eq. 28:

$$\begin{bmatrix} I_{x(0)} \\ I_{y(0)} \end{bmatrix} = -\begin{bmatrix} Y_{ii(0)} & Y_{ij(0)} \\ Y_{ji(0)} & Y_{jj(0)} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (28)$$

But, from Fig. 6, we observe that for a series-series connection Eq. 29 and 30:

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} I_{x(1)} \\ I_{y(1)} \end{bmatrix} + \begin{bmatrix} I_{x(2)} \\ I_{y(2)} \end{bmatrix} + \begin{bmatrix} I_{x(0)} \\ I_{y(0)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (29)$$

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} V_{x(1)} \\ V_{y(1)} \end{bmatrix} = \begin{bmatrix} V_{x(2)} \\ V_{y(2)} \end{bmatrix} = \begin{bmatrix} V_{x(0)} \\ V_{y(0)} \end{bmatrix} \quad (30)$$

Performing the addition indicated in Eq. 29 and making the substitution, Eq. 25-27, we get the result in Eq. 31:

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} n_{i(1)}.I_{Si(1)} \\ n_{j(1)}.I_{Sj(1)} \end{bmatrix} - \begin{bmatrix} Y_{ii} & Y_{ij} \\ Y_{ji} & Y_{jj} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (31)$$

Where:

$$Y_{ii} = Y_{ii(1)} + Y_{ii(2)} + Y_{ii(0)} \quad (32)$$

$$Y_{ij} = \frac{n_{i(1)}}{n_{j(1)}} Y_{ij(1)} + \frac{n_{i(2)}}{n_{j(2)}} Y_{ij(2)} + Y_{ij(0)} \quad (33)$$

$$Y_{ij} = \frac{n_{j(1)}}{n_{i(1)}} Y_{ij(1)} + \frac{n_{j(2)}}{n_{i(2)}} Y_{ij(2)} + Y_{ji(0)} \quad (34)$$

$$Y_{jj} = Y_{jj(1)} + Y_{jj(2)} + Y_{jj(0)} \quad (35)$$

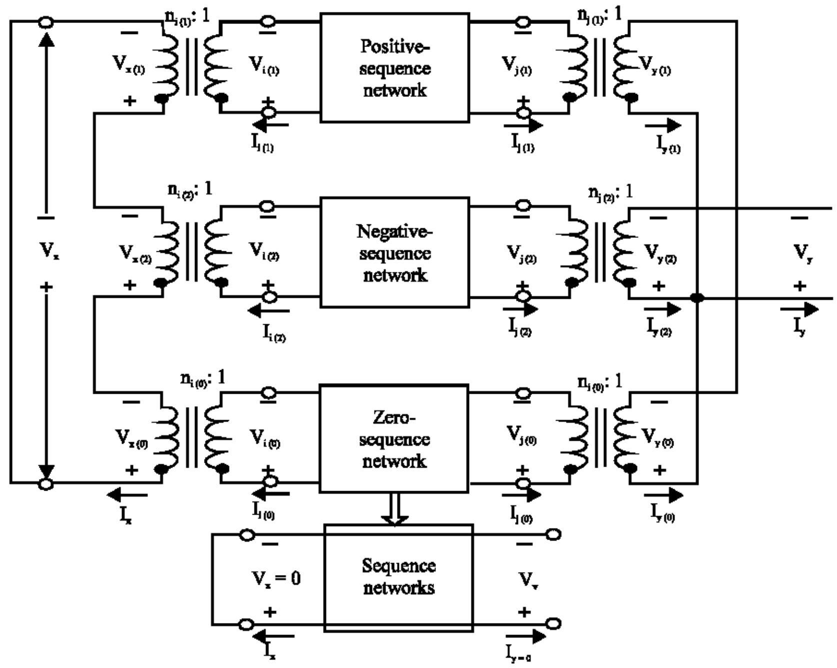

Fig. 4: Sequence network connection for multiple H-type faults

A series fault and a shunt fault (H type faults): We use the series-parallel connection of the two-port sequence networks to study the following type of faults:

- A single line to ground fault and double line to ground fault at i and j, respectively
- A single line to ground fault and one line open fault at i and j, respectively
- Two line open fault and two line open fault at i and j, respectively
- Two line open fault and one line open fault at i and j, respectively

But from Fig. 4, we observe that for a series-parallel connection:

$$\begin{bmatrix} V_x \\ I_y \end{bmatrix} = \begin{bmatrix} V_{x(1)} \\ I_{y(1)} \end{bmatrix} + \begin{bmatrix} V_{x(2)} \\ I_{y(2)} \end{bmatrix} + \begin{bmatrix} V_{x(0)} \\ I_{y(0)} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (36)$$

$$\begin{bmatrix} I_x \\ V_y \end{bmatrix} = \begin{bmatrix} I_{x(1)} \\ V_{y(1)} \end{bmatrix} = \begin{bmatrix} I_{x(2)} \\ V_{y(2)} \end{bmatrix} = \begin{bmatrix} I_{x(0)} \\ V_{y(0)} \end{bmatrix} \quad (37)$$

Performing the addition indicated in Eq. 36 and making the substitution, we get the result in Eq. 38:

$$\begin{bmatrix} V_x \\ I_y \end{bmatrix} = \begin{bmatrix} n_{i(1)}.E_{i(1)} \\ n_{j(1)}.I_{sj(1)} \end{bmatrix} - \begin{bmatrix} h_{ii} & h_{ij} \\ h_{ji} & h_{jj} \end{bmatrix} \begin{bmatrix} I_x \\ V_y \end{bmatrix} \quad (38)$$

We use Eq. 39 to calculate the hybrid parameter matrices (H-parameters) from the two-port Z-parameter matrices (Anderson, 1971):

$$\begin{bmatrix} H_{(k)} \end{bmatrix} = \begin{bmatrix} \dfrac{\det Z_{(k)}}{Z_{jj(k)}} & \dfrac{Z_{ij(k)}}{Z_{jj(k)}} \\ -\dfrac{Z_{ji(k)}}{Z_{jj(k)}} & \dfrac{1}{Z_{jj(k)}} \end{bmatrix} \quad (39)$$

Where det $Z_{(k)}$ the determinant of matrix $Z_{(k)\text{ and}}$ k the 0, 1 and 2 represent the zero, positive and negative-sequence network, respectively.

