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Extension of the Accurate Voltage-Sag Fault Location Method in Electrical Power Distribution Systems

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Accurate Fault location in an Electric Power Distribution System (EPDS) is important in maintaining system reliability. Several methods have been proposed in the past. However, the performances of these methods either show to be inefficient or are a function of the fault type (Fault Classification), because they require the use of an appropriate algorithm for each fault type. In contrast to traditional approaches, an accurate impedance-based Fault Location (FL) method is presented in this paper. It is based on the voltage-sag calculation between two measurement points chosen carefully from the available strategic measurement points of the line, network topology and current measurements at substation. The effectiveness and the accuracy of the proposed technique are demonstrated for different fault types using a radial power flow system. The test results are achieved from the numerical simulation using the data of a distribution line recognized in the literature.

Keywords: Available Strategic Measurement Points, Electric Power Distribution Systems, Fault location, Fault Classification, Voltage-Sag.

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1. Introduction

Power distribution systems play important roles in modern society. When distribution system outages occur, speedy and precise fault location is crucial in accelerating system restoration, reducing outage time and significantly improving system reliability, and thus improving the quality of services and customer satisfaction. Nevertheless, Owing to the expansion of distribution networks, to their radial topology and to the existence of short and heterogeneous lines and of intermediate loads, it is very difficult and complicated to locate the fault in these networks.

In the past, various fault location algorithms have been developed. Novosel et al. (1998) make use of apparent impedance, defined as the ratio of selected voltage to current based on fault type and faulted phases, to locate faults in [1]. In [2], Das (1998) locates the faulted section and next the distance to the fault in this section is calculated. Yang and Springs (1998) propose a fault location method which corrects the fault resistance effects in [3]. The method proposed by Das et al. (2000) in [4] used the fundamental frequency voltages and currents measured at a line terminal before and during the fault. In [5] the method proposed by Saha and Rosolowski (2002) estimates the fault location by comparing the measured impedance with the calculate feeder impedance assuming faults each section line. Choi et al. (2004) locating faults by solving a quadratic equation resulting from the direct circuit analysis in [6]. Senger et al. (2005) in [7] proposed a method which was based on measurement provided by intelligent electronics Devices (IEDs). In [8] Kim et al. (2007) estimated fault location on distribution feeders using Power Quality monitoring data. A way to optimally place faulted circuit indicators along the feeder is developed in [9] by Almeida

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et al. (2011). Methods to reduce and eliminate the uncertainty about the fault location are discussed by authors of [10, 11] (2012). In [12], Sadeh et al. (2013) suggested a new algorithm for radial distribution systems using modal analysis. Wanjing et al. presented a novel method based on two types of fault location approaches using line to neutral or line to line measurement at substation in [13] (2014). In [14], Zahri et al. (2014) proposed a new hybrid method based on ANN and Apparent impedance calculation to determinate the Faulty section of line. A reduced algorithm for fault location in EPDS is suggested by Zahri et al, in [15] (2015), utilizing voltages and currents measurement only at the sub-station as input data to calculate the fault current, and therefore, avoid the iterative aspect of the classic algorithm for single line to ground fault location and reduce its computational charge.

According to literature review, it is shown that existing fault location methods either show inefficiency which hinders their practical implementation and their industrial use, or require the use of an appropriate computation in function of fault type which demands an extra computational charge for the fault classification.

Considering the limitation mentioned previously, in this paper, an accurate impedance-based Fault Location (FL) technique is presented. It is an independent method from the fault classification, based on the voltage-sag calculation between two measurement points chosen carefully from the available strategic measurement points of the line, the network topology, and current measurements at substation. The effectiveness of the proposed technique is demonstrated for different types of fault using a radial power flow system. The test results are achieved from the numerical simulation using the data of a distribution line recognized in the literature. A comparison is performed between the proposed method and a classic iterative technique in order to prove its accuracy.

The rest of this paper is organized as follows: The New Single Line to Ground (SLG) Fault Location Formulation and Proposed Extension are presented in sections 2 and 3 respectively. In section 4, the Fault Location algorithm is illustrated. The test results are shown in Section 5, whereas the conclusions of this work are presented in Section 6.

2. The New SLG Fault Location Formulation

In order to determinate the Single-Line to Ground (SLG) Fault Location, the following mathematical development is performed using a simplified modeling of a distribution network illustrated in figure.1. The fault location is computed using the calculated voltage-sag between two measurement points, esteemed fault current and line parameters.

2.1. Case of One Section of Line

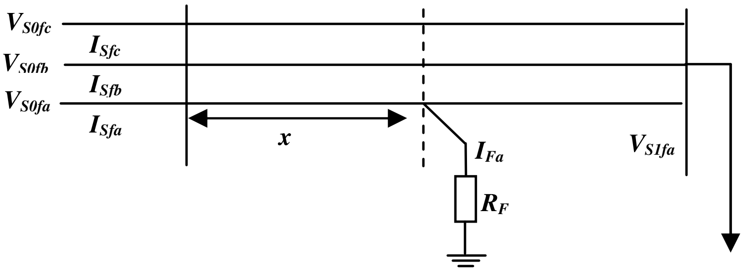


Fig.1. During-fault one section distribution line modeling

$I_{Sf\,a,b,c,}$	*Phase a, b and c Sending-end current during the fault;*
$V_{S0fa,b,c}$	*Phase a, b and c Sending-end voltage during the fault;*
$V_{S1fa,b,c}$	*Phase a, b and c Voltage at the end of the line during the fault;*
I_{Fa}	*Phase a fault current;*
l_0	*Line length;*
Z_0	*Line impedance Matrix;*
x	*Fault Distance;*
Z_{ii}	*Self impedance;*
Zij	*Mutual impedance.*

