An Extended Fault Location Formulation for Unbalanced Distribution Feeders with Distributed Generation

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***Abstract*— This paper presents an extended impedance-based formulation for fault location on deregulated electric power distribution systems. Distribution feeders are inherently unbalanced and traditionally radial. Deregulated distribution systems can have distributed generation, which changes the fault period power flow and decreases the accuracy of current state-of-the-art impedance based fault location formulations. Therefore, in this paper an extended impedance-based formulation is proposed. The work includes the formulation analytical development as simulation test results. Comparative test results are also presented, highlighting the formulations increased accuracy compared with current impedance-based fault location techniques.**

Keywords- Distributed generation; Electric power distribution systems; Fault location.

I. Introduction

Fault location estimation is an important aspect in power systems restoration. This estimate helps to reduce the time spent by the maintenance teams to locate the defect and therefore improves power quality indexes. Currently, the fault location methods presented consider the distribution system radial, not taking into account the effect of distributed generation (DG) [1]-[4]. With of the DG insertion on electric power distribution systems (EPDS), distribution networks are transformed to a non-radial power flow and therefore affecting the coordination and setting of protection equipment [5]-[6]. The current algorithms for fault location, in general, have as input the fault current, which is modified by the presence of generators at EPDS, as described in [6]. Thus, new methods must be developed to eliminate the errors inherent in traditional fault location methods, caused by the insertion points of generation in the systems. Recently, a extended fault location method to EPDS with the DG was proposed [7]. This method, however, is based on the positive apparent sequence impedance, used for balanced systems. This technique has limited performance when applied un unbalanced distribution systems. Furthermore, the methodology was developed only for three-phase short circuits, and should be extended to other fault types, especially for line-to-ground faults, which are the most frequent case in aerial distribution systems. Given the limitations described in the existing methodologies, this paper proposes the development of a novel fault location formulation based on the work of [7], extending it to line-to-ground faults and considering unbalanced systems. The proposed work represents the EPDS on phase coordinates. Three-phase power flow based on the Ladder technique, in order to determine the pre-fault conditions (voltages and currents) [8] is also used. The formulation was implemented on Matlab environment [9] and tested using simulated EPDS data using ATP/EMTP software [10]. This paper is structured as follows: Section II describes the state-of-the-art impedance fault location formulation; Section III discusses the proposed extensions; a case study is presented in Section IV; Sections V and VI present the test results and the work conclusions, respectively.

II. Fault Location in Distribution Systems

Consider the distribution system subject to line-*a*-to-ground fault, as illustrated in Fig.1.

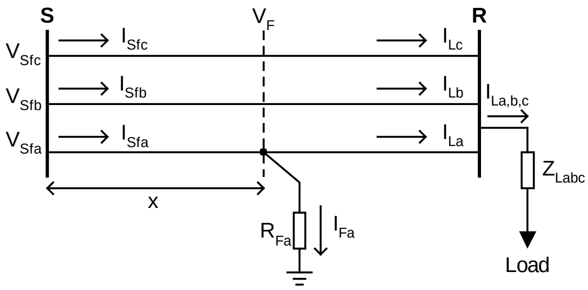

Figure 1. Line-*a*-to-ground fault.

The fault distance estimate depends of the voltage and currents three-phase components obtained from the local end S, configuration of feeders and system loads data. The relationship between the voltages and currents at the local end and the voltages at the fault point can be obtained from (1):

$$\begin{bmatrix} V_{Sfa} \\ V_{Sfb} \\ V_{Sfc} \end{bmatrix} = x \cdot \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} I_{Sfa} \\ I_{Sfb} \\ I_{Sfc} \end{bmatrix} + \begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix} \quad (1)$$

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To a fault line-*a*-to-ground, the equation of the voltage at the local end is obtained by (2):

$$V_{Sfa} = x \cdot (Z_{aa} \cdot I_{Sfa} + Z_{ab} \cdot I_{Sfb} + Z_{ac} \cdot I_{Sfc}) + I_{Fa} \cdot R_{Fa} \quad (2)$$

where:

V_{Sfa}	Phase *a* terminal *S* voltage
$I_{Sfa(bc)}$	Phase *a* (*b*, *c*) terminal *S* current
Z_{aa}	Phase *a* self impedance [Ω/m]
Z_{ab}, Z_{ac}	Phase *a* and *b*(*c*) mutual impedance [Ω/m]
R_{Fa}	Phase *a* fault resistance
I_{Fa}	Phase *a* fault current
V_{Fa}	Phase *a* fault point voltage
x	Fault distance (m)

The load current is considered equal to the current pre-fault on the terminal S, as (3):

$$I_{La} = I_{Sa} \quad (3)$$

Therefore, the fault current is obtained by the difference between the terminal S current and the load current through (4):

$$I_{Fa} = I_{Sfa} - I_{La} \quad (4)$$

Since the fault current is calculated, the initial value of the distance from the fault can be determined. Decomposing (2) in real and imaginary components, we obtain a system of two equations and two unknowns, being the unknown distance and fault resistance, as (5)-(6):

$$V_{Sfa(r)} = x \cdot M + R_{Fa} \cdot I_{Fa(r)} \quad (5)$$

$$V_{Sfa(i)} = x \cdot N + R_{Fa} \cdot I_{Fa(i)} \quad (6)$$

The two equations are placed in the matrix form and fault distance is obtained by (7):

$$\begin{bmatrix} V_{Sfa(r)} \\ V_{Sfa(i)} \end{bmatrix} = \begin{bmatrix} M & I_{Fa(r)} \\ N & I_{Fa(i)} \end{bmatrix} \cdot \begin{bmatrix} x \\ R_{Fa} \end{bmatrix}$$

$$x = \frac{V_{Sfa(r)} \cdot I_{Fa(i)} - V_{Sfa(i)} \cdot I_{Fa(r)}}{M \cdot I_{Fa(i)} - N \cdot I_{Fa(r)}} \quad (7)$$

where the components (r) and (i) represent respectively the real and imaginary components of voltage and current phasors and M and N represent respectively the real and imaginary components of line parameters, which are obtained by (8)-(9):

$$M = \sum_{k=\{a,b,c\}} \left[Z_{ak(r)} \cdot I_{Sf_{k(r)}} - Z_{ak(i)} \cdot I_{Sf_{k(i)}} \right] \quad (8)$$

$$N = \sum_{k=\{a,b,c\}} \left[Z_{ak(r)} \cdot I_{Sf_{k(i)}} + Z_{ak(i)} \cdot I_{Sf_{k(r)}} \right] \quad (9)$$

The fault distance obtained by (7) is a function of fault current, which is dependent on the load current, as (4). To estimate the load current an iterative algorithm is used [1]-[4].

III. Proposed Fault Location Method

With the inclusion of DG in EPDS, the fault current will be modified by injection of current from the generator at the fault moment, causing an error in fault location. In this case, let us consider the distribution system with DG, illustrated in Fig. 2.

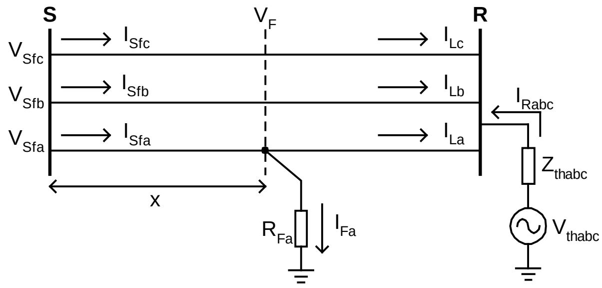

Figure 2. Line-*a*-to-ground fault, at upstream of DG.

The fault location equation for line-*a*-to-ground faults, shown in Section II, is still used in the proposed extension. The main extension in the new formulation is in the update of the three-phase load current to faults that occur upstream of DG. In these cases, it is necessary to consider the contribution of power from the remote end of the faulted section [7]. Thus, the faulted system is represented by a equivalent load Z_{th}, and an equivalent source V_{th}, both located at the remote end of the fault, as illustrated in Fig. 2. The algorithm starts considering the possibility of fault occurrence at the beginning of the feeder, in the first section of line after the substation bus, as follows:

I. Initially it is assumed that the load current is equal to the current in the pre-fault period, according to (3).

II. Estimate a fault current using equation (4).

III. Calculate the initial estimative of the fault distance, using equation (7).

IV. Once estimated the distance, is made the analysis of convergence of the algorithm, by equation (10):

$$[x(n) - x(n-1)] < 0.0001 * L \quad (10)$$

where *n* represents the number of iterations and *L* is the length of line section analyzed.