When we can multiple faults occur in different phases, we can use ideal phase-shifting transformers to shift the phases of the sequence network currents and voltages in order to meet the appropriate these boundary conditions (Han, 1982). The sequence network voltages and currents in Fig. 2-4 between the isolation transformers are all referenced to A-phase of the power system. The connections on the other side of the isolation transformers represent the boundary conditions for the series or shunt unbalance of the particular phases involved. The isolation transformer ratios are all 1:1 and may include a phase shift equal to $a^2 = e^{j240}$. This isolation transformer ratios depends on the types of shunt and series faults, specific faulted phase and sequence network as shown in Table 2 (Anderson, 1971).

Table 2: Isolation transformer ratio

Fault type	Zero seq.	Pos. seq.	Neg. seq.
A-G	1	1	1
B-G	1	a^2	a
C-G	1	a	a^2
B-C-G	1	1	1
C-A-G	1	a^2	a
A-B-G	1	a	a^2
A-phase open	1	1	1
B-phase open	1	a^2	a
C-phase open	1	a	a^2
B&C-phases open	1	1	1
C&A-phases open	1	a^2	a
A&B-phases open	1	a	a^2

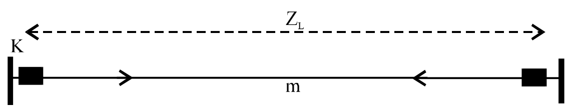

Fig. 5: Transmission line without fault

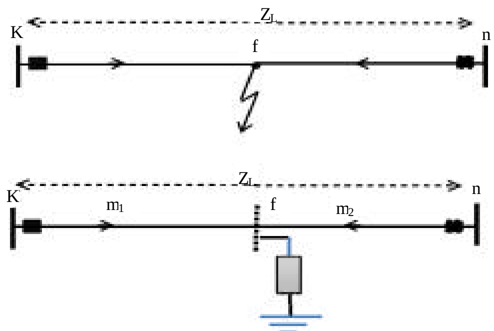

Fig. 6: Transmission line during fault

Representation of fault on the transmission lines: The system has a bus impedance/admittance matrix of dimension n×n. The bus admittance matrix before fault takes the form:

$$[Y_{bus}\text{ before fault}] = \begin{bmatrix} y_{11} & \cdots & y_{1k} \cdots & y_{1n} \\ . & . & . \quad . & . \\ y_{k1} & \cdots & y_{kk} \cdots & y_{kn} \\ . & . & . \quad . & . \\ y_{n1} & \cdots & y_{nk} \cdots & y_{nn} \end{bmatrix} \quad (40)$$

where, (Y_{bus} before fault) is the bus admittance before fault matrix, k is one of busses and n is number of busses in the system. Fig. 5 shows a transmission line supplied from both ends.

If fault occurs on the line that connect two buses k and n, an imaginary bus will be generated to be. Remove all link between bus k and bus n. Figure 6 shows that the fault point is considered as a third bus (imaginary bus) in the system. The bus admittance matrix after fault takes the form Eq. 41:

$$[Y'_{bus}\text{ after fault}] = \begin{bmatrix} y'_{11} & \cdots & y'_{1k} \cdots & y'_{1n} & y'_{1f} \\ . & . & . \quad . & . & . \\ y'_{k1} & \cdots & y'_{kk} \cdots & y'_{kn} & y'_{kf} \\ . & \cdots & . \cdots & . & . \\ y'_{n1} & \cdots & y'_{nk} \cdots & y'_{nn} & y'_{nf} \\ y'_{f1} & \cdots & y'_{fk} \cdots & y'_{fn} & y'_{ff} \end{bmatrix} \quad (41)$$

where, (Y_{bus} after fault) is the bus admittance matrix after fault:

$$y'_{kk} = y_{kk} - \left(Z^{-1}_{\text{line kn}}\right) + \left(Z^{-1}_{\text{line kn}}/m_1\right)$$

m_1 = Lengths from each bus (K) to the fault point (f):

$$y'_{kn} = y'_{nk} = 0$$

$$y'_{kf} = y'_{fk} = -\left(Z^{-1}_{\text{line kn}}/m_1\right)$$

$$y'_{f1} = y'_{1f} = 0$$

$$y'_{fn} = y'_{nf} = -\left(Z^{-1}_{\text{line kn}}/m_2\right)$$

m_2 = Lengths from each bus (n) to the fault point (f) = (1- m_1):

$$y'_{ff} = \left(Z^{-1}_{\text{line kn}}/m_1\right) + \left(\left(Z^{-1}_{\text{line kn}}/m_2\right)\right) + \left(Z^{-1}_{\text{line kn}}\right)$$

Mathematical model

Fault detection: Fault detection enables faults to be sensed on buses or transmission lines by monitoring the phase impedances and/or phase-current amplitudes and/or phase-voltage amplitudes and/or zero-sequence current amplitude. The fault current magnitude may be any-where from 10-30 times the full-load or rated current of the equipment (Saadat, 1999) and the voltage magnitude is reduced down to 60-70% of the normal value. It is difference between pre-fault measurement and fault measurement as shown: it is difference between pre-fault measurement and fault measurement as shown: If Eq. 42:

$$V_{bus}(0) = \begin{bmatrix} V_1(0) \\ V_i(0) \\ V_j(0) \\ V_n(0) \end{bmatrix} \quad (42)$$

where, V_{bus} (0) is the prefault voltages obtained from power flow solution and Eq. 43:

$$VV_{bus} = \begin{bmatrix} VV_1 \\ VV_i \\ VV_j \\ VV_n \end{bmatrix} \tag{43}$$

where, ΔV_{bus} is the bus voltage changes caused by the fault. Then, Eq. 44:

$$V_{bus}(f) = V_{bus}(0) + VV_{bus} \tag{44}$$

V_{bus} (f) is the voltages during the fault. Which lead to:

$$I_{bus} = Y_{bus} . V_{bus} \tag{45}$$

where, I_{bus} is the bus current entering the bus and Y_{bus} is the bus admittance matrix:

$$\begin{bmatrix} 0 \\ \vdots \\ I_i(f) \\ I_j(f) \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{11} & \dots & Y_{1i} & Y_{1j} & \dots & Y_{1n} \\ M & M & M\dots & M & M & M \\ Y_{i1} & \dots & Y_{ii} & Y_{ij} & L & Y_{in} \\ Y_{j1} & \dots & Y_{ji} & Y_{jj} & \dots & Y_{jn} \\ M & M & M\dots & M & M & M \\ Y_{n1} & L & Y_{ni} & Y_{nj} & \dots & Y_{nn} \end{bmatrix} \begin{bmatrix} nV_1 \\ \vdots \\ nV_i \\ nV_j \\ \vdots \\ nV_n \end{bmatrix} \tag{46}$$

where, I_i (f) and I_j (f) is the fault current at bus i and j, respectively" or:

$$I_{bus}(f) = Y_{bus} . VV_{bus} \tag{47}$$

Solving ΔV_{bus}, we have:

$$VV_{bus} = Z_{bus} . I_{bus}(f) \tag{48}$$

where, $Z_{bus} = Y_{bus}^{-1}$ is knowing as the bus impedance matrix. Substituting Eq. 48 into Eq. 44:

$$V_{bus}(f) = V_{bus}(0) + Z_{bus} . I_{bus}(f) \tag{49}$$

Writing above matrix equation in terms of its elements, we have Eq. 50:

$$\begin{bmatrix} V_1(f) \\ \vdots \\ V_i(f) \\ V_j(f) \\ \vdots \\ V_n(f) \end{bmatrix} = \begin{bmatrix} V_1(0) \\ \vdots \\ V_i(0) \\ V_j(0) \\ \vdots \\ V_n(0) \end{bmatrix} + \begin{bmatrix} Z_{11} & \dots & Z_{1i} & Z_{1j} & \dots & Z_{1n} \\ M & M & M\dots & M & M & M \\ Z_{i1} & \dots & Z_{ii} & Z_{ij} & L & Z_{in} \\ Z_{j1} & \dots & Z_{ji} & Z_{jj} & \dots & Z_{jn} \\ M & M & M\dots & M & M & M \\ Z_{n1} & L & Z_{ni} & Z_{nj} & \dots & Z_{nn} \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ I_i(f) \\ I_j(f) \\ \vdots \\ 0 \end{bmatrix} \tag{50}$$

Multiple fault classification: Fault classification technique used in electric power system is vital for secure operation of power systems and has to be accurate to facilitate quick repair of the system. Fault classification that used to define the fault type and identify the faulty phases. The fault classification is based on detecting distinct magnitude of current phase, voltage phase, zero component current, the nature of the power system and fault conditions (Saadat, 1999). Table 3 show current and voltage conditions for different types of faults.

Impedance based multiple fault location: An accurate fault location is an important requirement that computes an estimate of the distance the fault on the transmission line from the point measurement. Determination of the point at which a fault occurs in an electric power transmission line is vital for economic operation of power systems. The faults are in the form of short circuit between the conductors or to the ground. Fault locating can be viewed as a process that analyzes available data after inception of a disturbance providing more accurate information about the location, possible cause and phases of the line involved in the fault. The impedance based methods can be classified into two types: one-end data methods and two-end data methods. One-end data algorithms is known that one end impedance based fault locaters calculate the measured the voltage and current and the line parameters in order to calculate the apparent impedance, hence, to the distance to the fault. One-end data algorithms can be classified into four types: reactance based method; takagi method; modified takagi method. In the research, one-end data methods are adopted to find multiple fault location. Single-line diagram of fault on transmission lines between two buses is shown in Fig. 7 where V_k refers to sending end bus-bar voltage, V_n refers to receiving end voltage, I_{Fk} and I_{Fn} refer to fault currents from sending end and receiving end respectively and Z_L represents the entire line impedance. Figure 8 illustrates the equivalent circuit for a fault on transmission line. The voltage drop from bus k can be written easily along with the per unit fault location (m_1):

$$V_k = Z_L I_{Fk} + R_F I_F \tag{51}$$

Table 3: Current and voltage conditions for different types of faults

Types of fault/Specific phase	Current condition	Voltage condition	Boundary condition
Single line to ground			
A-G	$I_1 = I_2 = I_0$	$V_1+V_2+V_0 = 0$	$I_b = I_c = 0$
B-G	$I_1 = a^2, I_2 = aI_0$	$V_1+a^2 V_2+aV_0 = 0$	$I_c = I_a = 0$
C-G	$I_1 = aI_2 = a^2 I_0$	$V_1+aV_2+a^2 V_0 = 0$	$I_a = I_b = 0$
Double line to ground fault			
B-C-G	$I_1+I_2+I_0 = 0$	$V_1 = V_2 = V_0$	$I_b = -I_c, I_a = 0, V_b = V_c = 0$
A-C-G	$I_1+a^2 I_2+aI_0 = 0$	$V_1 = a^2 V_2 = aV_0$	$I_a = -I_c, I_b = 0, V_a = V_c = 0$
A-B-G	$I_1+aI_2+a_2 I_0 = 0$	$V_1 = aV_2 = a^2 V_0$	$I_a = -I_b, I_c = 0, V_a =V_b = 0$
Line to Line fault			
B-C	$I_1 = -I_2, I_0 = 0$	$V_1 = V_2$	$I_b = -I_c, I_a = 0, V_b = V_c$
A-C	$I_1 = -a^2 I_2 , I_0 = 0$	$V_1 = a^2 V_2$	$I_a = -I_c, I_b = 0, V_a = V_c$
A-B	$I_1= -aI_2, I_0 = 0$	$V_1 = aV_2$	$I_a = -I_b, I_c = 0, V_a = V_b$
Three Phase fault			
(A-B-C-G)	$I_0 = I_2 =0$	$V_0 = V_2 = 0$	$I_a = I_b = I_c, V_a = V_b = V_c = 0$
One line open fault			
A-O	$I_1+I_2+I_0 = 0$	$V_1 = V_2 = V_0$	$I_a = 0, V_b+I_bZ = 0, V_c+I_cZ = 0$
B-O	$I_1+a^2 I_2+aI_0 = 0$	$V_1 = a^2 V_2 = aV_0$	$I_b = 0, V_c+I_cZ = 0, V_a+I_aZ = 0$
C-O	$I_1+aI_2+a^2 I_0 = 0$	$V^1 = aV_2 = a_2 V_0$	$I_c = 0, V_a+I_aZ = 0, V_b+I_bZ = 0$
Two line open fault			
B-C-O	$I_1 = I_2 = I_0$	$V_{s1}+V_{s2}+V_{s0} = 0$	$Ib = Ic = 0, V_a +I_aZ = 0$
A-C-O	$I_1 = a^2 I_2 = aI_0$	$V_{s1}+a^2V_{s2}+aV_{s0} = 0$	$I_c = I_a = 0, V_b+I_bZ = 0$
A-B-O	$I_1 = aI_2 = a^2 I_0$	$V_{s1}+aV_{s2}+a^2V_{s0} = 0$	$I_a = I_b = 0, V_c +I_cZ = 0$

