Dynamic Fault Classification and Location in Distribution Networks

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Abstract. *This paper presents a method for detecting, classifying and localizing faults in MV distribution networks. This method is based on only two samples of current or voltage signals. The fault detection, faultclassification and fault localization are based on the maximum value of current and voltage as a function of time. A study is presented in this work to evaluate the proposed method.A comparative study between current and voltage method detection has been done to determine which is the fastest. In addition, the classification and localization of faults were made by the same method using two samples signal. Simulation with results have been obtained by using MATLAB / Simulink software. Results are reported and conclusions are drawn.*

Keywords

Distribution Network, Fault Detection, Fault Classification, Fault Localization.

1. INTRODUCTION

Electric power systems have developed rapidly in recent years and these systems have become important in all branches of the modern economy. With the growth of world population, and development in all areas, the demand for electric power is growing rapidly.

Medium-Voltage electrical power distribution lines are an essential part of an electrical power grid that must ensure the continuity of power supply to Medium Voltage (MV) and Low Voltage (LV) consumers. That is not always the case, These lines experience faults which are caused by storms, lightning, snow, freezing rain, insulation breakdown and, short circuits caused by birds and other external objects [1]. These faults must be detected, classified and localized quickly and correctly so that our system remains stable.

When a fault occurs in a distribution networks, the fault current is always greater than the rated load current and the fault voltage will be smaller than the nominal network voltage. The detection and localization of faults in electrical networks plays an important role in the correct operation of protective relays.

Fault detection and localization conventional methods for distribution lines are broadly classified as impedance based method which uses the steady state fundamental components of voltage and current values [2]-[6]. Wavelet method which is based on low pass filters and high pass filters [7]-[9], and knowledge based method which uses artificial neural network and/or pattern recognition techniques [10]-[12].

Digital relays that use the wavelet method and methods based on artificial neural networks for detecting and locating faults have a weakness because they have been designed for specific networks unlike the digital relay based on conventional algorithms that are designed on the basis of current or voltage amplitude measurements

Increase of current magnitude or decrease of voltage magnitude could be considered as a measure to detect andclassifya system in fault. The measure of reactance or impedance of the line is considered to locate the fault.

In [13] the authors use two methods to localise the fault in transmission line. The first method is based on the first and second derivative of the circuit equation and the second method is based on the integral of the circuit equation.

In this paper, an algorithm is proposed to detect, classify and locate faults on distribution network as a function of time. The method is based only on two samples of signal current or voltage.

2. USED METHOD

For the detection of electrical faults in any network there are several methods. Most methods use the maximum values of the voltage or current ($\mathrm{V}_{\max}$, $\mathrm{I}_{\max}$) comparing them to a threshold value, in this paper we will use a new method based on two samples which is as follows:

The equation of the voltage is as follows:

$$v = V_{\max} * \sin(w_0 * t) \tag{1}$$

We have the voltage at the moment k:

$$v_k = V_{\max} * \sin(w_0 * t_k) \tag{2}$$

The voltage at the moment $k+1$:

$$v_k = V_{\max} * \sin(w_0 * t_k) \tag{3}$$

$$v_{k+1} = V_{\max} * \sin(w_0 * (t_k + \Delta t)) \tag{4}$$

$$v_{k+1} = V_{\max} * \sin((w_0 * t_k) + (w_0 * \Delta t)) \tag{5}$$

$$\Delta t = t_{k+1} - t_k = 0.001\,\mathrm{sec}.$$

We know that:

$$\sin(A+B) = \sin A * \cos B + \cos A * \sin B \tag{6}$$

Therefore, Eq. (5) becomes:

$$\begin{aligned} v_{k+1} &= V_{\max} * \sin(w_0 * t_k) * \cos(w_0 * \Delta t) \\ &\quad + V_{\max} * \cos(w_0 * t_k) * \sin(w_0 * \Delta t)\,. \end{aligned} \tag{7}$$

We replace Eq. (2) in Eq. (7) and we get:

$$\begin{aligned} v_{k+1} &= v_k * \cos(w_0 * \Delta t) \\ &\quad + V_{\max} * \cos(w_0 * t_k) * \sin(w_0 * \Delta t) \end{aligned} \tag{8}$$

So

$$V_{\max} * \cos(w_0 * t_k) = \frac{v_{k+1} - v_k * \cos(w_0 * \Delta t)}{\sin(w_0 * \Delta t)} \tag{9}$$