V. The three-phase voltages at the fault point are determined by equation (11):

$$\begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix} = \begin{bmatrix} V_{Sfa} \\ V_{Sfb} \\ V_{Sfc} \end{bmatrix} - x \cdot \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} I_{Sfa} \\ I_{Sfb} \\ I_{Sfc} \end{bmatrix}. \quad (11)$$

VI. With the three-phase voltages at the fault point, obtained in Step V, determine an equivalent circuit of the entire system downstream of the fault. From the equivalent circuit data and three-phase voltages at the fault point phase, the load currents are calculated. The equivalent circuit downstream of the fault is obtained by observing the location of the first estimative of fault distance. If the fault location as estimated in step III, is the upstream of DG, an equivalent impedance matrix and a vector of the equivalent three-phase voltages, as seen from the remote end of the faulted section must be determined, representing the rest of the system downstream of the fault, taking into account the contribution of DG to the fault, and from these, an estimated three-phase load currents, according to (12):

$$\begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \cdot \begin{bmatrix} V_{Fa} - V_{tha} \\ V_{Fb} - V_{thb} \\ V_{Fc} - V_{thc} \end{bmatrix}. \quad (12)$$

If the location estimated in step III is downstream of the DG, it means that the downstream circuit is entirely passive. In this case the load phase currents are obtained by (13):

$$\begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \cdot \begin{bmatrix} V_{Fa} \\ V_{Fb} \\ V_{Fc} \end{bmatrix}. \quad (13)$$

VII. With the updated value of the vector of the three-phase load currents, return to the step II.

This algorithm runs until convergence, obtaining an estimate of the fault location. If the fault is located on the first section of the feeder, the method is finished and we have a final estimate for the fault location. If the fault is estimated after the first section or the distance found is negative, it is necessary to update the components of three-phase voltages and currents for the next bus. Thus, the algorithm runs again, until a new estimate of the fault distance is obtained. This process is repeated successively until the fault is located within the corresponding section.

A. Distributed Generation Model

The electrical circuit of the generator used in the fault location algorithm is a circuit of three-phase synchronous generator, connected in Y and with neutral solidly grounded. The model in each phase assumes that concatenated flows in the rotor are constant in this sub transient period, eliminating only the differential equation associated with the electrical characteristics of the machine. Thus, each phase can be represented simply by the generator sub transient reactance $X_S^{"}$, by its armature resistance R and by their internal voltages $E_g^{"}$, as shown in Fig. 3.

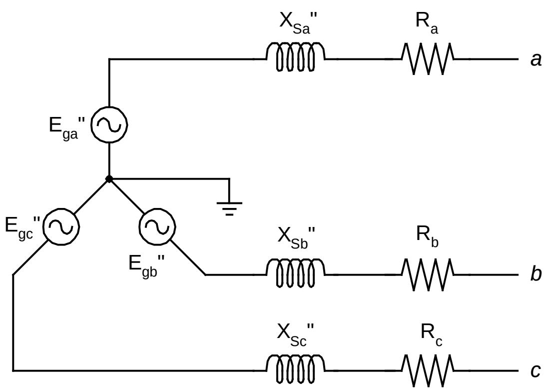

Figure 3. Eletrical model of distributed generation to EPDS.

This model is suitable for short circuit studies in which you want to compute the value of the fundamental frequency component of the system states [11]. As the rotor concatenated flows do not vary instantaneously, the generator internal voltage remains constant during the fault. With this consideration and with the three-phase voltages during the fault at the terminal of DG, it is possible to determine the contribution of current from the generator to the system during the fault, according to equation (14):

$$\begin{bmatrix} I_{gfa} \\ I_{gfb} \\ I_{gfc} \end{bmatrix} = \begin{bmatrix} R_a + jX_{sa}^{"} & 0 & 0 \\ 0 & R_b + jX_{sb}^{"} & 0 \\ 0 & 0 & R_c + jX_{sc}^{"} \end{bmatrix}^{-1} \cdot \begin{bmatrix} E_{ga}^{"} - V_{kfa} \\ E_{gb}^{"} - V_{kfb} \\ E_{gc}^{"} - V_{kfc} \end{bmatrix}$$

(14)

where the variable k represents the bus in which DG is connected. Generator internal voltage in the pre-fault is obtained through a program of three-phase power flow based on Ladder technique [8], including some modifications to the algorithm to include the DG system.