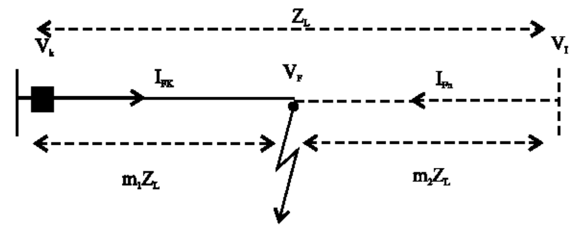

Fig. 7: One-line diagram and equivalent circuit of fault on transmission lines between two buses

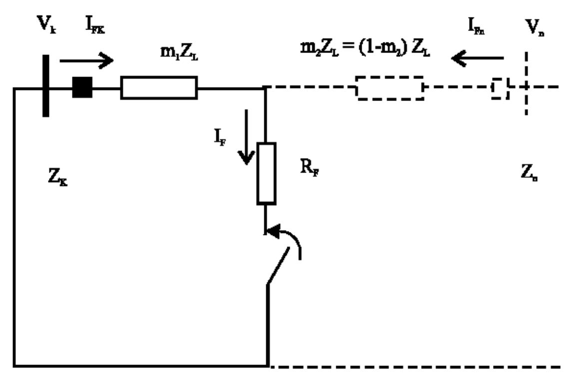

Fig. 8: Equivalent circuit for a fault on transmission line

The value of the impedance measured at terminal k may be found by dividing Eq. 51 by the measured current (I_{Fk}):

$$Z_{Fk} = \frac{V_k}{I_{Fk}} = m_1 Z_L + R_F \frac{I_F}{I_{Fk}} \quad (52)$$

here (Z_{Fk}) is the apparent impedance to the fault measured at terminal (k). For other types of faults, $V_{selected}$, $I_{selected}$ values are presented in table in Table 4 to calculate apparent impedance which to lead to estimate fault location.Where:

Table 4: Selected voltage and current for various fault types

Fault type	$V_{selected}$	$I_{selected}$
A-g	V_a	$(I_a + k .3I_0)$
B-G	V_b	$(I_b + k.3I_0)$
C-G	V_c	$(I_c + k.3I_0)$
A-B or A-B-G	V_{ab}	I_{ab}
B-C or B-C-G	V_{bc}	I_{bc}
C-A or C-A-G	V_{ca}	I_{ca}
A-B-C	V_{ab} or V_{bc} or V_{ca}	I_{ab} or I_{bc} or I_{ca}

K = $(Z_{0L}-Z_{1L}) / 3 Z_{1L}$
Z_{1L} = The positive-sequence line impedance
Z_{0L} = The Zero-sequence line impedance
I_0 = The zero-sequence fault current
Z_{fk} = Apparent impedance = $V_{selected}/I_{selected}$

The structure of the proposed diagram: A program was written in MATLAB environment for the detection and classification. The input data was calculated by a Newton-Raphson load flow program and considered as the initials values. The proposed method is described as follows Algorithm 1. Figure 9 show the flow chart of multiple fault detection and diagnosis.

Algorithm 1; Newton-Raphson load flow program:

Step 1: Input data of power transmission system including all the line data, bus data a, G&T data, input number of buses and location of two bus bar fault i and j

Step 2: Run the load flow program to calculate the initial values of currents and voltages and store the current and voltage before fault

Step 3: Formulate Z, Y bus matrices for all three sequence networks (Z0, Z1, Z2, Y0, Y1, Y2)

Step 4: input types of faults if:

a- Series-series connection (Z-type faults)
1.SLG at i-SLG at j
2.SLG at i-2LO at j
3. 2LO at i-SLG at j
4. 2LO at i-2LO at j
b- Parallel-parallel connection (Y-type faults)
1. DLG at i-DLG at j
2. DLG at i-1LO at j
3. 1LO at i-DLG at j
4. 1LO at i-1LO at j
c- Series-parallel connection (H- type faults)
1. SLG at i-DLG at j
2. SLG at i-1LO at j
3. 2LO at i-DLG at j
4. 2LO at i-1LO at j

Step 5: Form fault port matrices for all sequence network and open circuit voltage for positive sequence network is calculated

Step 6: Solve boundary (conditions) the voltage and current

Step 7: Bus voltages and currents of the buses affected by occurrence of the fault are calculated

Step 8: the next fault analysis if yes goes to step 4 else go to

Step 9: Store the line current fault and voltage for each bus bar

Step 10: compare fault current and voltage with pre-fault current and voltage for each bus bar

Step 11: detect of the fault

Step 12: specify number of phase fault: one phase fault, two phase fault and three phase fault

