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Detection of faulted phase type in distribution systems based on one end voltage measurement

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ABSTRACT

Distribution power systems exposed to various unexpected failures due to many random causes. These failures are mostly happened as a result of phase faults in power system and will affect negatively the availability and reliability of the power system. Accurate detection of these faults will help in restoration of power in a timely manner and not to cause any severe damage to the power system equipment. This paper investigates the problem of accurate detection of faulted phase types occurred in the distribution system. The features of the voltage waveforms recorded from one end measurement of the distribution system during the fault occurrence are used in the proposed technique. Clarke's transformation criterion used to identify if the fault is line-to-ground (grounded fault) or phase-to-phase (ungrounded fault). Then the fault types are classified by the high performance comparison method of the voltage signals using phase angle shift prior and during the fault occurrence. Different types of faults namely, single-phase to ground, double-phase to ground, phase–phase and balanced three-phase faults that are occurred at different locations with different fault resistances and inception angles are tested and analyzed. Results from simulation of faults on a model of 33 kV distribution system typical networks presented.

1. Introduction

Power distribution lines, among all other electrical components of the network, are exposed to different types of unexpected failures due to various random causes. The availability and reliability of the network is negatively impacted due to phase faults that lead to these failures. Accurate classification and detection of these faults will assist in the restoration of power in a timely manner and not to cause any severe damage to the power system equipment. There are several methods, in the last three decades, used for classification and detection of faults in the radial overhead distribution systems. Many researchers performed studies on fault classification and detection in distribution systems based mainly on wavelet transform, artificial neural networks and support vector machines. Wavelet multi-resolution approach is used with current measurement at the main substation to estimate the fault type of radial distribution system [1]. This method uses a set of rule base to identify ten different types of faults. In [2], fault type and fault location were determined by using artificial neural network (ANN). In this approach, three phase currents of main source feeder were normalized and used as an input array to the ANN. Use of Clark transformation with ANN was reported, to determine the fault location and fault type in power distribution systems [3,4]. In another work, authors used Traveling Wave (TW) and Clark Transformation (CT) based on voltage signals to estimate fault location and various types of faults in a distribution system [5]. In Clark transformation, voltage signals are transformed from phase domain into modal domain. Few works based on phase angle shift for estimation of fault type classification were also reported. In [6], phase angle shift method was used for fault type classification based on voltage captured by distribution PQ monitor.

This paper investigates the problem of accurate classification of faulted-phase type occurred in the distribution system. The proposed algorithm utilizes only the extracted features of the voltage waveforms recorded from one end of the radial distribution system during fault occurrence to find the accurate fault type. The faulted-phase type is determined into two parallel schemes. In the first scheme, distinctive features of voltage signals due to fault are extracted by the application of Clarke Modal Transformation (CMT) to verify between grounded and ungrounded faults. In the second scheme, Voltage phase angle shift of pre and during fault occurrence period is calculated to differentiate between faulty and un-faulty phases by certain criteria. Different types of faults (single-phase-ground, double-phase-ground, phase–phase and balanced three-phase) that are occurred at different locations are analyzed. Results from simulation of faults on a model of 33 KV distribution power system are presented. Validation of classification of faulted phase type is performed using ATP/EMTP for

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transient simulations and MATLAB for software applications. Fault location distance is not considered in this paper.

2. Classification of Fault Type Techniques

Clarke Modal Transformation (CMT) and voltage phase angle shift (PAS) criteria are tools used in the faulted phase type detection in distribution systems technique. These tools performance is dependent on the features of only voltage waveforms recorded during the event of a fault from one end of the radial distribution system.

2.1. Clarke Modal Transformation (CMT)

To determine whether the fault is grounded or ungrounded, in the proposed approach, by the modal transformation matrix, from the phase domain signals the modal components are extracted, it is assumed in this study that all overhead distribution line models are fully transposed, the well known real transformation matrix and Clarke's constant will be used for this purpose. As stated below, the matrix is given by [7]:

$$T = \begin{bmatrix} 2/\sqrt{6} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix} \tag{1}$$

By implementation of this transformation matrix in (1) the phase signals are transformed into their modal components, as shown in the following equation,

$$\begin{bmatrix} V\alpha \\ V\beta \\ V0 \end{bmatrix} = \begin{bmatrix} 2/\sqrt{6} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix} * \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{2}$$

where

$$S_{\text{mode}} = \begin{bmatrix} V\alpha \\ V\beta \\ V0 \end{bmatrix} \text{ and } S_{\text{phase}} = \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{3}$$