With (Eq.(2) $)^2+$(Eq.(9) $)^2$, we give:

$$V_{\max k} = \sqrt{\frac{{v_k}^2 + {v_{k+1}}^2 - 2 * v_k * v_{k+1} * \cos(w_0 * \Delta t)}{(\sin(w_0 * \Delta t))^2}} \tag{10}$$

We do the same thing for the current "i", the result is:

$$I_{\max_k} = \sqrt{\frac{{i_k}^2 + {i_{k+1}}^2 - 2 * i_k * i_{k+1} * \cos(w_0 * \Delta t)}{(\sin(w_0 * \Delta t))^2}} \tag{11}$$

The current can be written as:

$$i_k = I_{\max} * \sin(w_0 * t_k + \theta_k) \tag{12}$$

$$\begin{aligned} i_k &= I_{\max} * \sin(w_0 * t_k) * \cos\theta_k \\ &\quad + I_{\max} * \cos(w_0 * t_k) * \sin(\theta_k) \end{aligned} \tag{13}$$

$$i_{k+1} = I_{\max} * \sin(w_0 * t_{k+1} + \theta_k) \tag{14}$$

$$i_{k+1} = I_{\max} * \sin(w_0 * (t_k + \Delta t) + \theta_k) \tag{15}$$

$$\begin{aligned} i_{k+1} &= \\ I_{\max} &* \begin{bmatrix} \sin(w_0 * t_k) * \cos(w_0 * \Delta t) \\ + \cos(w_0 * t_k) * \sin(w_0 * \Delta t) \end{bmatrix} * \cos(\theta_k) \\ + I_{\max} &* \begin{bmatrix} \cos(w_0 * t_k) * \cos(w_0 * \Delta t) \\ - \sin(w_0 * t_k) * \sin(w_0 * \Delta t) \end{bmatrix} * \sin(\theta_k) \end{aligned} \tag{16}$$

From Eq. (2) we have:

$$\sin(w_0 * t_k) = \frac{v_k}{V_{\max}} \tag{17}$$

From Eq. (7) we have:

$$\cos(w_0 * t_k) = \frac{v_{k+1} - v_k * \cos(w_0 * \Delta t)}{V_{\max} * \sin(w_0 * \Delta t)} \tag{18}$$

Using Eq. (13) and Eq. (16) we can obtaining the expression of θ_k. Using Eq. (17) and Eq. (18), we obtain the final value of θ_k:

$$\theta_k = -\cos^{-1}\left(\frac{E_1}{E_2}\right), \tag{19}$$

where

$$E_1 = i_k * v_k + i_{k+1} * v_{k+1} - (i_k * v_{k+1} + i_{k+1} * v_k) * \cos(w_0 * \Delta t)$$

$$E_2 = I_{\max k} * V_{\max k} * (\sin(w_0 * \Delta t))^2.$$

Using Eq. (2) and Eq. (12), the fault impedance Z_k can be determined as:

$$Z_k = \frac{v_k}{i_k} = \frac{V_{\max k} * \sin(w_0 * t_k)}{I_{\max k} * \sin(w_0 * t_k + \theta_k)} \tag{20}$$

$$Z_k = \frac{V_{\max_k}}{I_{\max_k}} e^{-j\theta_k} \tag{21}$$

We note:

$$\theta_{z_k} = -\theta_k$$

To localize the fault, the fault impedance Z_k can be determined by:

$$Z_k = \frac{V_{\max k}}{I_{\max k}} * (\cos\theta_{z_k} + j * \sin\theta_{z_k}) \tag{22}$$

With:

$$\theta_{z_k} = \cos^{-1}\left(\frac{E_3}{E_4}\right), \tag{23}$$

where

$$E_3 = i_k * v_k + i_{k+1} * v_{k+1} - (i_k * v_{k+1} + i_{k+1} * v_k) * \cos(w_0 * \Delta t)$$

$$E_4 = I\max_k * V\max_k * (\sin(w_0 * \Delta t))^2.$$

$$Z_k = R_k + jX_k \tag{24}$$

$$R_k = \frac{V_{\max k}}{I_{\max k}} * (\cos\theta_{z_k}) \tag{25}$$

$$X_k = \frac{V_{\max_k}}{I_{\max_k}} * (\sin\theta_{z_k}) \tag{26}$$

2.1. Fault detection and classification

Fig. 1 presents the flowchart of the method to detect and classify the fault.