Step 13: if one phase fault is single line to ground, if two phase fault is double line to ground when $I_0 \neq 0$ or line to line fault when $I_0 = 0$ and if three phase fault is three phase to ground

Step14: spcify type fault phase according to fault condition

Step 15:calculation of $Z_{0L}(R_{0L}, X_{0L})$, $Z_{1L}(R_{1L}, X_{1L})$

Step 16: Determine the fault type. The fault type is determined of subroutine multiple fault classification

Step 17: Calculation of Apparent Impedance for various fault conditions

Step 18: compute m to find fault distance on transmission line

Step 19: end

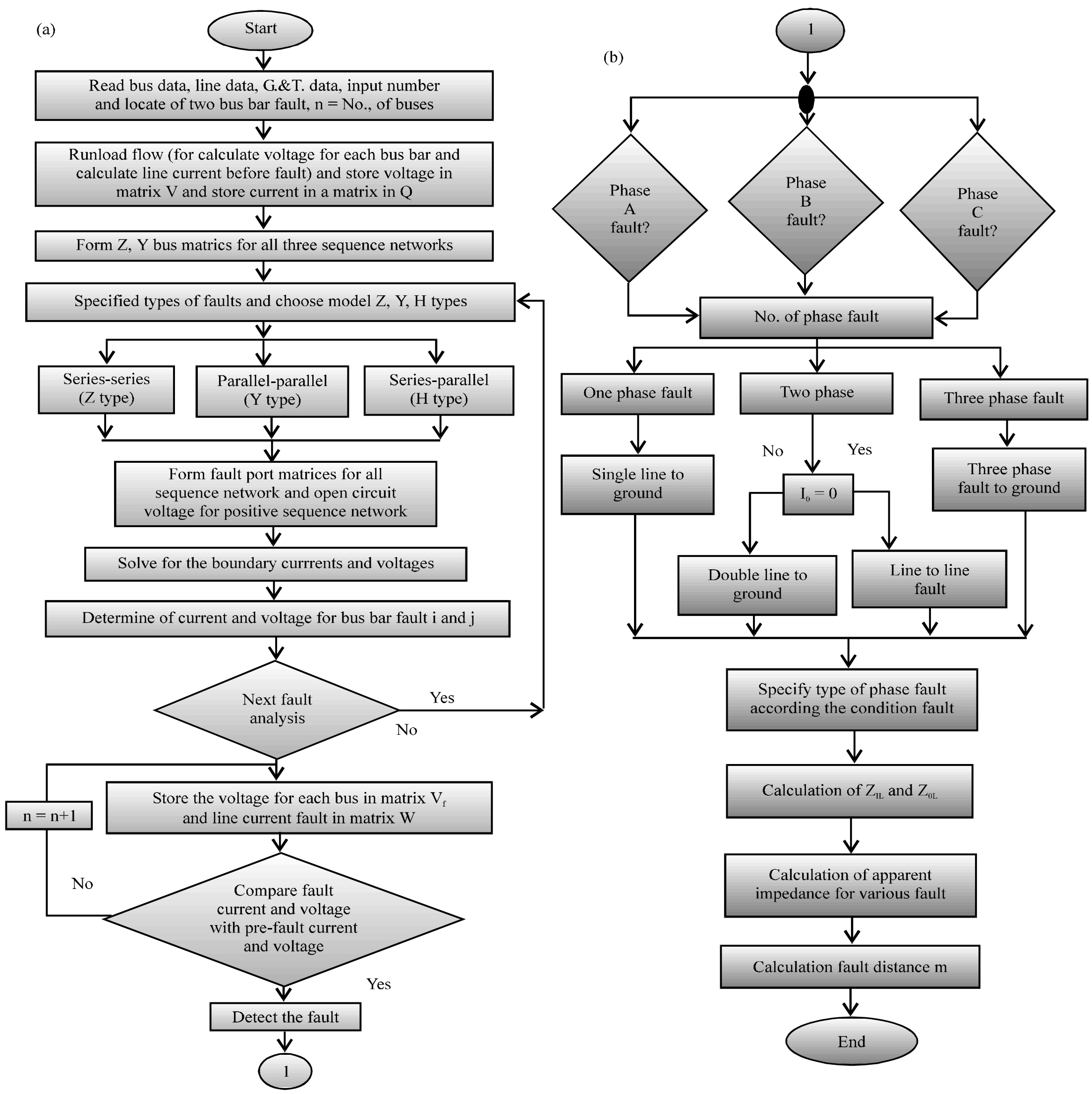

Fig. 9: a, b) Flow chart of multiple fault detection and diagnosis

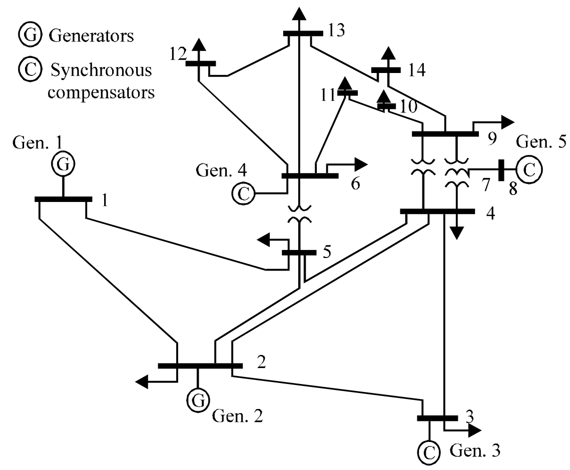

Fig. 10: Single line diagram of 14-bus power system

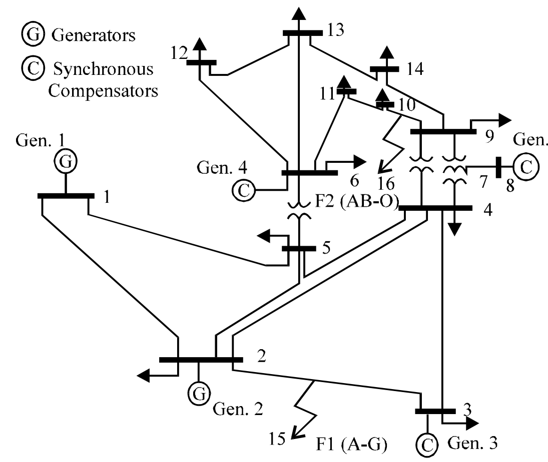

Fig. 11: Single line diagram of multiple faults of transmission lines

Table 5: Bus-data for 14-line network (Saadat, 1999)