The modal and phase signals (voltages or currents) vectors are the Smode and Sphase respectively. With any transposed line, the real Clarke's transformation can be used. An eigenvector based transformation matrix, which is frequency dependent have to be used, for the study of untransposed lines. The frequency for computation of this matrix should be equal or close to the frequency of the initial fault transients. At first the recorded three phase signals are changed into their modal components. To obtain the aerial and ground mode signals from the three-phase transients Clarke's transformation matrix can be used. The first two modes (mode α and mode β), are usually referred to as the areal modes, and the third (mode 0) is referred to ground mode, and only during faults having a path to ground its magnitude is significant. For the purpose of distinguishing between grounded and ungrounded fault situations, the faulted phase essentially based on the ground mode (mode 0) making use of the ground mode, the faulted phase type problem is formulated. Therefore, Eq. (2) can be rewritten as

$$V_0 = \begin{bmatrix} 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \end{bmatrix} * \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \tag{4}$$

Based on the V_0 value in (3), the fault situation can be decided either the fault scheme is ungrounded or grounded. Faulted phases of single-line-to-ground, double-line-ground and three-line-ground will be distinguished, in the grounded fault situation. Similarly, for ungrounded fault situation, line-to-line fault and three lines fault will be determined.

2.2. Phase angle shift (PAS) criterion

Phase angle shift (PAS) is a change in voltage phase angle associated with fault occurrence. Due to the type of fault, in addition to other factors, the characteristics of faults at certain locations are determined. PAS is related to X/R line impedance ratio of the source and the faulted feeder [8]. By calculating the difference between the during-fault voltage waveform angle and the pre-fault voltage waveform angle, which is related, the phase angle shift due to the fault occurrence can be obtained. PAS may have a negative or a positive value and can be in the form of angle (in radians or degrees), or of time (in milliseconds). The sampling of the voltage waveform that occurred due to fault in the system and used in the calculation of PAS is formed over the period of one cycle with ½ cycle to cover pre-fault and ½ cycle to cover during-fault data. There are several methods for the calculation of PAS. In this paper, calculation of PAS uses Fast Fourier Transform (FFT) method. This method is uncomplicated and suitable to the sampling data of the voltage waveform. In nominal case, PAS equals to zero since there is no phase shift between the pre-fault angle and during-fault angle.

3. Faulted Phase Type Classification Algorithm

The classification algorithm of faulted phase type is divided into two parts as shown in Fig. 1. One part is to determine if the fault is grounded or ungrounded by using the Clarke Modal Transformations (CMT). In the other part, faulted phase type is determined. This is accomplished by the comparison of calculated phase angle shift values of the voltage waveform due to a fault occurrence. The values of the three calculated PAS indicate which phase is in fault. In Fig. 1, the phase angle shift values are given the weight of large (L) or small (S) for comparison between the resulted phase angle shifts for each phase to indicate the fault type. The steps of flow chart in Fig. 1 are explained in the following procedure:

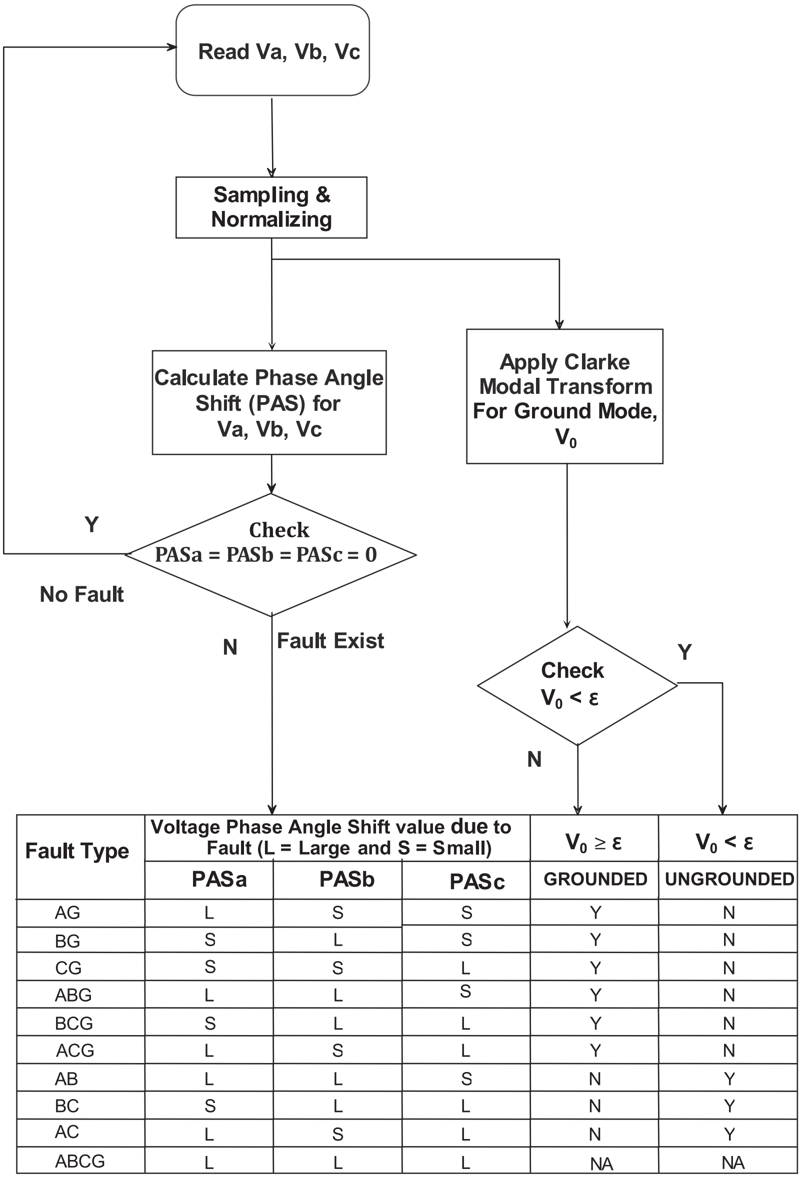
A. Faulted phase polarity determination:
   - Read, sampling and normalizing of *Va*, *Vb* and *Vc*.
   - Apply Clarke Modal Transform (CMT) for ground mode, V_0.
   - Compare the resulted V_0 value for grounded or ungrounded signal using certain threshold value.

B. Classification of faulted phase type:
   - Read, sampling and normalizing of *Va*, *Vb* and *Vc*. (As in part A above)
   - Calculate PAS for each phase (*Va*, *Vb*, *Vc*).
   - Compare the calculated values of PASa = PASb = PASc = 0.
   - If result is true then system is healthy (no-fault).
   - If result is false, then compare the values of all phases for L and S as in the tabulation of Fig. 1 to detect the type of faulty phases.

For faulted phase polarity, the threshold value of ε is to be determined by trial and error based on data collected.

4. Distribution system model

From a power system model simulated in Fig. 2, determination and classification of faults is performed. Using ATP/EMTP simulation program [9], in the overhead distribution system, the simulation of transient signals is performed. The power system consisting



Fault Type	Voltage Phase Angle Shift value due to Fault (L = Large and S = Small)			$V_0 \geq \varepsilon$	$V_0 < \varepsilon$
	PASa	PASb	PASc	GROUNDED	UNGROUNDED
AG	L	S	S	Y	N
BG	S	L	S	Y	N
CG	S	S	L	Y	N
ABG	L	L	S	Y	N
BCG	S	L	L	Y	N
ACG	L	S	L	Y	N
AB	L	L	S	N	Y
BC	S	L	L	N	Y
AC	L	S	L	N	Y
ABCG	L	L	L	NA	NA

Fig. 1. Flow chart of developed Faulted Phase Type Classification Algorithm.

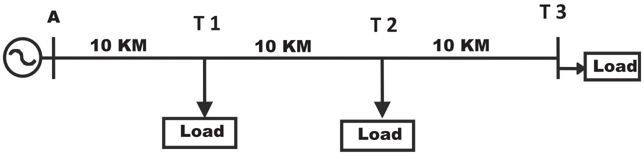


Fig. 2. The overhead distribution system used for this study.

Table 1
Overhead distribution line parameters.

