A novel fault location approach for radial power distribution systems

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ABSTRACT

Power distribution systems (PDS) are increasingly complex and spread over long distances and in different locations. Given their radial configuration, the loads could be inserted at the same distances from the substation. This leads to multiple estimation of fault location (FL) and yields time consuming for iterative FL algorithms. In this article, we provide a novel practical approach to fault localization in order to defeat these limitations. The central idea of the proposed approach is to divide the multilateral distribution system into a possible number of mono-lateral sub systems (MLS) using a proposed communicating sensor. Next, we apply two different fault locator algorithms only to the defective MLS. The first variant of the approach is based on the impedance method, while the second variant is non-parametric used only when there is lack in the line data. To test the proposed technique in practice, we used the IEEE 13 Node test feeder, and a real Algerian PDS. The results obtained clearly show the contribution of the dedicated method for locating faults in the PDS.

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1. INTRODUCTION

Service continuity, stability, and power quality are inordinate challenges for electrical power companies; yet these are vital for economic developments. Outage time related to faults is translated as a cost of a not delivered power for which distribution companies are held accountable. Owing to the increasing demand on electrical energy, power systems become more expanded and highly compounded, which made them more exposed to faults caused by the diverse events, such as traffic incidents, devices failures and weather conditions. In order to enrich the performance and reliability indices of power distribution systems (PDSs) such as, system average interruption duration index (SAIDI) and customer average interruption duration index (CAIDI) [1], the fault location (FL) process must be executed accurately and in timely manner. This goal is quite mature in power transmission systems (PTS), because of the homogeneity of conductors and the straightforward topology. Contrary, FL task is very difficult in PDS due to a number of intrinsic features such as radial nature, laterals and ramifications, different models and dimensions of conductors, active topologies, unstable operations, load uncertainty, and variation fault resistance, all this generate its heterogeneity aspect. In nowadays, PDSs are equipped by different smart devices to facilitate the FL process such as FL indicators and supervisory control and data acquisition (SCADA). During fault situation, a maintenance team inspects the PDS, based on fault indicator devices inserted along the feeder.

This technique is efficient, yet time consuming. Another technique is based on breaker re-closer and SCADA sensors usage to isolate the defective section. This method is more convenient and quite fast, but it wears out the power supply material and causes damage when re-powering with a short circuit. However, the cost and the need of regular maintenance make these methods uneconomical solutions. Hence, fault location techniques with minimum implemented devices are a crucial solution to improve the PDS reliability indices along with acceptable implementation cost.

In the past couple decades, many efficient approaches have been devoted to FL in PDS. These can be categorized into three main groups: travel wave-based methods [2]–[7], artificial intelligent based methods [8]–[17], and impedance-based methods [18]–[25]. The first family uses the high frequencies waves originated by faults and propagating throughout the PDS. These techniques are very fast and accurate. However, they need digital relays with a high sampling rate and a high number of installed sensors to cover the big number of derivations in PDS. Moreover, for high resistive faults the travel signals are weak and can completely vanish, which affect the reliability of these methods. In the second family, a machine learning rule is used to interpret the complex link between the fault and its location from the substation. Diverse artificial intelligent techniques are proposed, fuzzy logic (FL) [8], [9], artificial neural networks (ANN) [10], [11], [17], supporting vector regression (SVR) [12], [13], [16], and genetic algorithms (GA) [14], [15]. Elaborating an appropriate and suitable training database is primordial condition for those techniques to be accurate. As an example, Farzan *et al.* [11] present an FL method for radial PDS. This technique uses the fault power peaks recorded at the main source during fault states at different positions, a good accuracy has been obtained, but it cannot be generalized for all faults types. Furthermore, loads are considered constant versus time, a continuous update and gathering of dataset at any modification of the PDS topology is mandatory, leading to time consuming drawback during the ANN learning step. The third family is the impedance-based methods where, measurements recorded at the sending extremity of the feeder are used to evaluate the apparent impedance between the fault position and the source. Due to their simplicity and facility for the implementation in commercialized digital relays, they are the most used. However, because of the radial configuration, fault resistance, and load uncertainty, the multiple FL estimation is the main difficulty of these techniques.