B. Update of three-phase voltages and currents

Consider EPDS with the presence of DG, illustrated in Fig. 4.

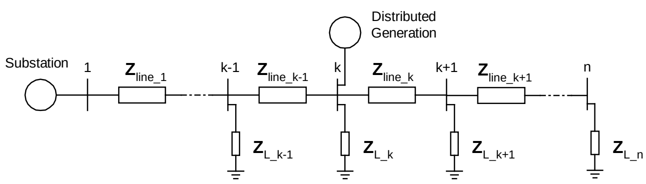

Figure 4. Distribution system with the presence of the DG.

The system can be divided into two parts: the circuit upstream and downstream of the generator. As can be seen in Fig. 4, the circuit upstream of the generator corresponds to the buses 1 to $k-1$, and the circuit downstream of the generator corresponds to the buses $k+1$ to n. If the fault location estimate is not located within the first section of the feeder regarding components of voltage and current in the substation, it is necessary to update the components of three phase voltage and current to the next bus, according to (15)-(16), respectively:

$$\boldsymbol{V}_{Sf_k} = \boldsymbol{V}_{Sf_{k-1}} - L \cdot \boldsymbol{Z}_{line_{k-1}} \cdot \boldsymbol{I}_{Sf_{k-1}} \tag{15}$$

$$\boldsymbol{I}_{Sf_k} = \boldsymbol{I}_{Sf_{k-1}} - \boldsymbol{Y}_{L_k} \cdot \boldsymbol{V}_{Sf_k} \tag{16}$$

Therefore, the fault location algorithm is applied until a new distance in the line section is obtained. Equation (16), used to update the vector of currents at the fault moment is used in almost all sections of the system, except for the section that precedes the generator bus. In this case, the vector of currents at the fault moment on the generator bus should be updated as (17):

$$\boldsymbol{I}_{Sf_k} = \boldsymbol{I}_{Sf_{k-1}} - \boldsymbol{Y}_{L_k} \cdot \boldsymbol{V}_{Sf_k} + \boldsymbol{I}_{gf} \tag{17}$$

The update of vector $\boldsymbol{V}_{Sf}$ and $\boldsymbol{I}_{Sf}$ may be better understood through the simplified algorithm presented in Fig. 5. Through this algorithm it is clear that the presence of the generator contributes to the fault current, with direct effect in the fault location estimate.