Bus No.	Type	|V| (p.u)	Angle (°)	Pl (p.u)	Ql (p.u)	Pg (p.u)	Qg (p.u)	Qmin (p.u)	Qmax (p.u)	Q inject
1	1	1.060	0	0.0	0.0	0	0.0	0	0	0
2	2	1.045	0	21.7	12.7	40	42.4	-40	50	0
3	2	1.010	0	94.2	19.0	0	23.4	0	40	0
4	0	1.000	0	47.8	-3.9	0	0.0	0	0	0
5	0	1.000	0	7.6	1.6	0	0.0	0	0	0
6	2	1.070	0	11.2	7.5	0	12.2	-6	24	0
7	0	1.000	0	0.0	0.0	0	0.0	0	0	0
8	2	1.090	0	0.0	0.0	0	17.4	-6	24	0
9	0	1.000	0	29.5	16.6	0	0.0	0	0	0
10	0	1.000	0	9.0	5.8	0	0.0	0	0	0
11	0	1.000	0	3.5	1.8	0	0.0	0	0	0
12	0	1.000	0	6.1	1.6	0	0.0	0	0	0
13	0	1.000	0	13.5	5.8	0	0.0	0	0	0
14	0	1.000	0	14.9	5.0	0	0.0	0	0	0

Case study: To verification of the proposed program accuracy and methodology are an important task in order to create a reliable tool for calculation, the program was applied on the IEEE 14-bus test system. The system consists of 14-bus IEEE test system and 20-line. The parameter of the system in per-unit and the single line diagram of this system is shown in "Fig. 10" and its data are explained in the Table 5 and 6. Table 7 shows power flow solution by newton-raphson program. Table 7 shows Power Flow Solution by Newton-Raphson program.

When two faults occur on transmission lines to make sure the accuracy of the program, single line to ground (A-G) fault on transmission line (L2-3) and double line to ground (AB-O) on transmission line (L9-10). The single line diagram of multiple fault of transmission lines is shown in "Fig. 11" (Table 8-10).

Table 8 shows value of fault current on fault location (point 15, 16) at transmission lines (L2-3) and (L9-10).

Table 9 and 10 shows comparisons of bus bar voltages (amplitude and phase) and transmission line

Table 6: Line-Data of the 14-Line network

From bus	To bus	R0 (p.u)	X0 (p.u)	R1 (p.u)	X1 (p.u)	B (p.u)	Tap
1	2	0.038383	0.117189	0.01938	0.05917	0.0528	1
1	5	0.107009	0.441742	0.05403	0.22304	0.0492	1
2	3	0.093066	0.39209	0.04699	0.19797	0.0438	1
2	4	0.11509	0.349211	0.05811	0.17632	0.034	1
2	5	0.112792	0.344378	0.05695	0.17388	0.0346	1
3	4	0.132717	0.338734	0.06701	0.17103	0.0128	1
4	5	0.02644	0.083401	0.01335	0.04211	0	1
4	7	0	0.414173	0	0.20912	0	0.978
4	9	0	1.101543	0	0.55618	0	0.969
5	6	0	0.499138	0	0.25202	0	0.932
6	11	0.188113	0.393932	0.09498	0.1989	0	1
6	12	0.24343	0.506645	0.12291	0.25581	0	1
6	13	0.131013	0.258006	0.06615	0.13027	0	1
7	8	0	0.348874	0	0.17615	0	1
7	9	0	0.21788	0	0.11001	0	1
9	10	0.063001	0.167357	0.03181	0.0845	0	1
9	14	0.251748	0.535501	0.12711	0.27038	0	1
10	11	0.162504	0.380404	0.08205	0.19207	0	1
12	13	0.437543	0.395873	0.22092	0.19988	0	1
13	14	0.338536	0.689271	0.17093	0.34802	0	1

Table 7: Power flow solution by Newton-Raphson method

Bus No.	Volt. (Mag.)	Angle (Deg.)	Load MW	Load Mvar	Generation Mvar	Generation Mvar	Injected Mvar
1	1.06	0	0	0	221.265	-285.91	0
2	1.065	-0.572	21.7	12.7	40	-46.325	0
3	1.06	-1.242	94.2	19	0	-74.373	0
4	1.065	-1.091	47.8	-3.9	0	0	0
5	1.064	-0.95	7.6	1.6	0	0	0
6	1.12	-1.597	11.2	7.5	0	-1.096	0
7	1.094	-1.289	0	0	0	0	0
8	1.09	-1.289	0	0	0	-22.378	0
9	1.098	-1.393	29.5	16.6	0	0	0
10	1.102	-1.445	9	5.8	0	0	0
11	1.11	-1.522	3.5	1.8	0	0	0
12	1.117	-1.666	6.1	1.6	0	0	0
13	1.115	-1.636	13.5	5.8	0	0	0
14	1.104	-1.585	14.9	5	0	0	0
Total	-	-	259	73.5	261.265	-430.08	0

Table 8: Fault current on fault location at transmission lines (L2-3) and (L9-10)

	Bus current fault					
	a		b		c	
Bus No.	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)
15	11.4287	-1.3567	0	0	0	0
16	0	0	0	0	9.6125	0.8830

Table 9: Comparison of voltages of an unsymmetrical fault on transmission line (L2-3) and series fault on (L9-10)