In general, impedance-based algorithms using iterative estimations may converge to an erroneous estimation. In the work of Lee *et al.* [20] a load current model is used to construct an iterative FL algorithm based on the assumptions that the impedance of loads are known and do not vary versus time, which is not usually correct because of the unpredictable behavior of customers, and the lack of the online measurements at each node throughout the feeder. Thus, the algorithm may converge to a false estimation. This problem improved in the paper of Ye *et al.* [21] by traversing the entire values of fault distances. In the study of Khaleghi *et al*. [22], the distributed parameter line model in phase domain is used, voltage and current for all sections of PDS are computed using the extracted components from the phasor measurement units installed through the feeder. Even though a high precision is acquired, however, the load uncertainty impact is neglected. In the article of Morales-Espana *et al.* [23], load uncertainty is treated by aggregating all loads at the ending extremity of the feeder; an initial distance at the beginning of each PDS line-section is adopted and incremented to cover the entire length of the feeder, and then the FL is estimated where the reactance value is smallest. This technique yields a high reliability; nevertheless, it needs a high number of iterations. Also, the problem of multiple FL is not addressed in this study.

To defeat this difficulty, a novel practical FL approach is suggested in this work. Based on the PDS topology, which is previously known, the multilateral system is divided into a possible number of mono-lateral sub-systems (MLSs) using a new dedicated communicant sensor (CS), smartly installed across the feeder. Then, a FL process is run just at the defective MLS using two different algorithms, namely FLA1 and FLA2. The here proposed approach is an off-line technique; it treats the multiple estimation problem of FL in PDS by decreasing the number of tests and providing a unique FL candidate. The remaining of the article is organized as follows. The section 2 describes the proposed approach. The section 3 sets the tests and analysis of the technique using the IEEE 13 Node test feeder, and a real Algerian PDS. Finally, section 4 concludes the paper.

2. THE PROPOSED APPROACH

The principal idea behind the approach is to divide a radial PDS to several possible MLSs using communicant sensors (CSs). The number and positions of the inserted sensors depends on the design and configuration of the PDS. The fault signal generated by the sensor is transmitted to the dispatching station in the first step. Thus, the affected section is accurately detected. In the next step a FL algorithm is employed exclusively at the faulty MLS through the established equivalent model of the PDS, during fault condition. More details are illustrated in the following subsections.

2.1. The proposed communicant sensor

The proposed CS as shown in Figure 1 can convert the detected fault current to a usable communication signal using the interconnection circuit illustrated in Figure 2. Various efficient techniques to inject faults are proposed in the literature such as, AVR-INJECT tool [26] which is used to automate the fault injection on wireless sensor networks. Owing to high short-circuit values in PDSs; the injection current box is utilized in this work to emulate the high fault peaks in order to calibrate the sensor.

