IMPACT OF DISTRIBUTED GENERATION ON AUTOMATIC FAULT LOCATION IN UNBALANCED DISTRIBUTION NETWORKS. AN EXTENDED IMPEDANCE BASED FAULT LOCATION FORMULATION.

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Abstract – The increased global interest in clean energy production and energy market liberalization are factors that motivate the connection of distributed generation in distribution systems. In this new context, the demand for energy that was previously only supplied by the substation, now has the distributed generation as an alternative way of supply. Automatic fault location must be able to adapt to this new scenario, including in their algorithm an active network model. This paper presents an impedance-based fault location formulation and simulation results on a test system considering different levels of distributed generation. These results are compared with a fault location method developed for distributed generation systems based on positive sequence impedance in order to evaluate the performance of these methods under different generation levels.

Keywords: Automatic fault location, Distributed generation, Distribution networks.

1 INTRODUCTION

The increased global interest in clean energy production and energy market liberalization are factors that motivate the development of new generation technologies such as distributed generation (DG). This new generation form is characterized by being directly connected to the distribution, or close to consuming facilities [1]. Despite the environmental and economical benefits mentioned, this electrical sector deregulation could lead to technical impacts on the system operation [2]-[3]. The high level of DG penetration changes the distribution networks (DN) nature, from passive networks with a single direction of power flow, to active networks, where power flow can have more than one direction [4]-[5]. In transients analysis, the most visible impact is the system faulted currents modification, having a direct effect in protection systems [2]-[3].

The electric power systems are constantly exposed to the faults that affect reliability, security and ability to provide electricity [6]. The main causes of electric power systems failures are: system loading abrupt changes, contacts being, objects or vegetations in the lines, lightning and others [7]. In this context, the fault location (FL) has a important role in electric power systems restoration. The first procedures of FL in DN were based on field methods such as visual inspection or brute force methods that include: restoration by switching, call from consumers, smell of burn wires and others. Then, came the automatic FL methods based on impedance measurement, travelling waves and application of artificial intelligence such as neural networks [8]. The impedance based FL methods stand out especially for the construction low cost when using only one data terminal.

State of the art impedance based FL consider DN radial, ignoring the presence of DG [6]-[9]. Recently, some positive sequence impedance based FL techniques have been developed for DN with DG [10]-[11]. However, DN are inherently unbalanced and this reduces the accuracy of modal or sequence components based techniques. The work presented in [12] shows that the state of the art impedance based FL methods are significantly affected by the faults downstream of the DG. This occurs because the methods have been developed for radial systems. Motivated by these, this work presents proposed developments on a apparent impedance based FL methodology using the system representation by phase coordinates. Numerical analysis is presented using computer simulations in a test feeder [13] under different levels of DG using the ATP/EMTP software [14]. The results are compared with a FL technique for DG systems based on positive sequence impedance [10], in order to assess the impact of DG in these methods. The mathematical formulation is numerically implemented in MATLAB [15]. This paper is structured as follows: Section 2 describes the state-of-the-art impedance based FL for DG systems; Section 3 discusses the proposed extensions to unbalanced DG systems; A case study is presented in Section 4; Sections 5 and 6 illustrate results and conclusions, respectively.

2 FAULT LOCATION IN DISTRIBUTED GENERATION SYSTEMS

Consider the deregulated distribution system illustrated in Fig. 1 [10]. Analyzing the following system, we found that this may be subject to faults downstream or upstream of the generating unit. If the failure occurs downstream of the generator, the faulted system is represented by an equivalent impedance (Z_{th}) downstream to the fault, as illustrated in Fig. 2. However, if the fault occurs upstream of the generator, there will be a current contribution from the remote end to the fault. In this case the faulted system is represented by an equivalent impedance Z_{th} and a source V_{th}, both located at the remote end of the fault, as illustrated in Fig. 3. In both cases, the equivalent impedance Z_{th} is the result of all downstream loads aggregated.

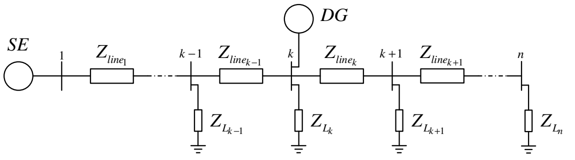

Figure 1: Distribution system with distributed generation.