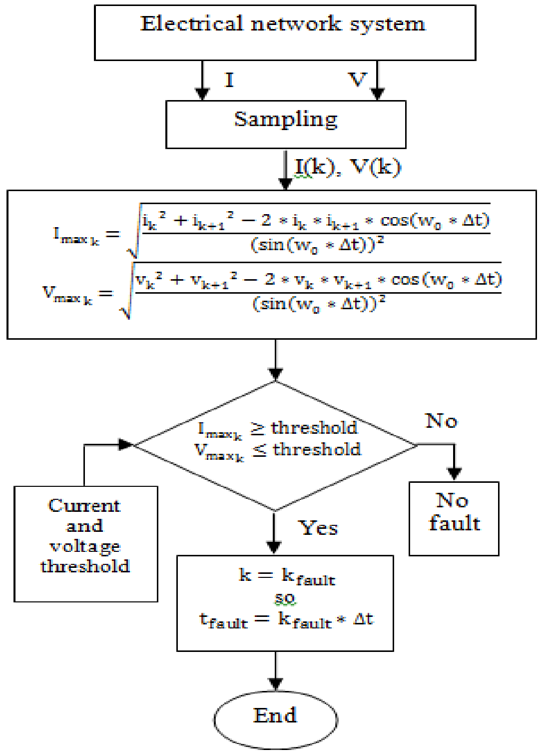

Fig. 1: The flowchart of the methodfor fault detection and classification.

2.2. Fault localization

The apparent positive-sequence fault impedance measured is proportional to the fault distance, which can be estimate for each fault type [14, 15] as shown in Table 1.
Where

a, b and c indicates faulty phases.

g indicates ground fault.

V_a, V_b and V_c indicate voltage phasors.

I_a, I_b and I_c indicate current phasors.

$$k = \frac{Z_{OL} - Z_{dL}}{3Z_{dL}} \tag{27}$$

Z_{OL} is the zero-sequence line impedance.

Z_{dL} is the positive-sequence line impedance.

I_R is the residual current ($3I_0$).

I_0 is the zero- sequence current.

The fault location (m) can be determined by using impedance Z_k or the reactance X_k. Using the reactance, the fault location (m) is:

$$m = \frac{X_k}{X_d} \tag{28}$$

X_d is the positive sequence line reactance (Ω/km).

3. POWER SYSTEM MODEL

Fig. 2 shows the block Simulink of our 25 kV, 50 Hz network under the software MATLAB. The

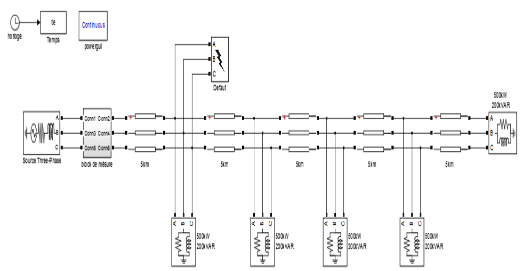

Fig. 2: Power system model.

distribution line parameters are as follows:
Positive Sequence Resistance: $R_d = 0.2236$ Ω/km.
Zero Sequence Resistance: $R_0 = 0.368$ Ω/km.
Positive Sequence Inductance: $L_d = 1.11$ mH/km.
Zero Sequence Inductance: $L_0 = 5.05$ mH/km.
Positive Sequence Capacitance: $C_d = 11.13$ nF/km.
Zero Sequence Capacitance: $C_0 = 5$ nF/km.
The line is divided into 5 parts of 5 km; at the end of each part, we have a load.
All loads have an active power of 500 kW and a reactive power of 200 kvar.
Fig. 3 shows the steps performed by the digital relay for fault detection, classification and localization.

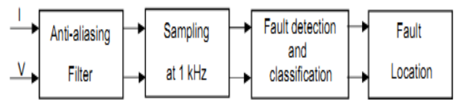

Fig. 3: The steps performed by the digital relay for fault detection, classification and localization.

The currents and voltage signals are filtered using the antialiasing filter (Butterworth low-pass) and sampled at 1 kHz.

4. SIMULATIONSAND RESULTS

When a fault appears in distribution line, the maximum value of current increases and the maximum value of voltage decreases. By comparing with a threshold at each sample “k” we can detect and classify the fault.

4.1. Fault detection

To detect fault in distribution line, we can use the maximum value of the current or voltage signal.