Referring to figure.1, the following equations can be obtained:

$$V_{Sof} - V_{S1f} = x \cdot Z_o \cdot (I_{Sf}) + (l_o - x) \cdot Z_o \cdot (I_{Sf} - I_F) \tag{1}$$

$$V_{Sof} - V_{S1f} = x \cdot Z_o \cdot I_F + l_o \cdot Z_o \cdot (I_{Sf} - I_F) \tag{2}$$

$$x \cdot Z_o \cdot I_F = V_{Sof} - V_{S1f} - l_o \cdot Z_o \cdot (I_{Sf} - I_F) \tag{3}$$

For a SLG fault, the fault current is:

$$I_F = \begin{bmatrix} I_{Fa} \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

The equation (5) is then obtained:

$$x \cdot Z_o \cdot \begin{bmatrix} I_{Fa} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} V_{Sofa} \\ V_{Sofb} \\ V_{Sofc} \end{bmatrix} - \begin{bmatrix} V_{S1fa} \\ V_{S1fb} \\ V_{S1fc} \end{bmatrix} - l_o \cdot Z_o \cdot \left(\begin{bmatrix} I_{Sfa} \\ I_{Sfb} \\ I_{Sfc} \end{bmatrix} - \begin{bmatrix} I_{Fa} \\ 0 \\ 0 \end{bmatrix} \right) \tag{5}$$

The fault distance can be estimated by (6):

$$x = \frac{V_{Sofa} - V_{S1fa} - l_o \cdot Z_{oa} \cdot (I_{Sfa} - I_{Fa})}{Z_{oa} \cdot I_{Fa}} \tag{6}$$

It is possible to obtain from (6) the fault distance from the parameters of the system: the sending-end pre-fault current, and the voltage-sag between the sending-end point and a second measurement point during the fault.

2.2. Case of Multi-Sections of Line

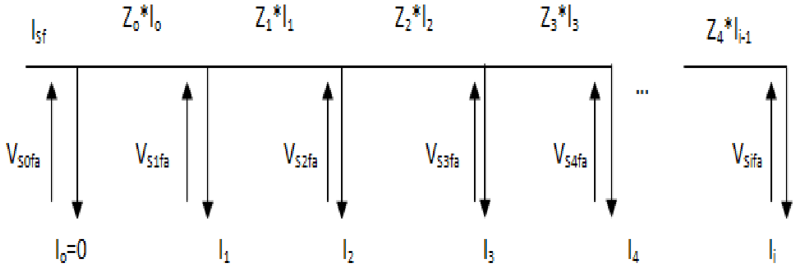


Fig.2. During-fault Simplified distribution network modeling

i. Fault in the first Section of Line

$$V_{Sofa} - V_{S1fa} = \mathrm{x} \cdot Z_o \cdot I_{Fa} + Z_o \cdot \mathrm{l}_o \cdot (I_{Sfa} - I_{Fa}) \tag{7}$$

$$V_{S1fa} - V_{S2fa} = Z_1 \cdot \mathrm{l}_1 \cdot \left(I_{Sfa} - I_{Fa} - I_1\right) = Z_1 \cdot \mathrm{l}_1 \cdot (I_{Sfa} - I_{Fa} - I_1) \tag{8}$$

$$V_{S2fa} - V_{S3fa} = Z_2 \cdot \mathrm{l}_2 \cdot \left(I_{Sfa} - I_{Fa} - I_1 - I_2\right) = Z_2 \cdot \mathrm{l}_2 \cdot (I_{Sfa} - I_{Fa} - I_1 - I_2) \tag{9}$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$V_{Si-1fa} - V_{Sifa} = Z_{i-1} \cdot \mathrm{l}_{i-1} \cdot \left(I_{Sfa} - I_{Fa} - I_1 - I_2 - \cdots - I_{i-1}\right) \tag{10}$$

By the summation of the equations terms, equation (11) is obtained:

$$V_{Sofa} - V_{Sifa} = I_{sfa} \textstyle\sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k - \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k \cdot \sum_{i=1}^{k-1} I_j - I_{Fa} \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k + \mathbf{x} \cdot \boldsymbol{Z_o} \cdot \boldsymbol{I_{Fa}} \tag{11}$$

ii. Fault in the second Section of Line

$$V_{Sofa} - V_{S1fa} = l_o \cdot Z_o \cdot \left(I_{Sfa} - I_{Fa}\right) = Z_o \cdot \mathrm{l}_o \cdot \left(I_{Sfa} - I_o - I_{Fa}\right) + l_o \cdot Z_o \cdot I_{Fa} \tag{12}$$

$$V_{S1fa} - V_{S2fa} = Z_1 \cdot \mathrm{l}_1 \cdot \left(I_{Sfa} - I_1 - I_{Fa}\right) + x \cdot Z_1 \cdot I_{Fa} \tag{13}$$

$$V_{S2fa} - V_{S3fa} = Z_2 \cdot \mathrm{l}_2 \cdot \left(I_{Sfa} - I_1 - I_{Fa} - I_2\right) \tag{14}$$

$$\vdots \qquad \vdots \qquad \vdots$$

$$V_{Si-1fa} - V_{Sifa} = Z_{i-1} \cdot \mathrm{l}_{i-1} \cdot \left(I_{Sfa} - I_1 - I_2 - \cdots - I_{Fa} - I_{i-1}\right) \tag{15}$$