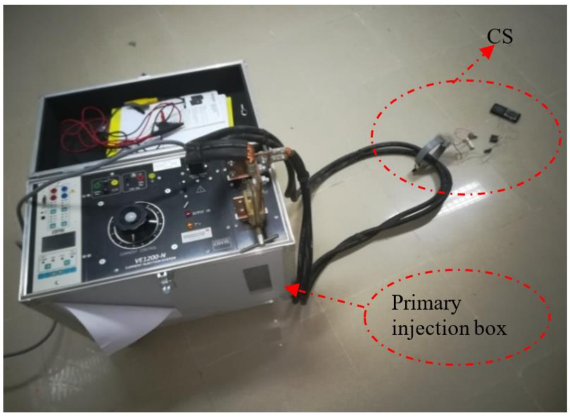


Figure 1. The experimental bench for test and calibrate the proposed CS

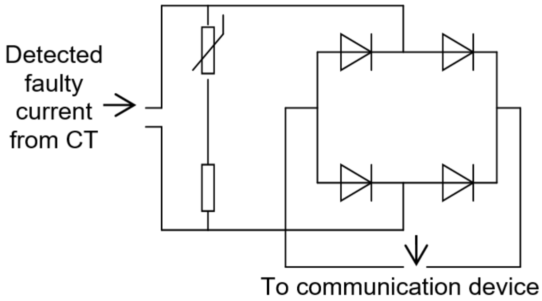


Figure 2. The interconnection circuit

2.2. Fault location algorithm using impedance-based method (FLA1)

The proposed impedance algorithm in this study relies on the minimum fault reactance principle [23]–[25]. The reactance of fault is computed for each incremented distance, this process is repeated to cover the whole system. While considering the faults resistive characteristic, the candidate FL is fixed at the position where the reactance is smallest. Generally, in PDSs, the measurements are accessible only at the sending extremity of the feeder, so the online measurements at each load are not always available. To treat the loads variations states, all loads are summed up and accumulated at the farthest receiving extremity of the analyzed feeder, as presented in the equivalent circuit depicted in Figure 3.

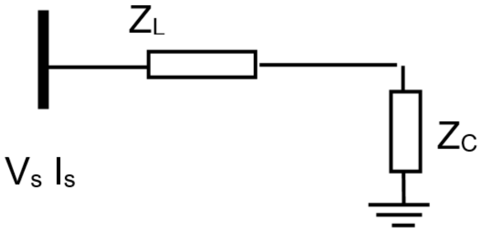


Figure 3. Simplified PDS model in pre-fault conditions

From Figure 3, we have:

$$Z_C = (V_S/I_S) - Z_L \quad (1)$$

where $V_S[3 \times 1]$and $I_S[3 \times 1]$are the voltages and currents before the fault, respectively at the sending extremity. Z_L=ΣZ_{LMLSj}, j is incremented from 1 to n (n is total MLSs); with ΣZ_{LMLSj} [3x3] are the series impedances of every homogeneous MLS. In the presented methodology and by identifying the defective section the rest of system sections' can be skipped from the overall FL process, hence reducing the field of the process, and resulting a unique FL candidate. During a fault condition, the equivalent model of the PDS is proposed as illustrated in Figure 4.

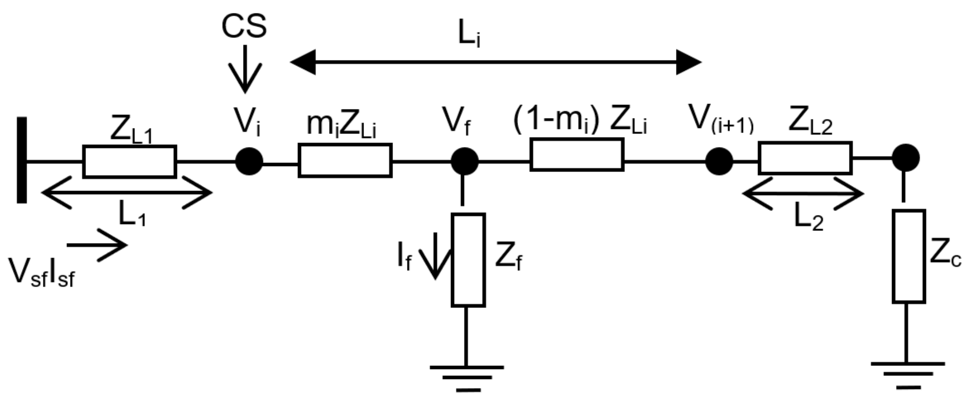


Figure 4. Equivalent model of the PDS in fault state

Where L_1 is the length between the defective MLS and the sending extremity. L_2 is the length between the defective MLS and the receiving extremity. I is the defective MLS. L_i is the defective MLS length. Z_{Li} $[3 \times 3]$ is the impedance of the defective MLS. $Z_{L1}[3 \times 3]$= Z_{LMLSj}, j is incremented from 1 to $(i-1)$. $Z_{L2}[3 \times 3]$= Z_{LMLSj}, j is incremented from $(i+1)$ ton. V_{Sf} $[3 \times 1]$ is the sending voltage during the fault. $I_{Sf}[3 \times 1]$ is the sending current during the fault. m_i is the per unit fault length at MLSi.
From Figure 4, the fault location L_f is evaluated using (2).