Using the network illustrated in Fig. 2, a single-phase to ground fault (a-g) was applied at the instant 60 ms with a distance of 5 km using neutral regime connected directly to ground and a zero-fault resistance $R_fault = 0$ Ω. The fault is detected by both maximum voltage and currentvalues.

Fig. 4 shows the current signal, the maximum current value and the output fault detector signal in function of time.

Fig. 5 shows the voltage signal, the maximum voltage value and the output fault detector signal in function of time.

In Fig. 4(a) the black dots represent the maximum current value calculated at each instant. In Fig. 4 (b) we can see, the first dot that is dif-

Table 1. Single fault impedance equation for negligible fault resistance.

Fault type	Fault impedance Z_k
a-g	$\frac{V_a}{(I_a+kI_R)}$
b-g	$\frac{V_b}{(I_b+kI_R)}$
c-g	$\frac{V_c}{(I_c+kI_R)}$
a-b or a-b-g	$\frac{V_a-V_b}{(I_a-I_b)}$
b-c or b-c-g	$\frac{V_b-V_c}{(I_b-I_c)}$
c-a or c-a-g	$\frac{V_c-V_a}{(I_c-I_a)}$
a-b-c or a-b-c-g	$\frac{V_a-V_b}{(I_a-I_b)}$ or $\frac{V_b-V_c}{(I_b-I_c)}$ or $\frac{V_c-V_a}{(I_c-I_a)}$

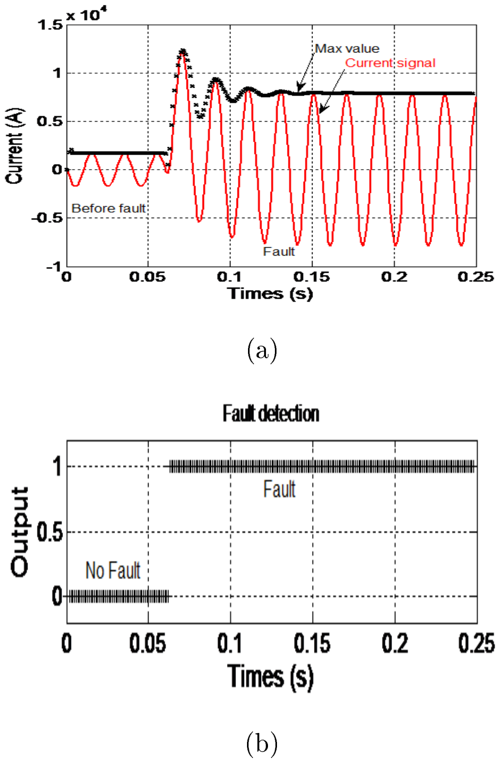

Fig. 4: Fault detector output using the maximum current value.

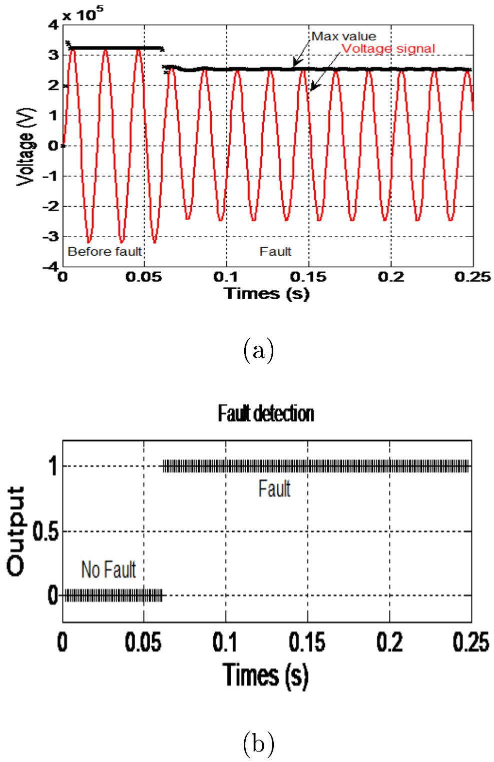

Fig. 5: Fault detector output using the maximum voltage value.

ferent from zero is at the instant 0.062 sec. (62 ms). Therefore, the fault is detected 2 ms late.

In Fig. 5 (a) the black dots represent the maximum voltage value calculated at each instant. In Fig. 5 (b) we can see, the first dot that is different from zero is at the instant 0.061 sec. (61 ms). Therefore, the fault is detected 1 ms behind.