As for (11), the summation of (12), (13), (14) and (15) allow to obtain the equation (16):

$$V_{Sofa} - V_{Sifa} = I_{sfa} \textstyle\sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k - \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k \cdot \sum_{i=1}^{k-1} I_j - I_F \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k + \boldsymbol{l_o} \cdot \boldsymbol{Z_o} \cdot \boldsymbol{I_{Fa}} + \mathbf{x} \cdot \boldsymbol{Z1} \cdot \boldsymbol{IFa} \tag{16}$$

iii. *Fault in the third Section of Line*

$$V_{Sofa} - V_{Sifa} = I_{sfa} \textstyle\sum_{k=0}^{i-1} Z_k \cdot l_k - \sum_{k=0}^{i-1} Z_k \cdot l_k \cdot \sum_{i=1}^{k-1} I_j - I_{Fa} \sum_{k=0}^{i-1} Z_k \cdot l_k + \boldsymbol{l_o} \cdot \boldsymbol{Z_o} \cdot \boldsymbol{IFa} + \boldsymbol{l1} \cdot \boldsymbol{Z1} \cdot \boldsymbol{IFa} + \boldsymbol{x} \cdot \boldsymbol{Z2} \cdot \boldsymbol{IFa} \tag{17}$$

From equations (11), (16) et (17), It can be seen that the bold terms are function of the fault distance in each case, in reel electric networks, lines are generally of the same nature, thus, the impedances per length unit are identical (Z_o=Z_1=Z_2=Z), the relations (11), (16) et (17) become then:

$$V_{Sofa} - V_{Sifa} = I_{sfa} \textstyle\sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k - \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k \cdot \sum_{i=1}^{k-1} I_j - I_{Fa} \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k + \boldsymbol{x} \cdot \boldsymbol{Z_o} \cdot \boldsymbol{I_{Fa}} \tag{18}$$

$$V_{So} - V_{Si} = I_s \textstyle\sum_{k=0}^{i-1} Z_k \cdot l_k - \sum_{k=0}^{i-1} Z_k \cdot l_k \cdot \sum_{i=1}^{k-1} I_j - I_F \sum_{k=0}^{i-1} Z_k \cdot l_k + (\boldsymbol{l_o} + \boldsymbol{x}) \cdot \boldsymbol{Z_o} \cdot \boldsymbol{I_F} \tag{19}$$

$$V_{Sofa} - V_{Sifa} = I_{sfa} \textstyle\sum_{k=0}^{i-1} Z_k \cdot l_k - \sum_{k=0}^{i-1} Z_k \cdot l_k \cdot \sum_{i=1}^{k-1} I_j - I_{Fa} \sum_{k=0}^{i-1} Z_k \cdot l_k + (\boldsymbol{l_o} + \boldsymbol{l1} + \boldsymbol{x}) \cdot \boldsymbol{Zo} \cdot \boldsymbol{IFa} \tag{20}$$

Considering

$$A = I_{sfa} \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k - \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k \cdot \sum_{i=1}^{k-1} I_j - I_{Fa} \sum_{k=0}^{i-1} Z_k \cdot \mathrm{l}_k \qquad (21)$$

And

$$B = V_{Sofa} - V_{Sifa} \qquad (22)$$

The fault distance x is obtained then by equation (23):

$$x = \frac{A-B}{Z_o \cdot I_{Fa}} \qquad (23)$$

3. Proposed Extension

The fault location method described in Section 2 was already exanimated in a previous work. This method, however, was proposed only for SLG faults, which limits its practical application. The application of the proposed fault location formulation to all remaining fault types (Double Line to Ground ‘DLG’, Line to Line ‘LL’, Three Phase to Ground ‘TPG’) is proposed as an extension of the method in this paper. The fault location algorithm remains the same. Also, the equations used for all fault type are the same, which allow avoiding the use of a fault classification algorithm.

All fault types can be illustrated in the general fault modeling presented in figure.3.

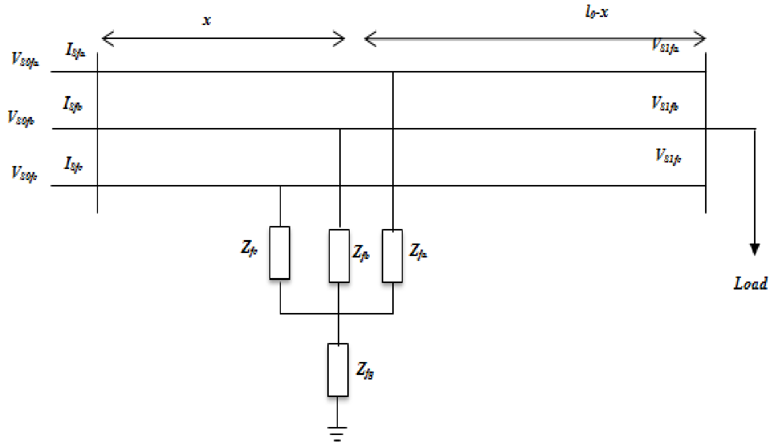


Fig.3. General fault modeling.