$$L_f = L_1 + m_i L_i \quad (2)$$

The incoming voltages $V_i[3 \times 3]$ at node i, voltages at fault position $V_f[3 \times 3]$, and the fault currents $I_f[3 \times 3]$ are calculated using (3), (4) and (5), respectively.

$$V_i = V_{Sf} - Z_{L1} I_{Sf} \quad (3)$$

$$V_f = V_i - m_i Z_{Li} I_{Sf} \quad (4)$$

$$I_f = [I_{Sf}] - \left[\left((1 - m_i)Z_{Li} + Z_{L2} + Z_C\right)^{-1} V_S\right] \quad (5)$$

Then the fault reactance is

$$Z_F(m_i) = \left(V_f(m_i)/I_f(m_i)\right) \quad (6)$$

$$X_F(m_i) = imag\left(Z_F(m_i)\right) \quad (7)$$

by varying the per unit distance (m_i) from zero to 1, the FL is estimated at the position where the reactance is smallest. The required data used to estimate the fault reactance for each fault type are grouped in Table 1, and the flow chart of the proposed algorithm (FLA1) is showed in Figure 5.

Table 1. The required data to estimate the fault reactance for each fault type

Fault type	Fault reactance (Ohms)	Fault currents (A)	Fault voltages (V)
AG	$X_F(A)$	$I_F(A)$	$V_F(A)$
BG	$X_F(B)$	$I_F(B)$	$V_F(B)$
CG	$X_F(C)$	$I_F(C)$	$V_F(C)$
AB&ABG	$X_F(B)$-$X_F(A)$	$I_F(B)$& $I_F(A)$	$V_F(B)$& $V_F(A)$
AC&ACG	$X_F(C)$-$X_F(A)$	$I_F(C)$ & $I_F(A)$	$V_F(C)$ & $V_F(A)$
BC&BCG	$X_F(C)$-$X_F(B)$	$I_F(C)$ & $I_F(B)$	$V_F(C)$ & $V_F(B)$
ABC	$X_F(B)$-$X_F(A)$	$I_F(B)$ & $I_F(A)$	$V_F(B)$ & $V_F(A)$