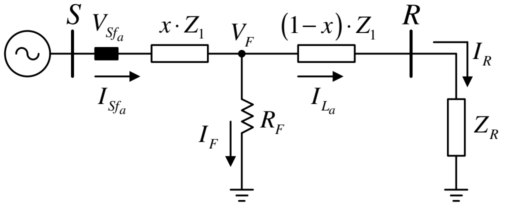

Figure 2: Equivalent system for fault downstream of DG.

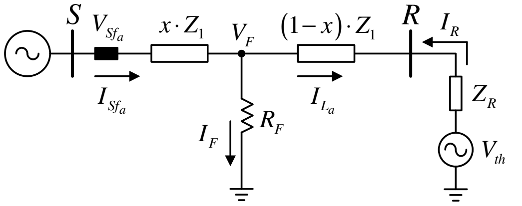

Figure 3: Equivalent system for fault upstream of DG.

Observing the equivalent circuits of Fig. 2 and Fig. 3, the voltage at the sending end is obtained by (1):

$$V_{Sf_a} = x \cdot \left(Z_1 \cdot I_{Sf_a}\right) + R_F \cdot I_F \tag{1}$$

where

V_{Sf_a}	Phase *a* terminal *S* voltage
I_{Sf_a}	Phase *a* terminal *S* current
Z_1	Positive sequence impedance [per km]
x	Fault distance
V_F	Fault point voltage
I_F	Fault current
R_F	Fault resistance
I_R	Terminal *R* current
Z_{th}	Thévenin equivalent impedance
V_{th}	Thévenin equivalent voltage.

Multiplying both sides of Equation (1) by I_F^* (fault current complex conjugate), and knowing that the term $I_F \cdot I_F^* \cdot R_F$ results in a real number, we obtain the expression (2):

$$x = \frac{\mathrm{Im}\left(V_{Sf_a} \cdot I_F^*\right)}{\mathrm{Im}\left(Z_1 \cdot I_{Sf_a} \cdot I_F^*\right)} \tag{2}$$

The pre-fault load current is considered equal to pre-fault current at the local end, as (3):

$$I_{L_a} = I_{S_a} \tag{3}$$

The initial estimate of fault current is obtained by the difference between the sending end during the fault current and load current through (4):

$$I_F = I_{Sf_a} - I_{L_a} \tag{4}$$

With these equations, the following algorithm can be used to estimate the fault location:

I. It is assumed I_{L_a} as the load current before the fault occurrence, according to (3).

II. Using (4) an estimate of the fault current is calculated.

III. Using (2), a fault location is estimated.

IV. Using (5) the voltage at the estimated fault location is calculated. This is done by considering system topology.

$$V_F = V_{Sf_a} - x \cdot Z_1 \cdot I_{Sf_a} \tag{5}$$

V. Using the fault point voltage estimated in the previous step, a Thévenin equivalent circuit is determined of the all upstream system. If the fault location estimate in step III is downstream of the DG, as illustrated in Fig. 2, the equivalent circuit is the parallel impedance of all the system (also considering the line impedances) to upstream at the fault point. After this calculation, the current in the remote end is updated again with equation (6).

$$I_{L_a} = \frac{V_F}{Z_{th}} \tag{6}$$

VI. In the case of fault location being estimated downstream of DG, the Thévenin equivalent will have a generating source. In this case the current in the remote end is obtained using equation (7):

$$I_{L_a} = \frac{(V_F - V_{th})}{Z_{th}} \tag{7}$$

VII. With the updated value of the load current, return to the step II.

The routine is continued until the fault is located. If the fault location estimate is located on the first section of the feeder, the method is finished and it is obtain a final estimate for the fault location. If the fault is estimated after the first section of the system, the values of voltage and current measured at the local terminal are upgraded to the next system buses and the steps I to VI are run again. This update is performed on until the fault is estimated within of the section.

2.1 Distributed Generation Model

The electric model of distributed generation used is the model of a synchronous generator in the subtransient time period [16]. The model, shown in Fig. 4, consists of the subtransient reactance $X_S^{"}$, armature resistance R and the value of its internal voltage $E_g^{"}$. The generator internal voltage can be obtained through a power flow program [17], which determines the voltage on the bus of the generator and the current injected by him.