Referring to figure.3, the following equations can be obtained:

$$V_{Sof} - V_{S1f} = x \cdot Z_o \cdot \left(I_{Sf}\right) + (l_o - x) \cdot Z_o \cdot \left(I_{Sf} - I_F\right) \qquad (24)$$

$$V_{Sof} - V_{S1f} = x \cdot Z_o \cdot I_F + l_o \cdot Z_o \cdot (I_{Sf} - I_F) \qquad (25)$$

$$x \cdot Z_o \cdot I_F = V_{Sof} - V_{S1f} - l_o \cdot Z_o \cdot (I_{Sf} - I_F) \qquad (26)$$

For a general case of fault, the fault current is:

$$I_F = \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} \qquad (27)$$

The equation (28) is then obtained:

$$x \cdot Z_o \cdot \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} = \begin{bmatrix} V_{S0fa} \\ V_{S0fb} \\ V_{S0fc} \end{bmatrix} - \begin{bmatrix} V_{S1fa} \\ V_{S1fb} \\ V_{S1fc} \end{bmatrix} - l_o \cdot Z_o \cdot \left(\begin{bmatrix} I_{Sfa} \\ I_{Sfb} \\ I_{Sfc} \end{bmatrix} - \begin{bmatrix} I_{Fa} \\ I_{Fb} \\ I_{Fc} \end{bmatrix} \right) \tag{28}$$

The fault distance x is obtained then by equation (29):

$$\boldsymbol{x} = \frac{\boldsymbol{A-B}}{\boldsymbol{Z_o \cdot I_F}} \tag{29}$$

4. Fault location algorithm

After the detection of the fault, the FL process is initialized. First, the system is divided into n branches, where n is the number of possible paths (end nodes). For each branch, the following procedure for determining the faulty location is started:

i. Voltage measurement on two points of the line;

ii. Voltage drop calculation between the two points;

iii. The load current during the fault period is different from the pre-fault load current, due to voltage drops and systems dynamics during the fault. For this reason, load current during the fault I_{La} is assumed to be the same as the pre-fault load current, thus, the fault current is calculated using (30):

$$I_F = I_{Sf} - I_S \tag{30}$$

With I_S is the sending-end pre-fault current.

iv. The fault distance is estimated using equation (29).

The Fault location algorithm is then illustrated in figure.4:

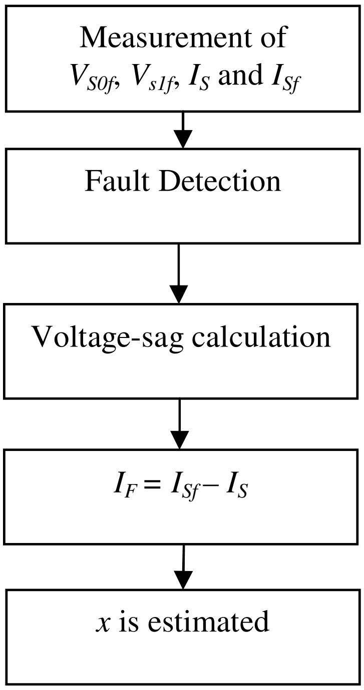


Fig.4. Fault location algorithm for each branch of the total line

5. Tests and results

5.1. Simulated System

The system studied, as shown in the figure.5, is a part of the underground distribution network, it is a line from 20 KV distribution network of total length 22.5 Km, composed of 6 sections of different lengths, simulated using distributed parameter line model as shown in Table 1.

Using Matlab [16] as simulation tool, a total of 26 fault cases is simulated at different FL between 0-100%, for different fault resistances (0.001, 10, 20, 50 and 100 Ω).

Table1. Studied Sections of lines Parameters

Input voltages [KV]	V_S=11.547, U=20
Rf [Ohms]	0.001; 10; 20; 50 and 100
Line impedance [Ohms/Km]	Z_1=0.56+j0.831, Z_0=0.845+j2.742
Line section length[Km]	l_1=2.4 ; l_2=4; l_3=4; l_4=4; l_5=4.1; l_6=4 ;

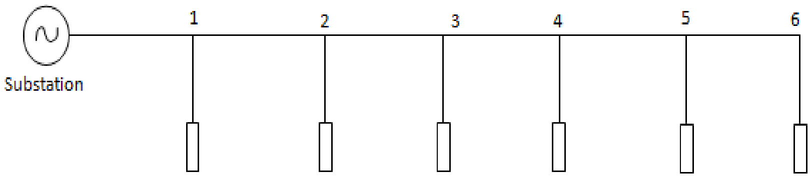


Fig.5. Simulated System without DG.