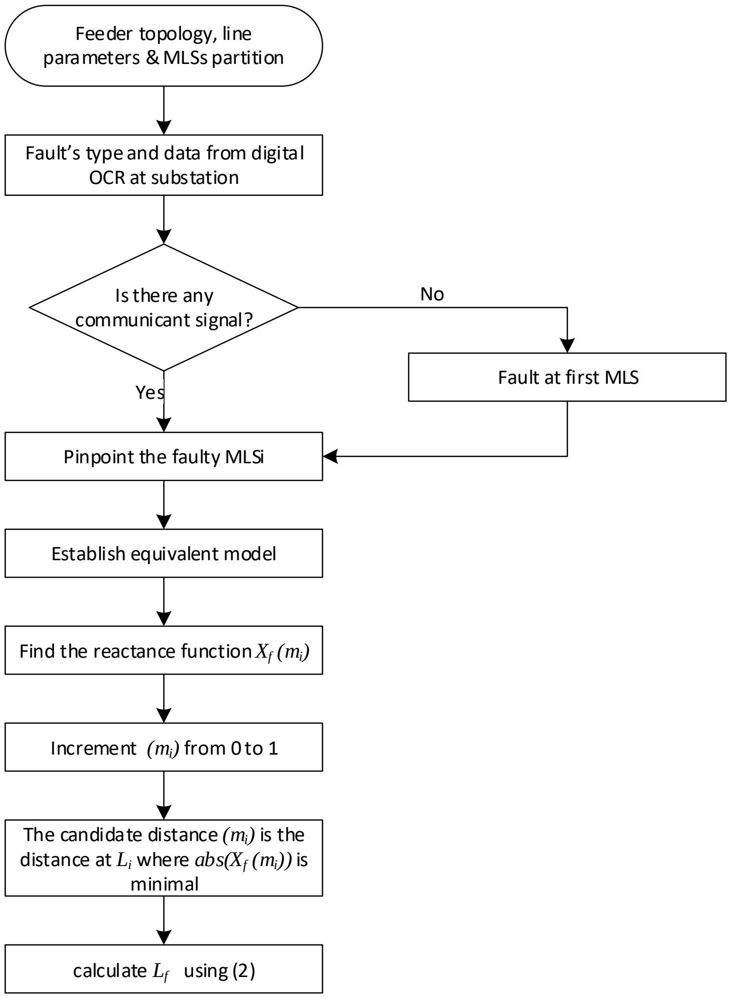


Figure 5. Flow-chart of the suggested approach using FLA1

2.3. Fault location algorithm using only currents measurements at a single sending end (FLA2)

The heterogeneity of PDSs (different types and dimensions of cables and lines, overhead and underground configurations, spread over geographic areas and exposed to wide range of a weather factors) makes line parameters vary and not always constants or even known, which has a direct effect on the accuracy of the bus impedance matrix. In addition, currents and voltages records at the sending/receiving ends are not always available. In some cases, optical character recognition (OCR) can record only currents from single terminal end. To overcome these limitations, an alternative methodology is suggested in this work. The approach uses only currents measurements at the sending extremity pre and during the fault state and without need of line parameters. The new suggested algorithm (FLA2) is based on the magnetic behavior of PDS during fault conditions, with the assumption of a "per unit" disturbance coefficient for each fault type. Let's assume a balanced PDS, in this case we have an equilibrate currents system.

$$I_a = I_b = I_c \quad (8)$$

The mutual magnetic flux (φ_{ab},φ_{ac},φ_{bC}) between phases can be written as

$$\varphi_{ab} = M_{ab}I_a = M_{ba}I_b = \varphi_{ba} \quad (9)$$

$$\varphi_{ac} = M_{ac}I_a = M_{ca}I_c = \varphi_{ca} \quad (10)$$

$$\varphi_{bc} = M_{bc}I_b = M_{cb}I_c = \varphi_{cb} \quad (11)$$

Due to the symmetrical geometries, the phases' mutual inductance parameters are equal to each other i.e. ($M_{ab} = M_{ba}$), ($M_{ac} = M_{ca}$), and ($M_{bc} = M_{cb}$). From (9)-(11), we suggest a healthy magnetic coupled coefficient (K_{hmn}), where (m, n) denote phases (a, b, c), and ($m \neq n$):

$$K_{hmn} = \varphi_{mn}/\varphi_{nm} = (M_{nm}I_n)/(M_{mn}I_m) = I_n/I_m \quad (12)$$

During fault conditions, the magnetic behavior of PDS will be change according to the fault type. Therefore, a fault magnetic coupled coefficient K_{fmn} is defined as (13),

$$K_{fmn} = I_{fn}/I_{fm} \quad (13)$$

where, I_{fn} and I_{fm} are the faulty currents. To interpret the magnetic perturbation caused by faults, a per unit disturbance coefficient K_{Pmn} depending on fault's type is assumed to be

$$K_{Pmn} = K_{fmn}/K_{hmn} \quad (14)$$

During pre-fault conditions, $K_{fmn} = K_{hmn}$, then ($K_{Pmn} = 1$). The per unit fault length m is calculated as in (15),

$$m = (1/K_{Pmn} during\ faulty\ conditions) \quad (15)$$

where ($0 < m < 1$); Then, the fault position estimation is (16),

$$L_f = mL_t \quad (16)$$

where L_f, L_t are fault distance and total length feeder, respectively.