$R1$	0.11763 Ω/km
$R0$	0.22961 Ω/km
$X1$	0.3712 Ω/km
$X0$	1.0717 Ω/km
$C1$	3.1 μF/km
$C0$	1.5 μF/km

of a radial overhead distribution system of 30 km with tapped loads and a single power supply of 33 KV, 50 Hz. The faults are simulated on different points on the power system. Faulted phases are simulated with different fault resistance, R_f (1 Ω and 10 Ω) and impact of different inception angles, A_i (0° and 90°) of faults are studied and analyzed. Faulted phase types (single-line-ground, double-line-ground, three-line-ground, phase–phase and balanced three-phase) with different fault resistances and inception angles are simulated and analyzed. The sampling simulation time is taken to be 60 ms (3 cycles at 50 HZ) with time step (ΔT) of 0.5 μs and a total of 1200 samples (400 samples per cycle) for each fault case.

System parameters with generator source resistance 0.89 Ω and source inductance of 12.37 mH are typical to Kuwait network at Wafra. Table 1 shows the overhead distribution line parameters.

In Fig. 3a and b, the sampling of three-phase of voltage waveforms is shown during the occurrence of single-phase-ground (AG) and phase–phase (AB) faults, respectively, at 10 km away from sending end with the no-load condition. Similarly, Fig. 3c demonstrates three-phase sampling of single-phase-ground fault (AG) at 10 km away from sending end, 1 Ω fault resistance and with the full-load condition.

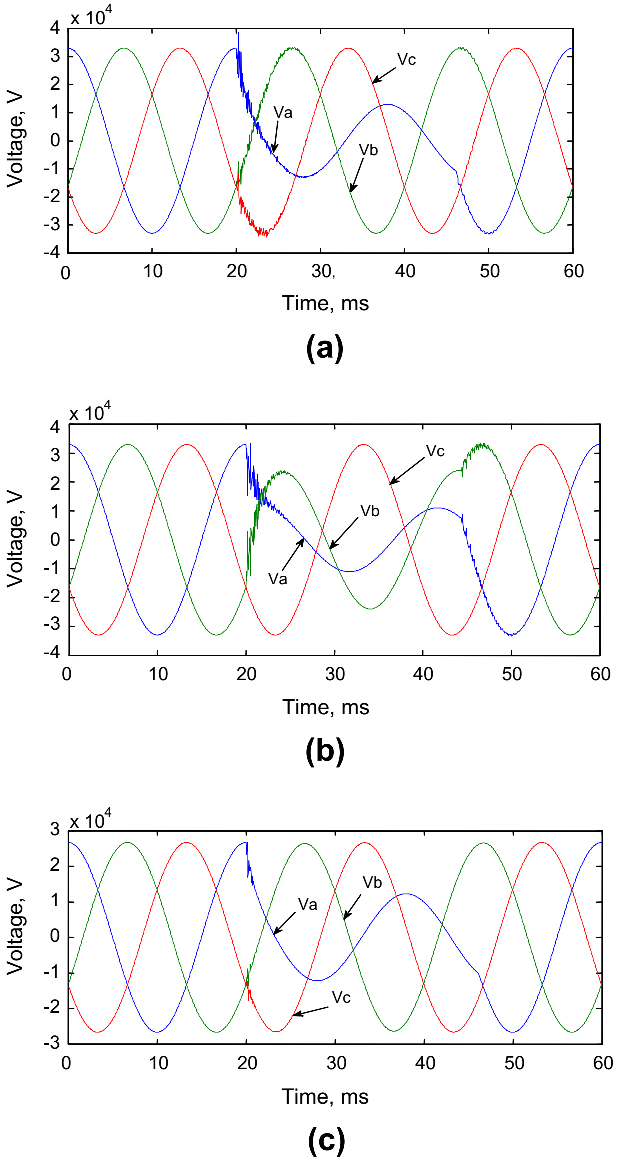


Fig. 3. Phase shift is shown clearly in the three phases of measured voltages at main substation during different faults at 10 km away from the sending end: (a) single-phase-ground (AG) fault with fault resistance of 1 Ω and at no-load. (b) phase–phase (AB) fault at no-load. (c) Single-phase-ground (AG) fault with fault resistance of 1 Ω and at full-load.

5. Results and discussions

Eq. (3) is applied to the simulated faulted voltage waveforms recorded at the main substation (point A) during single-phase-ground fault and phase–phase fault. The resulted signals are shown in Figs. 4 and 5. The concern here is the value of V_0 which indicate the grounded and ungrounded fault by its value. Note that in Fig. 4 (ground case) the curve value is exceptionally higher compared to the curve value in Fig. 5 (ungrounded case) where the value is close to zero.