5.2. Results:

The proposed technique is extensively tested to verify its effectiveness and accuracy, the performances of fault location algorithms are usually measured by the errors on the fault distance:

$$err\,(\%) = \left| \frac{x(actual\;) - x(estimated\;\;)}{l} \right| \tag{31}$$

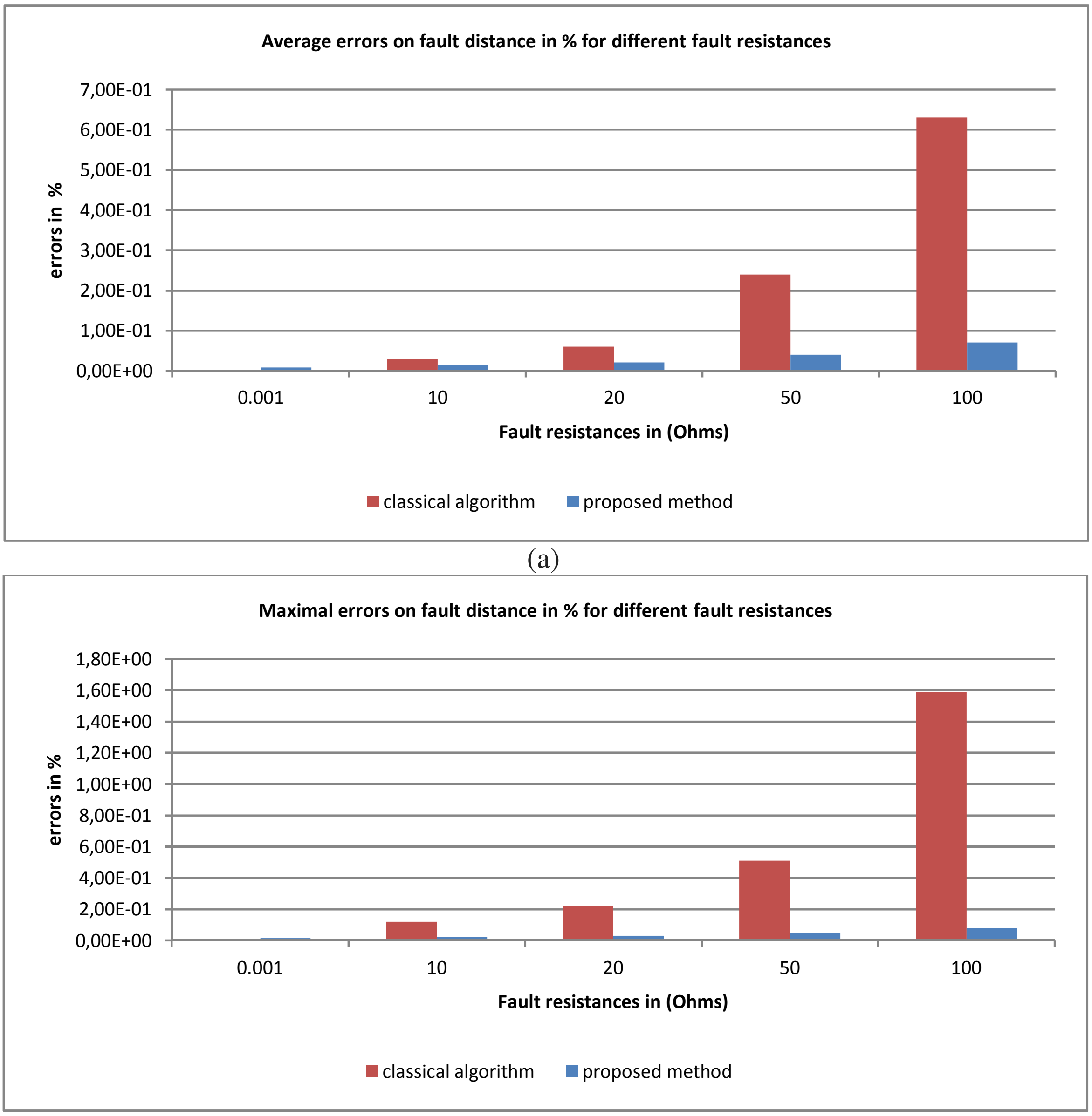
Where

x(estimated): estimated fault distance (in Km);
x(actual): real fault distance (in Km);
l : total line length (in Km).

Figures 6, 7, 8 and 9 illustrate some obtained test results for different fault types (Double Line to Ground ‘DLG’, Line to Line ‘LL’, Three Phase to Ground ‘TPG’), different location between 0 and 100% of the line and for different fault resistances (R_f = 0.001; 10; 20; 50 and 100 Ω). The obtained results show a comparison between the performances of the proposed technique and the classical iterative algorithm recognized in the literature [17]. The blue bar graph presents the errors on the fault distance using the new Fault location algorithm for the system simulated. The brown tracks the errors on fault distance using the classical iterative algorithm.

According to Figure 6, a significant difference appears between performances of the new technique and the iterative one, the average errors obtained by the proposed algorithm increase from “0.008 %” to “0.07 %” with the increment of the fault resistance. However, the increasing of the iterative algorithm is between “0.00 %” and “0.63 %”. In addition, it is evident that the errors on fault distance obtained here are in exceptionally good agreement with those obtained using the classical iterative algorithm in term of increasing of the average errors between the low and the high fault resistance caused by the effect of the fault resistance.