			When fault at two transmission lines (L2-3) and (L9-10) (after fault)					
	Before fault		a		b		c	
Bus No.	Voltage (Mag.)	Angle (°)	Voltage (Mag.)	Angle (°)	Voltage (Mag.)	Angle (°)	Voltage (Mag.)	Angle (°)
1	1.06	0	1.051032	-0.05585	1.058648	-119.995	1.052001	119.8092
2	1.065	-0.572	0.992128	0.51676	1.062517	-119.459	1.039493	120.1461
3	1.06	-1.242	0.667492	0.186066	1.069027	-119.415	0.974487	120.7961
4	1.065	-1.091	0.953509	-2.20264	1.091468	-117.192	0.739989	120.3095
5	1.064	-0.95	0.978823	-1.17771	1.077601	-117.931	0.812288	119.2111
6	1.12	-1.597	1.07667	1.743974	1.109428	-118.534	0.764473	108.4141
7	1.094	-1.289	1.105073	-4.7532	1.155424	-112.597	0.308692	91.95632
8	1.09	-1.289	1.065097	1.080343	1.09095	-118.627	0.847229	118.1423
9	1.098	-1.393	1.204635	-9.09568	1.228199	-107.04	0.455266	-19.2293
10	1.102	-1.445	1.245969	-11.7513	1.287057	-105.232	0.678312	-38.1136
11	1.11	-1.522	1.166383	-5.91818	1.194424	-110.63	0.201976	38.40054
12	1.117	-1.666	1.099573	-0.50842	1.132307	-116.152	0.66071	104.97
13	1.115	-1.636	1.116844	-1.59066	1.140669	-114.771	0.5734	102.4315
14	1.104	-1.585	1.144788	-4.86094	1.1706	-111.254	0.246256	46.04452
15	-	-	0.005064	138.4217	1.108771	-128.958	1.054013	128.4025
16	-	-	1.182023	-15.2431	1.20437	-103.804	0.925361	-40.9438

Table 10: Comparison of currents of a unsymmetrical faults on transmission line (L2-3) and series fault on (L9-10)

		Line current before fault					
		a		b		c	
Bus No.	Bus No	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)
1	2	1.6589	163.1876	1.6589	43.1875	1.6589	-76.8124
1	5	1.6088	179.0794	1.6088	59.079	1.6088	-60.9206
2	3	0.1028	-154.079	0.1028	85.9211	0.1028	-34.0789
2	15*	-	-	-	-	-	-
3	15*	-	-	-	-	-	-
2	4	0.0594	-177.193	0.05947	62.8070	0.0594	-57.193
2	5	0.0753	-167.741	0.0753	72.2591	0.0753	-47.7409
3	4	0.0891	78.9175	0.0891	-41.0825	0.0891	-161.082
4	5	0.0123	-8.9997	0.0123	-129	0.01237	111.0003
4	7	0.1428	111.9341	0.1428	-8.0658	0.1428	-128.066
4	9	0.1838	119.0987	0.1838	-0.9012	0.1838	-120.901
5	6	0.3152	121.7364	0.3152	1.7363	0.3152	-118.264
6	11	0.0536	-58.521	0.0536	-178.521	0.0536	61.47897
6	12	0.0721	-95.9944	0.072	144.0056	0.07211	24.0056
6	13	0.0229	-97.4879	0.0228	142.5121	0.0228	22.5121
7	8	0.0065	-88.7109	0.0065	151.2891	0.0065	31.289
7	9	0.0207	113.6388	0.0207	-6.36118	0.0207	-126.361
9	10	0.0147	134.9329	0.0147	14.932	0.0147	-105.067
9	16*	-	-	-	-	-	-
10	16*	-	-	-	-	-	-
9	14	0.0238	150.2688	0.0238	30.2688	0.0238	-89.7312
10	11	0.0605	128.0533	0.0605	8.0532	0.0605	-111.947
12	13	0.0110	-70.417	0.0110	169.583	0.0110	49.583
13	14	0.1018	-83.3654	0.1018	156.6346	0.1018	36.6345
Line current after fault(on (L2-3) and (L9-10))							
1	2	0.8332	-85.2255	0.2635	85.6936	0.243397	56.44626

Table 10: Continue

		Line current before fault					
		a		b		c	
Bus No.	Bus No	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)	Current (Mag.)	Angle (°)
1	5	0.3859	-91.773	0.0595	136.312	0.859325	48.77983
2	3	-	-	-	-	-	-
2	15*	7.675	-76.4255	0.7569	161.655	1.064687	62.85553
3	15*	4.9781	-75.6782	0.5869	-159.702	0.223523	36.90916
2	4	0.3365	-83.1944	0.0669	-170.144	1.28453	50.31337
2	5	0.2009	-90.1196	0.0772	-146.876	0.995129	53.03558
3	4	1.16121	113.2343	0.2518	-76.1042	0.879944	40.66695
4	5	0.5963	105.6935	0.1275	-86.4222	1.297649	-139.354
4	7	0.2880	113.9795	0.20087	-66.9015	1.760783	47.04129
4	9	0.0988	129.989	0.1033	-75.5772	1.536388	45.43201
5	6	0.2981	126.9641	0.2763	-64.2199	0.467201	94.21144
6	11	0.0670	-44.067	0.0554	138.219	2.466087	59.26817
6	12	0.05113	36.46034	0.0596	62.9709	0.272293	66.14916
6	13	0.11509	46.13534	0.14885	79.6908	0.985886	62.27155
7	8	0.2663	93.47177	0.0255	94.0954	2.553307	-137.151
7	9	0.15327	-130.106	0.1561	-97.2255	4.422769	44.21419
9	10	-	-	-	-	-	-
9	16*	2.2312	-54.4574	2.2602	-173.117	9.3938	52.00866
10	16*	2.3455	-53.7316	2.3171	-175.03	4.737432	62.49462
9	14	0.1934	-131.865	0.1927	-113.292	1.236683	-115.791
10	11	0.0644	135.4472	0.0546	-44.3459	2.463806	-120.761
12	13	0.0609	39.9212	0.0542	54.0410	0.268736	68.21167
13	14	0.1813	46.3369	0.1985	70.2745	1.245193	63.72594