In the next step, the phase angle shift value is calculated. Table 2 shows the values of phase angle shift. From these values, it is clear to predict the faulted phase in each fault type case. As per condition above, when the PAS value is too close or equal to zero, then the phase is not faulty. From the value of V_0, it is possible to detect the grounded or ungrounded cases. In the three phase faults, the value of V_0 is not applicable since it is too small and contradicts with value of phase–phase condition. Instead, the phase angle shift (PAS) values

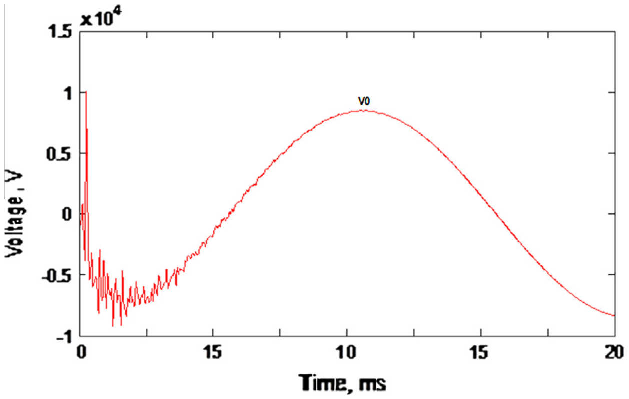


Fig. 4. Large value of Modal Transform (V_0) of voltage waveform during single-phase-ground fault at 10 km from the sending end with fault resistance of 10 Ω.

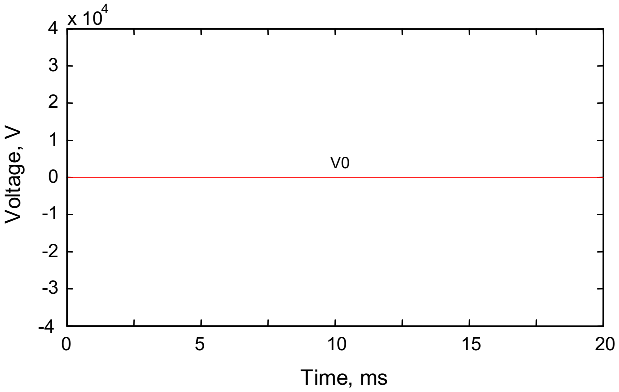


Fig. 5. Small value (~0) of Modal Transform (V_0) of voltage waveform during phase–phase fault at 10 km from the sending end.

Table 2
Phase angle shift and V_0 values for voltage waveforms during faults at 10 km away from the sending end with $R_f = 10\ \Omega$, $A_i = 90°$ and no-load condition.

Fault type	PASa	PASb	PASc	$V_0 > \varepsilon$ (0.1) (Y) or (N)	Matching YES or NO
AG	0.048950	0.000065	0.000070	0.33513 (Y)	YES
BG	0.000482	0.115919	0.000338	1.09022 (Y)	YES
CG	0.000545	0.000170	0.085941	1.42724 (Y)	YES
ABG	0.034633	0.067074	0.000209	66.1797 (Y)	YES
BCG	0.000319	0.092004	0.116463	64.4931 (Y)	YES
ACG	0.060185	0.000121	0.070271	1.29898 (Y)	YES
AB	0.249324	0.565607	0.000000	0.00071 (N)	YES
BC	0.000000	0.101564	0.471001	0.00159 (N)	YES
AC	0.351957	0.000000	0.122222	0.00025 (N)	YES
ABCG	0.039076	0.101901	0.085527	NA	YES

Table 3
Phase angle shift and V_0 values for voltage waveforms during faults at 30 km away from the sending end with $R_f = 10\ \Omega$, $A_i = 0°$ and full load condition.