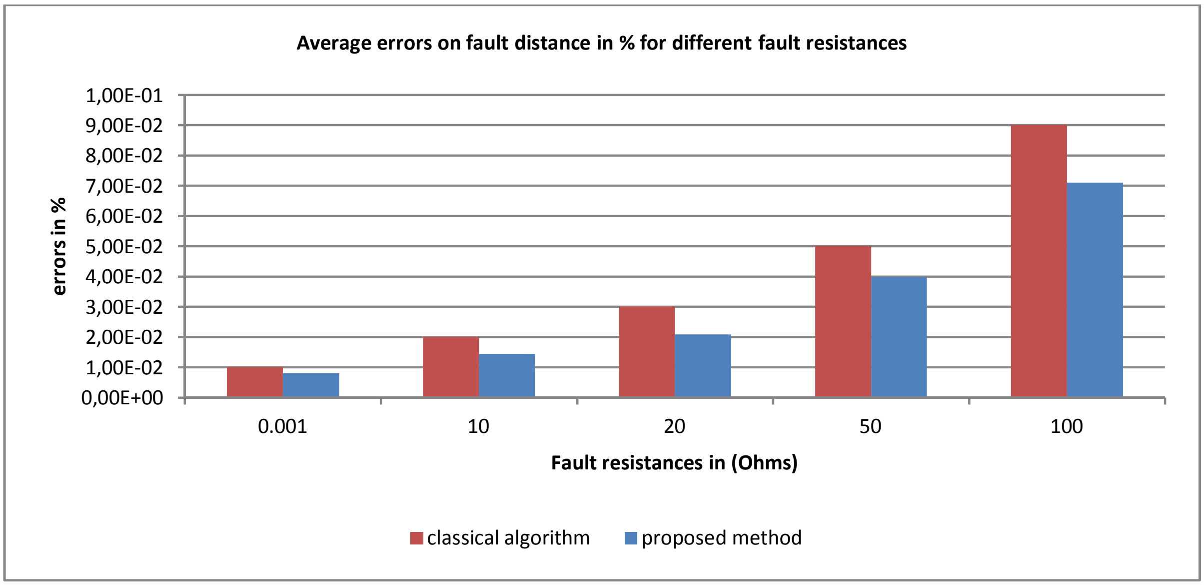
As seen on Figures.7, 8 and 9, the maximal errors obtained by the proposed algorithm are lower than those obtained by the classical iterative one. This reinforces and validates the proposition of the figure.6.



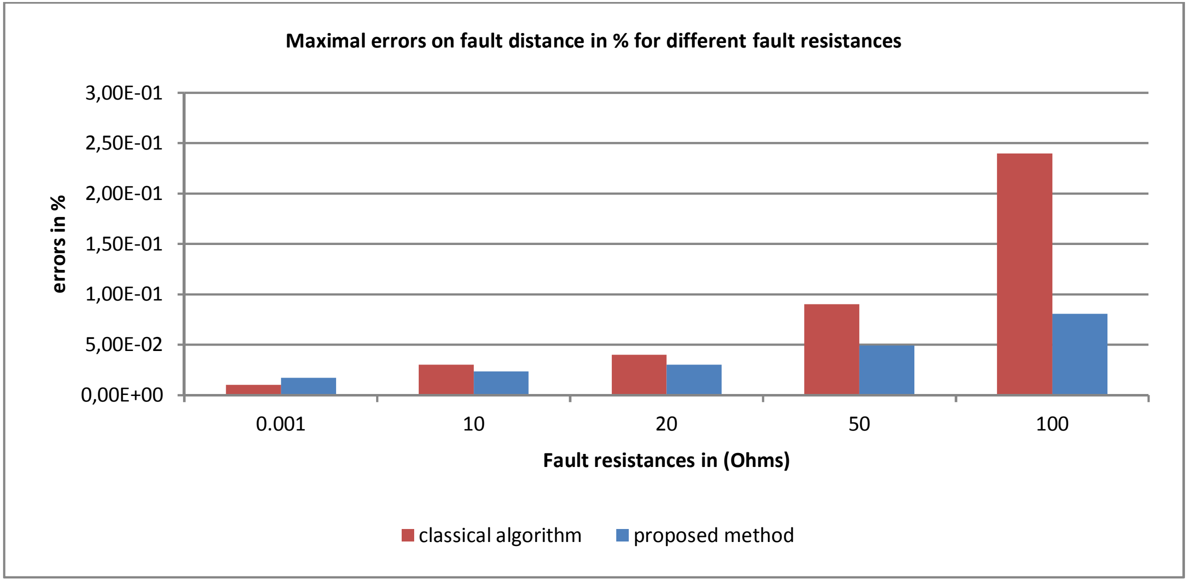
(a)

(b)

Fig.6. SLG faults.