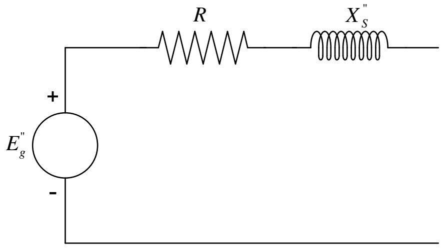

Figure 4: Electric model of distributed generation

As the time period studied is the subtransient corresponding to the first few cycles after fault occurrence, it is considered that the generator internal voltage remains constant during the fault. Thus it is possible to estimate the contribution of current supplied by the generator during the fault, according to (8):

$$I_{g_f} = \frac{\left(E_g^{"} - V_k\right)}{\left(R + X_S^{"}\right)} \tag{8}$$

where the variable k represents the bus in which the generator is connected.

2.2 Downstream system bus voltages and currents

Considering the faulted system, and assuming the loads, the line impedances and relay data known, the previous presented algorithm for fault location is run for the first section of the feeder. If the failure is not found within this section, an estimate of downstream system bus voltages and currents is calculated, as in equations (9) to (11).

$$V_{Sf_k} = V_{Sf_{k-1}} - L \cdot Z_{line_{k-1}} \cdot I_{Sf_{k-1}} \tag{9}$$

$$I_{L_k} = \frac{V_{Sf_k}}{Z_{L_k}} \tag{10}$$

$$I_{Sf_k} = I_{Sf_k} - I_{L_k} \tag{11}$$

If the line section in analysis is upstream the generator bus, the short-circuit current in the bus during the fault must be updated according to equation (12):

$$I_{Sf_k} = I_{Sf_{k-1}} - I_{L_k} + I_{gf} \tag{12}$$

3 PROPOSED FAULT LOCATION METHOD

The proposed formulation aims to extend the work described in Section 2, by representing the lines of a typical DN by phase coordinates. This method also demonstrates the development of a mathematical formulation, suitable for unbalanced systems. The proposed method also obtains the system downstream of the fault, however the operations are done in a matrix format considering that the distribution systems are three phase and unbalanced. The mathematical formulation, the iterative algorithm, the model of distributed generation and update process of the components of three-phase voltage and current are described below.

3.1 Mathematical Formulation

Consider the distribution system subject to a three-phase fault, illustrated in Fig. 5.

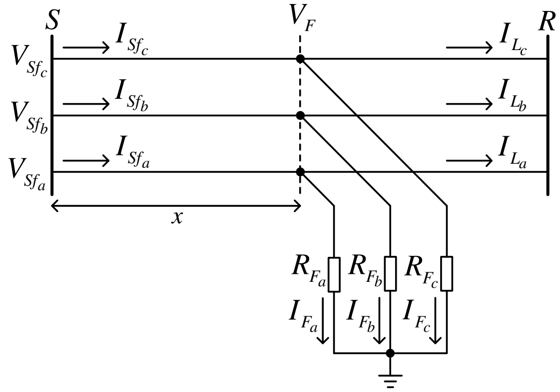

Figure 5: Three-phase fault with distributed generation.

The voltages in phases *a*, *b* and *c* in the terminal S during the fault period is estimated by:

$$\begin{bmatrix} V_{Sf_a} \\ V_{Sf_b} \\ V_{Sf_c} \end{bmatrix} = x \cdot \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} I_{Sf_a} \\ I_{Sf_b} \\ I_{Sf_c} \end{bmatrix} + \begin{bmatrix} I_{F_a} \cdot R_{F_a} \\ I_{F_b} \cdot R_{F_b} \\ I_{F_c} \cdot R_{F_c} \end{bmatrix} \tag{13}$$

The expression of equation (13) through its real and imaginary components results in the set of expressions:

$$V_{Sfa_r} = x \cdot T_1 + R_{F_a} \cdot I_{F_{a_r}} \tag{14}$$

$$V_{Sfa_i} = x \cdot T_2 + R_{F_a} \cdot I_{F_{a_i}} \tag{15}$$

$$V_{Sf\,b_r} = x \cdot T_3 + R_{F_b} \cdot I_{F_{a_r}} \tag{16}$$

$$V_{Sf\,b_i} = x \cdot T_4 + R_{F_b} \cdot I_{F_{a_i}} \tag{17}$$

$$V_{Sfc_r} = x \cdot T_5 + R_{F_c} \cdot I_{F_{c_r}} \tag{18}$$

$$V_{Sfc_i} = x \cdot T_6 + R_{F_c} \cdot I_{F_{c_i}} \tag{19}$$

where the parameters of lines are obtained by:

$$T_1 = \sum_{k=\{a,b,c\}} \left[Z_{ak_r} \cdot I_{Sf_{k_r}} - Z_{ak_i} \cdot I_{Sf_{k_i}} \right] \tag{20}$$

$$T_2 = \sum_{k=\{a,b,c\}} \left[Z_{ak_r} \cdot I_{Sf_{k_i}} + Z_{ak_i} \cdot I_{Sf_{k_r}} \right] \tag{21}$$

$$T_3 = \sum_{k=\{a,b,c\}} \left[Z_{bk_r} \cdot I_{Sf_{k_r}} - Z_{bk_i} \cdot I_{Sf_{k_i}} \right] \tag{22}$$

$$T_4 = \sum_{k=\{a,b,c\}} \left[Z_{bk_r} \cdot I_{Sf_{k_i}} + Z_{bk_i} \cdot I_{Sf_{k_r}} \right] \tag{23}$$

$$T_5 = \sum_{k=\{a,b,c\}} \left[Z_{ck_r} \cdot I_{Sf_{k_r}} - Z_{ck_i} \cdot I_{Sf_{k_i}} \right] \tag{24}$$

$$T_6 = \sum_{k=\{a,b,c\}} \left[Z_{ck_r} \cdot I_{Sf_{k_i}} + Z_{ck_i} \cdot I_{Sf_{k_r}} \right] \tag{25}$$

By the equations (14)-(19) verifies the presence of six equations and four unknowns, which are the fault distance and the fault resistance in the three phases. For the solution of this system is sufficient to choose only four equations as shown in (26):

$$\begin{bmatrix} x \\ R_{F_a} \\ R_{F_b} \\ R_{F_c} \end{bmatrix} = \begin{bmatrix} T_1 & I_{F_{a_r}} & 0 & 0 \\ T_2 & I_{F_{a_i}} & 0 & 0 \\ T_3 & 0 & I_{F_{b_r}} & 0 \\ T_4 & 0 & 0 & I_{F_{c_r}} \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_{Sfa_r} \\ V_{Sfa_i} \\ V_{Sfb_r} \\ V_{Sfc_i} \end{bmatrix} \tag{26}$$

The solution of equation (26) results in the estimate of the fault distance.

3.2 Iterative Algorithm

The algorithm starts considering the possibility of fault location at the beginning of the feeder, in the first section of line after the bus of the substation, as follows:

I. It is assumed that the vector of phase currents is equal to the vector of the S end currents, in the pre-fault period, according to (27):

$$\boldsymbol{I}_L = \boldsymbol{I}_S \tag{27}$$

II. It is estimated initially the fault current using equation (28):

$$\boldsymbol{I}_F = \boldsymbol{I}_{Sf} - \boldsymbol{I}_L \tag{28}$$

III. Calculate the initial estimate of the fault distance, using equation (26).

IV. Once estimated the distance, convergence analysis of the algorithm is performed by equation (29):

$$[x(n) - x(n-1)] < 0.0001 * L \tag{29}$$

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

V. The three-phase voltages at the fault point are determined by equation (30):

$$\begin{bmatrix} V_{F_a} \\ V_{F_b} \\ V_{F_c} \end{bmatrix} = \begin{bmatrix} V_{Sfa} \\ V_{Sfb} \\ V_{Sfc} \end{bmatrix} - x \cdot \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} I_{Sfa} \\ I_{Sfb} \\ I_{Sfc} \end{bmatrix} \tag{30}$$

VI. The system equivalent downstream of the fault is obtained by observing the first fault distance estimate. If the fault location is estimated in step III, is upstream of DG, an equivalent is obtained by:

$$\begin{bmatrix} I_{L_a} \\ I_{L_b} \\ I_{L_c} \end{bmatrix} = \begin{bmatrix} Y_{th_{aa}} & Y_{th_{ab}} & Y_{th_{ac}} \\ Y_{th_{ba}} & Y_{th_{bb}} & Y_{th_{bc}} \\ Y_{th_{ca}} & Y_{th_{cb}} & Y_{th_{cc}} \end{bmatrix} \cdot \begin{bmatrix} V_{F_a} - V_{th_a} \\ V_{F_b} - V_{th_b} \\ V_{F_c} - V_{th_c} \end{bmatrix} \tag{31}$$