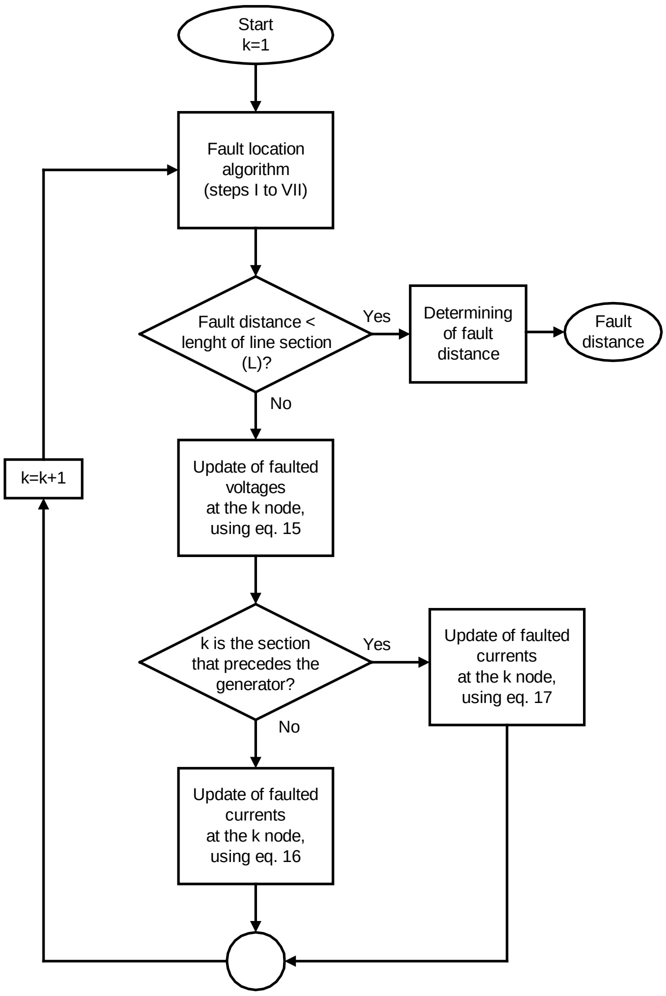

Figure 5. Simplified algorithm to update the voltages and currents.

IV. Case Study

In order to analyze the performance of the methodology proposed, a distribution feeder composed of 12 buses was simulated using ATP/EMTP software [10]. For implementation of the proposed formulation, the software used was MATLAB [9]. The 12 buses system is composed for 11 line sections, 10 load buses and a generator interconnected at half the system, as illustrated in Fig. 6.

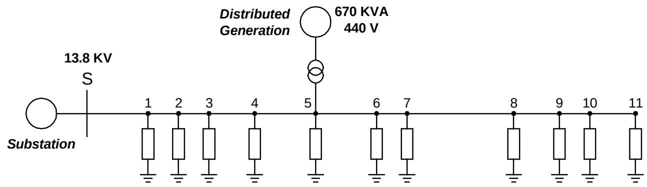

Figure 6. 12 buses system with distributed generation.

This system was based on a distribution feeder, obtained from [7], in which some modifications were necessary to validate the methodology. Among them the reduction of the total system three-phase power and the inclusion the unbalanced system operation. The system has a three-phase total output of 7,36 MVA, and the generator contributes with 0,67 MVA this power. The generator has an output voltage of 440 V and is connected to the distribution network through a transformer Y-Y 440/13,8 kV. The distribution feeder has a total length of 27,6 km and the generator was connected at km 11,86.

A. Data feeder

To validate the methodology, the line model was used as a RL four-wire grounded neutral. The feeder configuration presents an unequal spacing between phases and non-transposed lines, resulting in an unbalanced line impedance matrix [10]. Line impedance matrix was generated from a computational routine built in MATLAB, using Carson's equations [8]. The 12 buses system is composed by 11 different line sections, whose lengths are shown in Table I.

TABLE I. 12 BUSES DATA FEEDER

Bus From	Bus To	Distance [Km]
1	2	4.1843
2	3	1.2633
3	4	1.2633
4	5	2.1887
5	6	2.9612
6	7	3.1640
7	8	1.5530
8	9	6.2040
9	10	2.1726
10	11	0.8851
11	12	1.8025

The conductor used in each line segment was 447,000 26/7 ACSR, obtained from [8].

B. Load data

The system loads are balanced three-phase, connected in Y and with the neutral solidly grounded. The phases were modeled as constant impedance, and their values are shown in Table II.

TABLE II. 12 BUSES SYSTEM LOAD DATA

Bus	Impedance (Ω) $R + jX$
1	64.8 + j21.6
2	328.3 + j109.4
3	538.8 + j109.4
4	183.0 + j61.0
5	906.9 + j302.3
6	646.5 + j131.3
7	114.0 + j38.0
8	605.8 + j210.5
9	194.9 + j31.6
10	708.0 + j460.0
11	740.7 + j279.8

C. Generator data

The distributed generation system was interconnected to 12 buses through a three-phase transformer Y-Y 440/13,8kV, as illustrated in Fig. 6. The three-phase power generator that provides the system is 0,67 MVA, contributing about 7,6% of the total three-phase power system. The DG electrical circuit model is a three phase synchronous generator circuit connected in Y and with neutral solidly grounded. The parameters of this model were obtained according to the generator nominal specifications of the voltage and power, as [11].