*Significant values

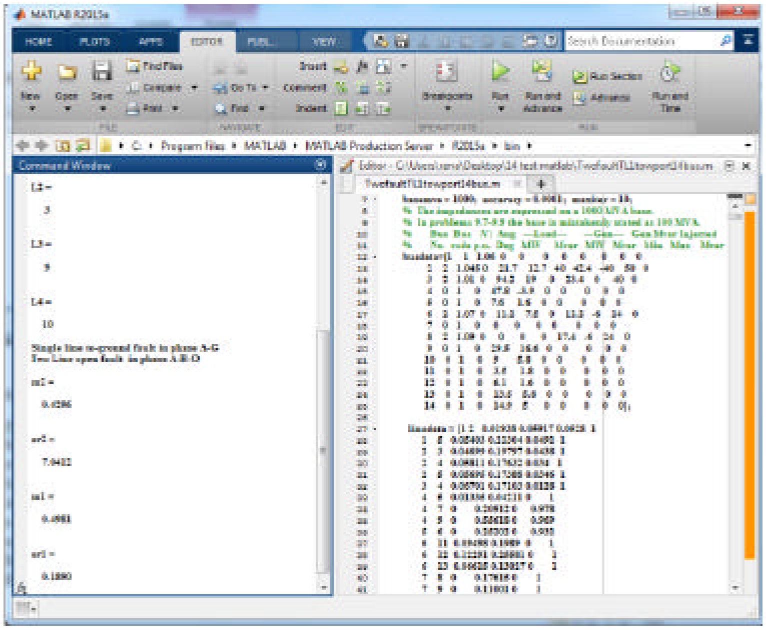

Fig. 12: Results given by MATLAB program

currents, respectively, before and after the occurrence of the unsymmetrical fault on transmission line (L2-3) and series fault on transmission line (L9-10).

Figure 12 show the results given by a MATLAB simulation from the fault detection, classification and location on transmission line (L2-3) and (L9-10).

Multiple fault detection, classification fault A-G on transmission line (L2-3) and (AB-O) on transmission line (L9-10) and location on transmission line (L2-3) and (L9-10). The actual location on transmission line (L2-3) and (L9-10) is 0.5 and 0.5, respectively. The estimation location (m 1, m 2) is 0.4981 and 0.4296, respectively. The error of fault location (er1, er2) is -0.001890 and 0. 070412, respectively:

$$\%\text{Error} = \frac{\text{n actual fault location-estimated fault locationn}}{\text{Total system length}} \times 100 \quad (53)$$

Before fault not connected between (buses 2 and imaginary bus (15)), (buses (3) and imaginary bus (15)), (buses (9) and imaginary bus (16)) and (buses (10) and imaginary bus (16)). Assumed imaginary bus bar to calculate fault in transmission lines.

CONCLUSION

The problem of multiple fault detection, classification and location in power system great importance for the economics and power quality of the power systems. It provides the essential continuity of service for reliable transmission. The importance of accurate fault location is increasing for fast repair and power system restoration. In this research, a conventional method using current and voltage values comparisons has been presented. The obtained results show the effectiveness and the accuracy of this method for multiple fault detection, classification and location.

REFERENCES

Anderson, P.M., 1971. Analysis of simulatenous faults by two-port network theory. IEEE. Trans. Power Apparatus Syst., PAS-90: 2199-2205.

Atabekov, G.I., 1960. The Relay Protection of High Voltage Networks. Pergamon Press, Oxford, UK., Pages: 564.

Girgis, A.A. and M.B. Johns, 1989. A hybrid expert system for faulted section identification, fault type classification and selection of fault location algorithms. IEEE. Trans. Power Delivery, 4: 978-985.

Gopakumar, P., M.J.B. Reddy and D.K. Mohanta, 2015. Transmission line fault detection and localisation methodology using PMU measurements. IET. Gener. Transm. Distrib., 9: 1033-1042.

Grainger, J.J. and D.W. Stevenson, 1994. Power System Analysis. 1st Edn., McGraw Hill, USA.

Guillemin, E.A., 1935. Communication Networks. John Wiley & Sons, Hoboken, New Jersey, USA., Pages: 1012.

Han, Z.X., 1982. Generalized method of analysis of simultaneous faults in electric power system. IEEE. Trans. Power Apparatus Syst., PAS-101: 3933-3942.

Huang, S.J., C.T. Hsieh and C.L. Huang, 1999. Application of morlet wavelets to supervise power system disturbances. IEEE Trans. Power Delivery, 14: 235-243.

Krishnanand, K.R., P.K. Dash and M.H. Naeem, 2015. Detection, classification and location of faults in power transmission lines. Intl. J. Electr. Power Energy Syst., 67: 76-86.

Othman, M.F., M. Mahfouf and D.A. Linkens, 2004. Transmission lines fault detection, classification and location using an intelligent power system stabiliser. Proceedings of the 2004 IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT 2004) Vol. 1, April 5-8, 2004, IEEE, Hong Kong, China, pp: 360-365.

Saadat, H., 1999. Power System Analysis. McGraw-Hill, New York, USA., ISBN:9780071167581, Pages: 697.

Silva, K.M., B.A. Souza and N.S.D. Brito, 2006. Fault detection and classification in transmission lines based on wavelet transform and ANN. IEEE Trans. Power Delivery, 21: 2058-2063.

Singh, M., B.K. Panigrahi and R.P. Maheshwari, 2011. Transmission line fault detection and classification. Proceedings of the 2011 International Conference on Emerging Trends in Electrical and Computer Technology (ICETECT), March 23-24, 2011, IEEE, Nagercoil, India, ISBN:978-1-4244-7923-8, pp: 15-22.

Takagi, T., Y. Yamakoshi, M. Yamura, R. Kondow and T. Matsushima, 1982. Development of a new type fault locator using the one-terminal voltage and current data. IEEE Trans. Power Apparatus Syst., 101: 2892-2898.

Tziouvaras, D., 2008. Analysis of Complex Power System Faults and Operating Conditions. Schweitzer Engineering Laboratories, Inc., Pullman, Washington, USA.,.