If the location estimate in step III is downstream of the DG, it means that the circuit downstream of the fault is entirely passive in this case the three-phase load currents are obtained simply by (32):

$$\begin{bmatrix} I_{L_a} \\ I_{L_b} \\ I_{L_c} \end{bmatrix} = \begin{bmatrix} Y_{th_{aa}} & Y_{th_{ab}} & Y_{th_{ac}} \\ Y_{th_{ba}} & Y_{th_{bb}} & Y_{th_{bc}} \\ Y_{th_{ca}} & Y_{th_{cb}} & Y_{th_{cc}} \end{bmatrix} \cdot \begin{bmatrix} V_{F_a} \\ V_{F_b} \\ V_{F_c} \end{bmatrix} \tag{32}$$

VII. With the updated value of the load current vector $\boldsymbol{I}_L$, returns to the step II.

This algorithm runs until convergence, where it is obtained an estimate of the fault location. If the fault is located on the first section of the feeder, the method is finished. If the fault is estimated after the first section or the distance found is negative, it is necessary to estimate the voltage and current vectors for the downstream system bus and the proposed algorithm is run again, from the steps I to VII, until a new estimate of the distance fault is calculated.

3.3 Distributed Generation Model

The electrical circuit of the DG used in the fault location algorithm is the circuit of a three phase synchronous generator, connected in Y and with neutral solidly grounded. The model assumes that concatenated flows in each phase of the rotor are constants in subtransient period, eliminating only the differential equation associated with the electrical characteristics of the machine. Thus, each phase can be represented simply by the subtransient reactance of the generator $X_s^{''}$, by its armor resistance R and for their internal voltages $E_g^{''}$, as shown in Fig. 6. The model used in the proposed method is similar to that described in Section 2, which is suitable for programs of short circuit in which you want to compute the value of the fundamental frequency component of short circuit currents [16].

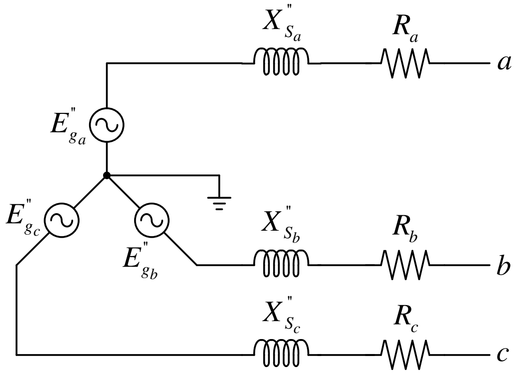

Figure 6: Modeling of generator for unbalanced DG systems.

However, in the proposed method, the modeling of the generator was made for the three phases, while in the method discussed in the previous section the modeling of the generator was made only for one phase. As the rotor concatenated flows do not vary instantaneously, the internal voltage generator 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 (33):

$$\begin{bmatrix} I_{gf_a} \\ I_{gf_b} \\ I_{gf_c} \end{bmatrix} = \begin{bmatrix} Z_{g_a} & 0 & 0 \\ 0 & Z_{g_b} & 0 \\ 0 & 0 & Z_{g_c} \end{bmatrix}^{-1} \cdot \begin{bmatrix} E''_{g_a} - V_{kf_a} \\ E''_{g_b} - V_{kf_b} \\ E''_{g_c} - V_{kf_c} \end{bmatrix} \qquad (33)$$

where generator impedance per phase is given by

$$Z_{g_{a(b,c)}} = R_{a(b,c)} + X''_{S_{a(b,c)}} \qquad (34)$$

where k represents the bus in which DG is connected. The generator internal voltage in the pre-fault is obtained through direct analysis of circuits.

3.4 Downstream system bus voltages and currents

Consider the DN with the presence of DG, illustrated in Fig. 1. It appears that the system can be divided into two parts: the circuit upstream and downstream of the generator circuit. As can be seen in Fig. 1, 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 is not estimated within the first section of the feeder referred to the voltage and current vectors of the substation, it is necessary to estimate the vectors of voltages and currents for the downstream system bus, according to the following equations (35) and (36), respectively:

$$\boldsymbol{V}_{Sf_k} = \boldsymbol{V}_{Sf_{k-1}} - L \cdot \boldsymbol{Z}_{line_{k-1}} \cdot \boldsymbol{I}_{Sf_{k-1}} \qquad (35)$$

$$\boldsymbol{I}_{Sf_k} = \boldsymbol{I}_{Sf_{k-1}} - \boldsymbol{Y}_{load_k} \cdot \boldsymbol{V}_{Sf_k} \qquad (36)$$