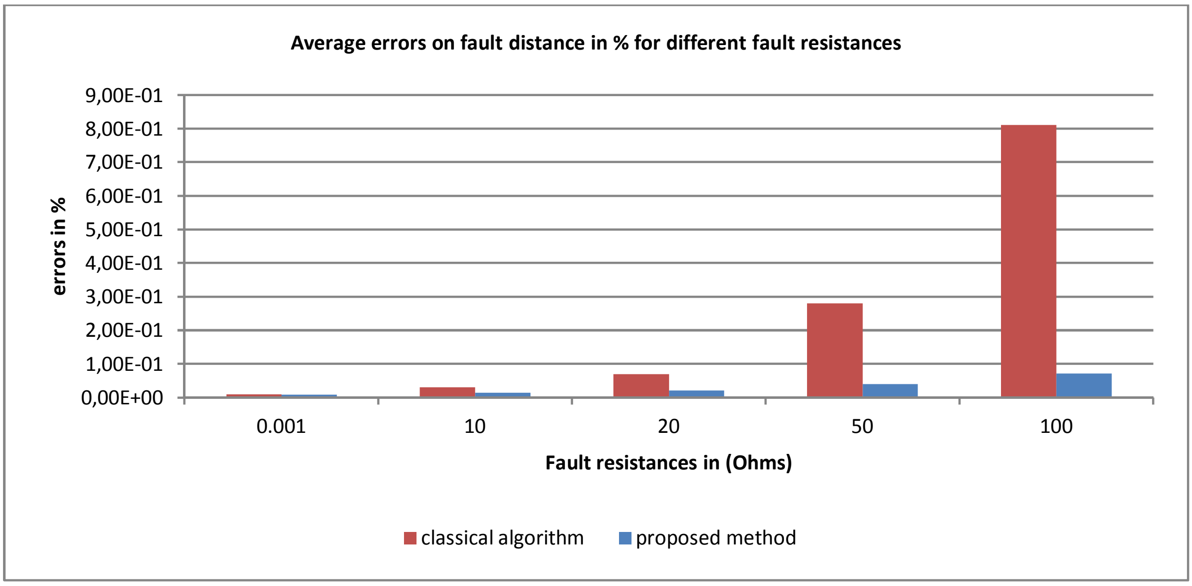


(a)

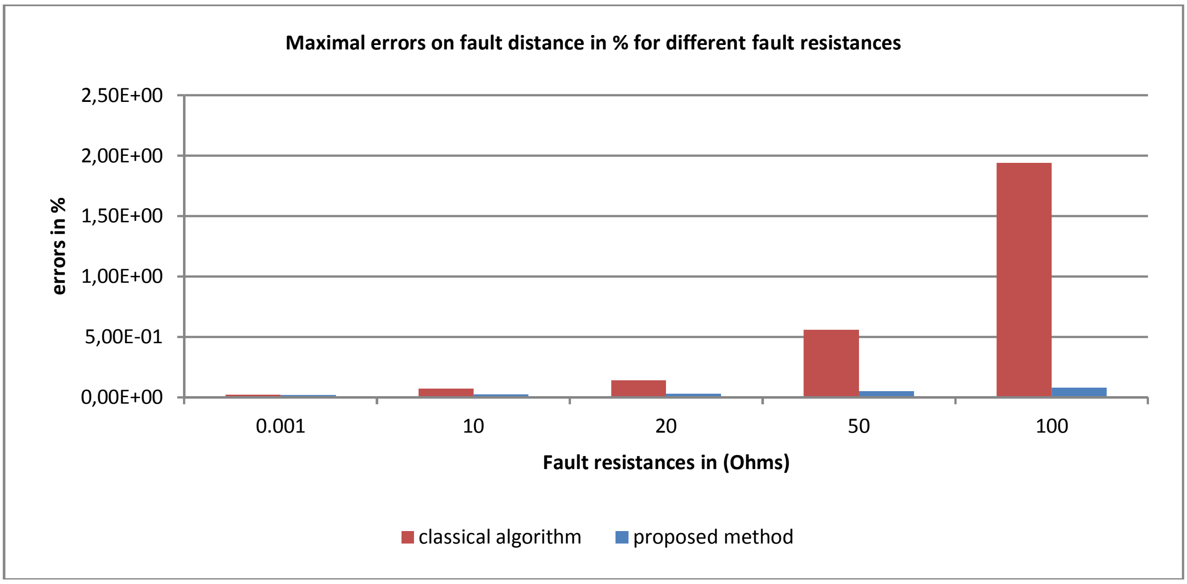


(b)

Fig.7. Line to Line (LL) Faults.



(a)