Therefore it is concluded that the detection by the developed method using the maximum voltage value is faster than the detection by the maximum current value.

4.2. Fault classification

To classify the fault by the proposed method, the maximum voltage values are used and the same steps as the detection for each phase are followed. To classify the ground fault, we use the zero sequence voltage signal.

We programmed a fault classifier algorithm and we created several types of faults. The results are as follows:

Fig. 6 represents the fault classifier output as a function of time for a single-phase to ground fault (a-g).

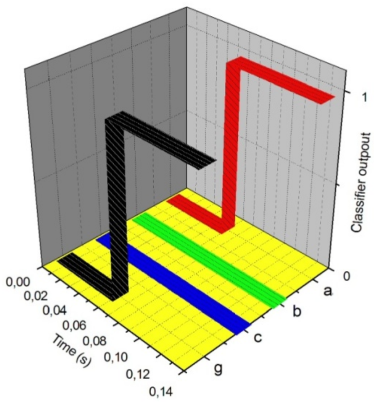

Fig. 6: Fault classifier output for the single-phase to ground fault in the phase "a".

The fault classifier indicates that the phases "b" and "c" are always zero, which implies that it is a single-phase fault (a-g). The fault is classified on phase "a" at time 0.062 sec. and on the ground at time 0.063 sec, so the fault classification time is equal to 0.063 sec, it's late by 3 ms.

Fig. 7 represents the fault classifier output as a function of time for a double-phase fault without ground (a-b).

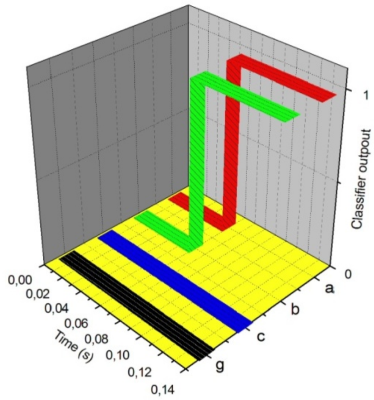

Fig. 7: Fault classifier output for the single-phase to ground fault in the phase "a".

The fault classifier indicates that the phase "c" and the ground are always zero, which implies that it is a double-phasefault (a-b). The fault is classified on phase "a" at time 0.061 sec. and on phase "b" at time 0.062 sec. so the fault classification time is equal to 0.062 sec, it's late by 2 ms.

Fig. 8 represents the fault classifier output as a function of time for a double-phase fault with-ground (a-c-g).

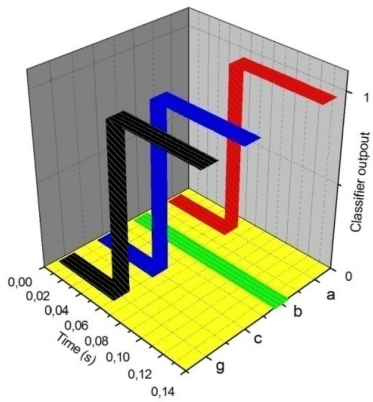

Fig. 8: Fault classifier output forthe double-phases fault with ground in the phases 'a', 'c' and the ground.

The fault classifier indicates that phase "b" is always zero, which implies that it is a double-phaseto ground fault (a-c-g). The fault is classified on phase "a" at time 0.063 sec. and on phase "c" and the ground at time 0.062 sec. so the fault classification time is equal to 0.063 sec, it's late by 3 ms.

Fig. 9 represents the fault classifier output as a function of time for a three-phase fault (a-b-c).

The fault classifier indicates that the phases "a", "b" and "c" vary from "0" to "1" so we can conclude that it is a three-phase fault. The fault is classified on the phase "b" at the instant 0.061 sec. and the phases "a" and "c" at the instants 0.062 sec. so the fault classification time is equal

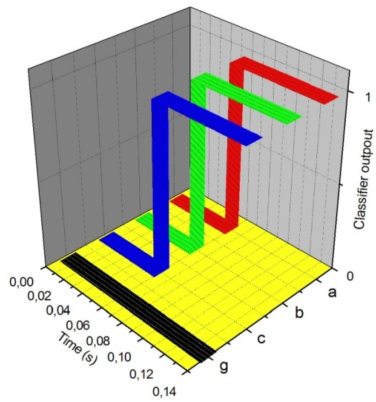

Fig. 9: Fault classifier output forthe three-phase fault'a', 'b', and 'c'.

to 0.062 sec, it's late by 2 ms.