Therefore, the fault location algorithm is run again until a new distance between the local bus and the fault point is obtained. This process is performed on until the fault is estimated in the section corresponding to the vectors $\boldsymbol{V}_{Sf}$ and $\boldsymbol{I}_{Sf}$ updated. Equation (36), used to update the vector of currents at the faulted period, is used in almost all sections of the system except for the section that precedes the generator bus. If the line section in the previous analysis is the generator bus, the vector of currents during the fault on the generator bus should be updated as (37):

$$\boldsymbol{I}_{Sf_k} = \boldsymbol{I}_{Sf_{k-1}} - \boldsymbol{Y}_{load_k} \cdot \boldsymbol{V}_{Sf_k} + \boldsymbol{I}_{gf} \qquad (37)$$

4 CASE STUDY

In order to analyze the performance of the proposed FL methodology, a test feeder was simulated in the software ATP/EMTP [14]. For implementation of the algorithm, the software used was MATLAB [12]. The test system was based on a distribution feeder obtained from the literature [13], where laterals branches were reduced in equivalent loads and a DG was introduced into the km 11.86 feeder, as illustrated in Fig. 7.

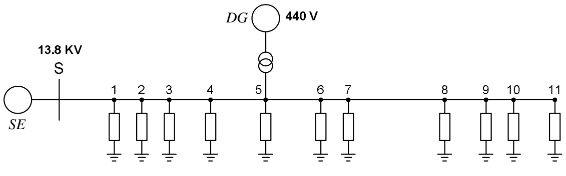

Figure 7: Test feeder.

The test feeder has rated voltage of 13.8 kV and the total power of three-phase loads of (7.33 + j3.27) MVA. The generator has a rated voltage of 440 V and is connected to the distribution network through a transformer Y-Y, 440 V/13.8 kV.

4.1 Data feeder

The line model used was a RL four-wire grounded neutral. The feeder configuration presents an unequal spacing between phases and non-transposed lines [18]. Line impedance matrix was generated from a computational routine built in MATLAB, using Carson's equations [17]. The test feeder is composed by 11 different line sections, whose lengths are shown in Table 1.

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

Table 1: Line lenghts of test feeder.

4.2 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 2.

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

Table 2: Load three-phase of test feeder.

4.3 Generator data

The distributed generation was interconnected to feeder through a three-phase Y-Y transformer of 440 V/13.8 kV, as shown in Fig. 7.

The power of distributed generation was established by the reference to the rating system, according to equation (38), such presented in [4]:

$$DG\ level[\%] = \frac{P_{DG}}{P_{Total}} \times 100 \qquad (38)$$

where P_{DG} is active power supplied by DG; P_{Total} is active power total of the system. The total active power of the system is obtained by:

$$P_{Total} = P_{DG} + P_{SE} \qquad (39)$$

where P_{SE} is active power supplied by substation.

As the model used for the DG of a voltage source in series with a impedance, then the power generating unit was established through the machine operating conditions (voltage and angle of operation). For this was run a three-phase power flow technique based on iterative ladder, in order to obtain the operation conditions of the DG. In this case, the DG branch was considered as a real power source, and the routine of this program provides the output voltages in all buses of system, including the DG. This voltage is then used as input data in the DG source by ATP/EMTP software, ensuring that power injected by it, is near the power allocated in the program of power flow. This procedure was performed for three different DG levels: 10%, 20% and 30% of the rated system power (RSP) and the operation conditions for each DG level, such illustrated in Table 3.

DG level [%]	Three-phase power [MW]	Positive sequence voltages	
		$\lvert V_1 \rvert$ [Volts]	$\angle V_1$ [Degrees]
10	0.73	240.66	-6.932
20	1.47	241.23	-5.233
30	2.20	241.71	-4.178

Table 3: Positive sequence voltages in DG terminal.

The DG parameters are obtained based on the nominal data of the machine (power and voltage), according to equation (40). The Table 4 shows the parameters corresponding to each level of DG.

$$Z_g = \left(R_{(pu)} + jX''_{S(pu)}\right) \cdot \left[\frac{\left(V_{base_{DG}}\right)^2}{S_{base_{DG}}}\right] \qquad (40)$$

DG level [%]	Rated power [MW]	Rated voltage [V]	Synchronous machine impedance	
			$R[\Omega]$	$X''_S[\Omega]$
10	0.73	440	0.005	0.092
20	1.47	440	0.003	0.046
30	2.20	440	0.002	0.031

Table 4: Synchronous machine parameters.