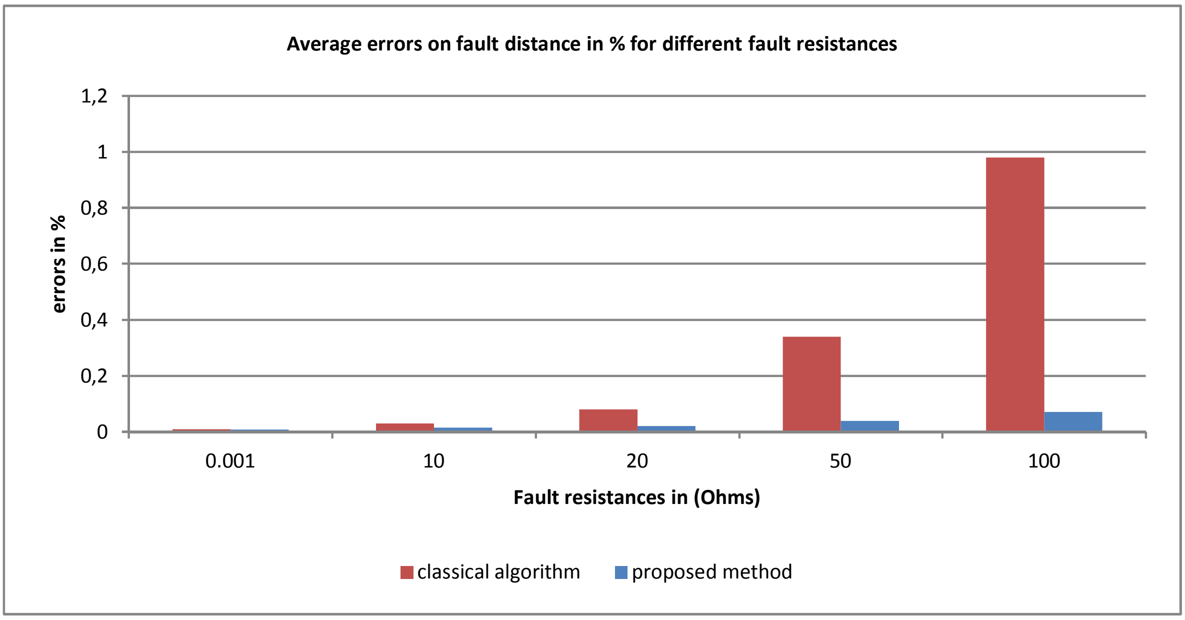
(b)

Fig.8. DLG Faults.

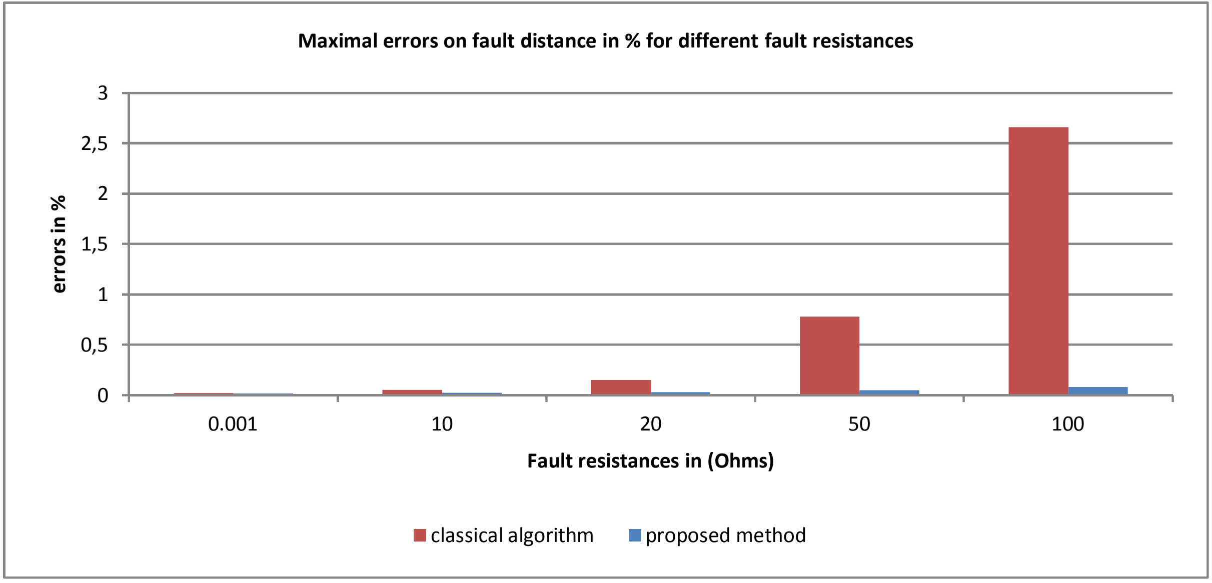
5.3. Discussions:

Prior works have documented different impedance-Based Fault Location methods. The review of these works either show inefficiency which hinders their practical implementation and their industrial use, or require the use of an appropriate computation in function of fault type which demands an extra computational charge for the fault classification. After the study of a new accurate SLG fault location method in EPDS based on voltage-sag calculation between two measurement points and network parameters, this paper presents an extension of the previous technique for the other types of faults.

We found that errors obtained using the new technique are significantly lower than those obtained using other methods. This is validated by the comparison performed between the new algorithm and the classical iterative one for all fault types. These findings demonstrate the accuracy and the effectiveness of the new method without necessity of a classification algorithm, and encourage studying its practical implementation.



(a)



(b)

Fig.9. TPG Faults.

6. Conclusion

An extension of the new accurate technique to estimate the fault location for Electrical Power Distribution Systems has been presented in this paper. Voltage-sag calculation between two measurement points which have been chosen carefully from the available strategic measurement points of the line, the network topology and current measurements at substation are utilized to estimate the fault distance. Most of the FL techniques found in the literature are either inefficient which hinder their practical implementation and their industrial use, or in need of the use of an appropriate computation in function of fault type which demands an extra computational charge for the fault classification.

The performances of this technique are verified by several tests simulating 26 cases of single phase to ground faults for different fault resistances.

Simulation results and mathematical formulation show that the proposed fault location algorithm is suitable to be used in EPDS thanks to its simplicity, accuracy and robust effectiveness.

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