Fault type	PASa	PASb	PASc	$V_0 > \varepsilon$ (0.1) (Y) or (N)	Matching YES or NO
AG	0.1412541	0.0078516	0.0086684	6.8984 (Y)	YES
BG	0.0070889	0.1019563	0.0059248	3.6889 (Y)	YES
CG	0.0083689	0.0103723	0.1496410	3.2053 (Y)	YES
ABG	0.1243793	0.1310767	0.0022987	2.6015 (Y)	YES
BCG	0.0012349	0.0843668	0.1162661	5.4496 (Y)	YES
ACG	0.1755149	0.0020967	0.1289525	2.8536 (Y)	YES
AB	0.1283842	0.2642558	0.0000000	0.00071 (N)	YES
BC	0.0000000	0.0763809	0.2344840	0.00108 (N)	YES
AC	0.3324277	0.0000000	0.1580232	0.00269 (N)	YES
ABCG	0.1591545	0.1079594	0.1553030	NA	YES

Table 4
Phase angle shift and V_0 values for voltage waveforms during faults at 10 km away from the sending end with $R_f = 10\ \Omega$, $A_i = 90°$ and full load condition.

Fault type	PASa	PASb	PASc	$V_0 > \varepsilon$ (0.1) (Y) or (N)	Matching YES or NO
AG	0.0603135	0.0020003	0.0039844	0.35808 (Y)	YES
BG	0.0059483	0.1203876	0.0033753	0.89324 (Y)	YES
CG	0.0029755	0.0045871	0.0969034	1.24839 (Y)	YES
ABG	0.0412886	0.1300573	0.0005035	1.21757 (Y)	YES
BCG	0.0027945	0.1020017	0.1113583	0.37776 (Y)	YES
ACG	0.0716623	0.0023974	0.0815456	0.83880 (Y)	YES
AB	0.1591552	0.5507101	0.0000000	0.00058 (N)	YES
BC	0.0000000	0.0372126	0.4670807	0.00275 (N)	YES
AC	0.3532765	0.0000000	0.0693507	0.00211 (N)	YES
ABCG	0.0530459	0.1122329	0.0962995	NA	YES

Table 5
Phase angle shift and V_0 values for voltage waveforms during faults at 30 km away from the sending end with $R_f = 1\ \Omega$, $A_i = 0°$ and no-load condition.

Fault type	PASa	PASb	PASc	$V_0 > \varepsilon$ (0.1) (Y) or (N)	Matching YES or NO
AG	0.2443211	0.0003043	0.0000953	168.581063	YES
BG	0.0002293	0.1725363	0.0000368	83.0611011	YES
CG	0.0001084	0.0000012	0.1666508	85.5187278	YES
ABG	0.2194046	0.2403249	0.0001149	69.5474508	YES
BCG	0.0001599	0.1418122	0.2209026	137.0906	YES
ACG	0.3259706	0.0003730	0.1572874	67.7253405	YES
AB	0.0589192	0.2859194	0.0000000	0.00194985	YES
BC	0.0000000	0.0135883	0.2536403	0.0004464	YES
AC	0.3674276	0.0000000	0.0761423	0.00010622	YES
ABCG	0.2791474	0.2123245	0.1950525	NA	YES

of three phase faults are close to each other, and none is close to zero; hence there is no need for V_0 to make a comparison. Resulted data in Tables 2 and 3 show clear evidence on the accuracy of proposed fault type classification method. In modal transformation and phase angle shift, MATLAB popular software [10] is selected for all calculations of data.

Using the power system model shown in Fig. 1, data set used in validation including different fault types was simulated. For different fault types and fault locations, investigation conducted to find out how the performance is of the proposed algorithm is effected due to these factors. Results with different system conditions are presented in Tables 2–5. As an example, test results for a single-phase-ground, BG fault at 10 km away from the main substation is presented in the second row of Table 4. For this fault, $V_0 = 1.09$, which indicate ground fault, ($V_0 > 0.1$) and PASa = 0.000482568 (S), PASb = 0.115919721 (L) and PASc = 0.000338411 (S) which satisfies the condition of fault at phase B-to-ground as indicated in the proposed method flow chart in Fig. 1. All values of V_0 and PAS's in Tables 2–5 can be verified in the same manner. Last column designate if the calculated values are matching with proposed method conditions and resulting the same fault type (YES or NO).

6. Conclusion

This paper presents a new accurate faulted phase type detection algorithm using phase angle shift for distribution power system. Application of Modal Transformation (MT) and phase angle shift (PAS) criterion have significantly demonstrated the effective accuracy of the proposed algorithm. Study and analysis of the algorithm on loaded network with different fault resistances of (1 Ω, 10 Ω) and different inception angles of (0° and 90°) showed accurate and robust results.

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