5 RESULTS

Simulations were made through solid three-phase faults in the ATP/EMTP in 65 different points of the test feeder, as described in Section 4. The estimated error in percentage of the distance is calculated based on the total length of the feeder, as described by (41):

$$Error\ (\%) = \left|\frac{x_{est} - x_{real}}{L_T}\right| \times 100 \qquad (41)$$

where x_{est} is the estimated fault distance, x_{real} is the real fault distance, and L_T is the line total length, which in this case is 27640 meters. In this section, the results are analyzed by comparing the proposed method with a fault location method based on positive sequence impedance for distributed generation systems [10]. The performance of the method based on positive sequence impedance is illustrated in Fig. 8, and the performance of the proposed method, in Fig. 9. In the curves of percentage error versus distance, shown in Fig. 8 and 9, the DG levels are expressed in percentage of RSP.

Analyzing the curves, that both Bretas *et al.* as the proposed method are less susceptible to the of the DG level increase. The errors remain nearly constant for three DG levels tested in the two methods. In the performance curves of the Bretas *et al.*, shown in Fig. 8, it is observed that the percentage error increases considerably with the distance, with error increase more pronounced for faults downstream of DG, located at km 11.86 of the feeder.

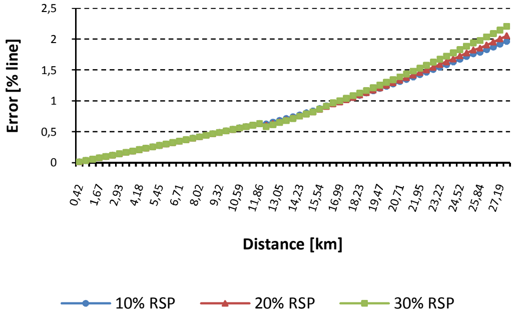

Figure 8: Results of Bretas *et al.* method for ABC-g faults.

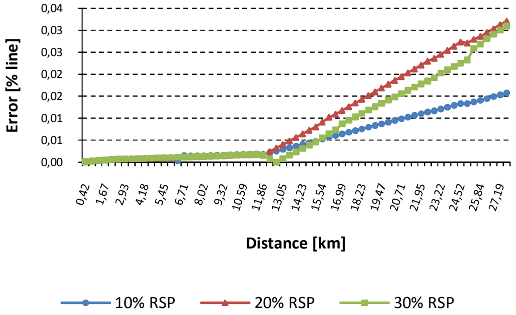

Figure 9: Results of proposed method for ABC-g faults.

However, the performance curves of the proposed method, shown in Fig. 9, shown that between substation and km 11.86, point where the generating unit is located, the percentage errors are negligible, while for faults located downstream of DG, the percentage errors becomes more evident.

The quantitative results of the simulations illustrated in Table 4 show that the performance of the proposed method is slightly superior to the Bretas *et al.*, with reduction in average and maximum errors around 0.9 % and 2.0 %, respectively, regardless of the DG level.

DG level [%]	Proposed Method		Bretas *et al.*	
	Average Error [%]	Maximum Error [%]	Average Error [%]	Maximum Error [%]
10	0.006	0.016	0.851	1.965
20	0.010	0.032	0.862	2.055
30	0.009	0.031	0.863	2.207

Table 5: Results.

Given that both approaches use the same analytical approach based on the fault current estimation, the superior performance of the proposed method is attributed to the use of phase coordinates as a system representation.

6 CONCLUSIONS

This paper proposes extensions to a fault location method based on apparent impedance for distribution networks using only local data terminal. The equations described are designed for three-phase faults in systems with distributed generation. Despite of the good performance for three-phase short-circuit, the extensions proposed in this paper are only an initial study on fault location in distributed generation systems. There is a need to further extend these studies and this methodology for analysis of broader conditions such as adaptation of the equation for high impedance faults, the expansion of the method for branched systems, method development for multiple generating units connected to the network distribution and the inclusion of generation units of the asynchronous type.

However, for the given conditions, the results show that the approach is suitable for locating faults in distribution networks, balanced and unbalanced, considered the presence of distributed generation, with good accuracy compared with a technique also developed for generation systems distributed based on the positive-sequence impedance.

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