According to the tests studied we note that faults without ground are classified faster than faults with ground.

4.3. Fault localization

The fault is supposed appears at the end of each section that is to say at 5 km, 10 km, 15 km and 20 km of the distribution line.

Fig. 10 shows the fault location as a function of time using the reactance for single-phase to ground.

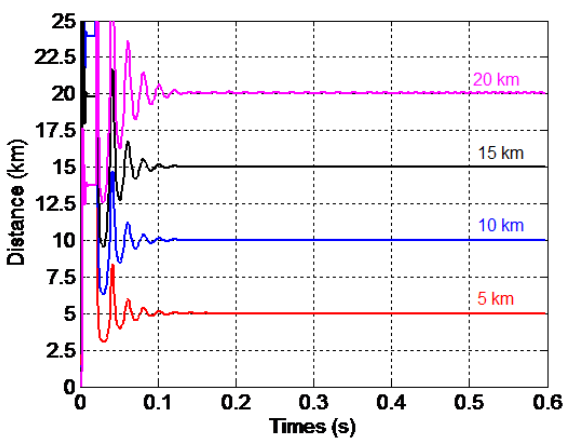

Fig. 10: Fault location as function of time using the reactance for single-phase to ground.

From Fig. 10 we can see a stability in the response and the distance is detected rapidly, it is clear that the final value of the fault locator is the same value of the supposed fault distance.

Figure 11 shows the fault location as a function of time using the reactance for double-phase fault with ground.

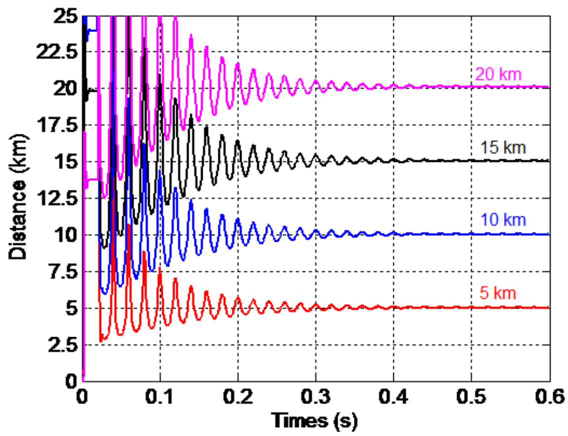

Fig. 11: Fault location as function of time using the reactance for double-phase fault with ground.

Figure 12 shows the fault location as a function of time using the reactance for double-phase fault without ground.

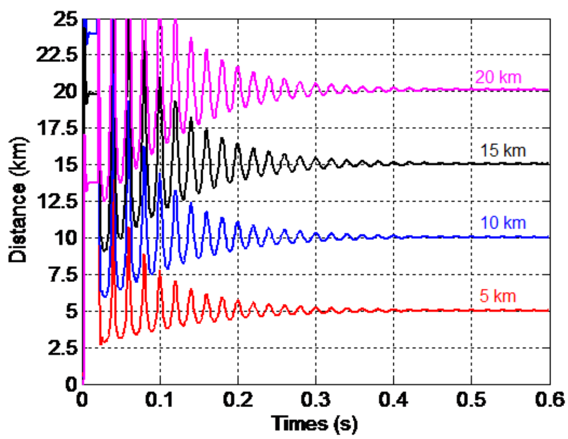

Fig. 12: Fault location as function of time using the reactance for double-phase fault without ground.

From Fig. 11 and Fig. 12, we can see an instability in the response and the distance is not detected rapidly, we can see that the final value oscillates around the final value of the supposed fault distance.

Note: the three-phase fault gives us the same results as the double-phase fault with ground.

However, the fault location estimative is affected by many parameters, including fault resistance RF, which may be high for ground faults. In this study we have noted that the maximum value of fault resistance that can be accepted by the proposed technique is 8 Ω for all fault type and at each section.

5. CONCLUSIONS

A method of two samples was presented in this paper to detect, classify and localize the fault in the distribution networkwith function of time.The method can be used by numerical relay.The fault detection by the voltage gives a faster response instead of the current. In addition, that faults without ground are classified faster than faults with ground. Concerning the fault locator, for single phase to ground fault, there is stability in the response and the distance is detected rapidly. The distance is determined after 100 ms. For multiphase fault, the fault locator takes some time to the approximate the final value, the response isunstable and the distance is not detected rapidly, but the distance is determined after 400 ms.

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