V. RESULTS

Simulations were made in the ATP/EMTP of the line-to-ground solid faults in 65 different points of the 12 system buses, taking into account the three phases of the system. The estimated error in percentage of the distance is calculated based on the total length of feeder, according to (18):

$$Erro\ (\%) = \left|\frac{x_{est} - x_r}{L_T}\right| \times 100 \quad (18)$$

where x_{est} is the estimated fault distance, x_r is the real fault distance, and L_T is the total length of the line, which in this case is 27640 meters. In this section, the results are analyzed by comparing the proposed method and a current proposed fault location formulation [3]. The results for the classical methodology are illustrated in Fig. 7, and the results for the proposed methodology are illustrated in Fig. 8. The results of the currently proposed method show that this is inappropriate for the line-to-ground fault location in distribution systems with the presence of distributed generation. Through the graphic, shown in Fig. 7, it appears that the error tends to increase from DG connection location to the remote end of the system. Furthermore, it appears that the errors in the *a*-phase are much greater than in the other phases, fact that occurs due to lines unbalance. However, even the errors in the other phases being smaller, they exceed 100% of the total length of feeder, which means that the method cannot find fault downstream of DG. The results show that the proposed methodology also has a certain DG effect, however the maximum error that obtained is 0.7% of the total length of the line for faults in the *a*-phase. In the other phases the maximum error is slightly lower, as illustrated in Fig. 8.

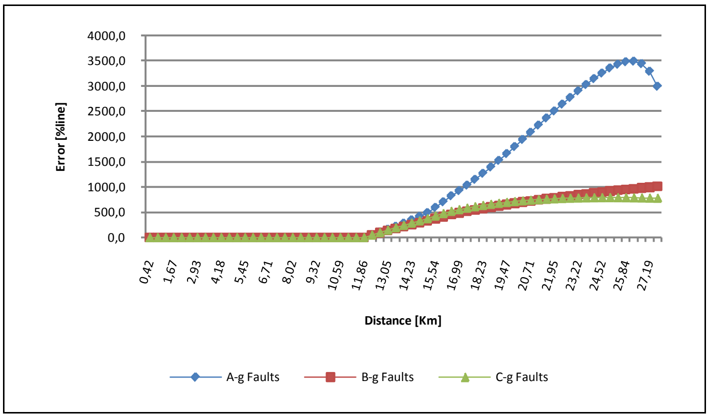

Figure 7. Classical method for line-to-ground short circuits.

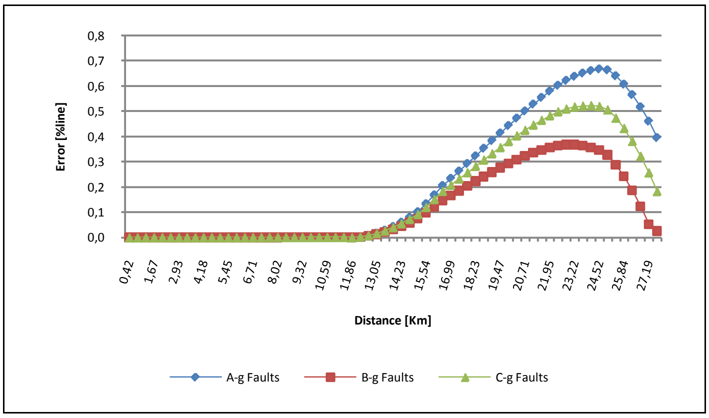

Figure 8. Proposed method for line-to-ground short circuits.

Comparing the results of the [3] with the proposed methodology by Table III, we can verify that the extended formulation is more appropriate for the line-to-ground fault location in distribution systems with the presence of distributed generation.

TABLE III. COMPARISON OF RESULTS

Fault Type	Proposed Method		Lee, et. al.	
	Average Error (%)	*Maximum Error (%)*	*Average Error (%)*	*Maximum Error (%)*
A-g	0.215	0.668	> 100	> 100
B-g	0.117	0.369	> 100	> 100
C-g	0.170	0.523	> 100	> 100

VI. CONCLUSIONS

This paper proposes a impedance based extended formulation for fault location for distribution systems using only one terminal data. The formulation described was developed for line-to-ground faults in distribution systems with distributed generation. The methodology is suitable for distribution systems, balanced or unbalanced, with high accuracy compared with current state of the art fault location formulations. The implementation of the proposed method can help energy companies reduce the system restoration time improving their power quality indexes.

ACKNOWLEDGMENT

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