2.3.1. Application for single line to ground (SLG) fault

Considering a SLG fault FAG occurred in phase (a) at distance (x) as shown in Figure 6(a). In this case the faulty phase will affect the healthy phases (b) and (c) by (K_{Pab}) and (K_{Pac}), respectively. m is defined as (17).

$$m = (1/K_{Pab}) + (1/K_{Pac}) \quad (17)$$

2.3.2. Application for line to line (LL) fault

Assuming an LL fault Fac as illustrated in Figure 6(b). In this case the faulty current $\left(I_{fc} = I_{fa}\right)$ and flowing in opposite direction, m is calculated as in (18).

$$m = 1/(0{,}5 * |[K_{Pab} - K_{Pac}]|) \quad (18)$$

2.3.3. Application for line to line to ground (LLG) fault

As shown in Figure 6(c), the faulty currents are flowing in the same direction ($I_g = I_{fc} + I_{fa}$), and we can get m as in (19).

$$m = 1/(0{,}5 * |[K_{Pab} + K_{Pac}]|) \quad (19)$$

The flow chart of the proposed procedure is given in Figure 7. The second proposed approach (FLA2) is compatible only for faults with lower resistances in the lack of line parameters, and it is incompatible for LLL and LLLG faults because of their symmetric behavior.

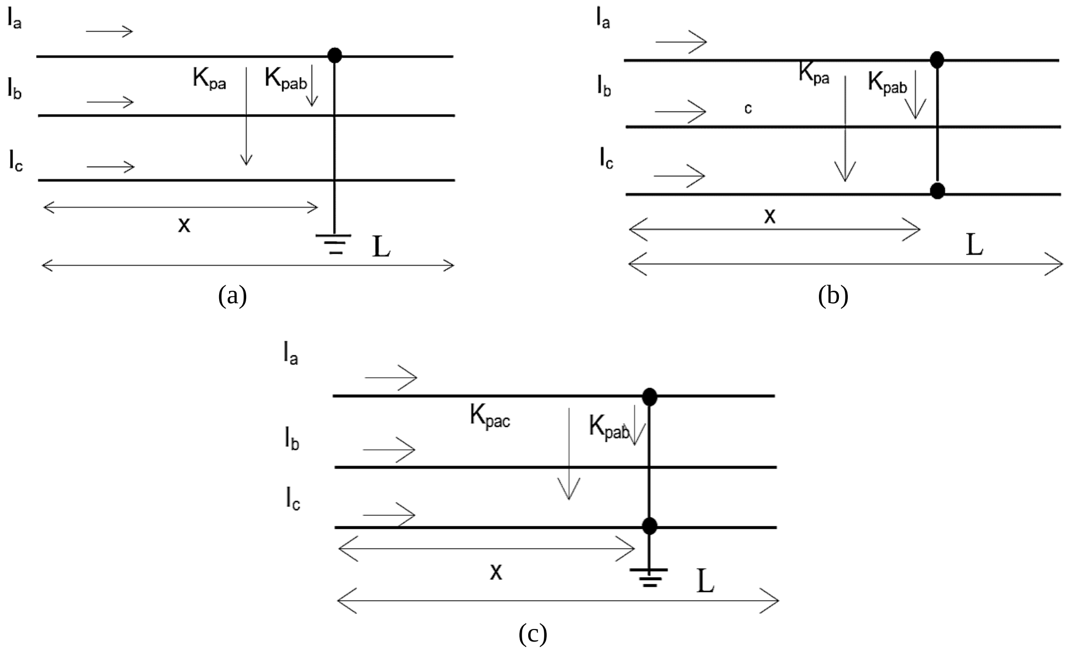


Figure 6. Fault types (a) SLG Fault, (b) LL fault, and (c) LLG fault

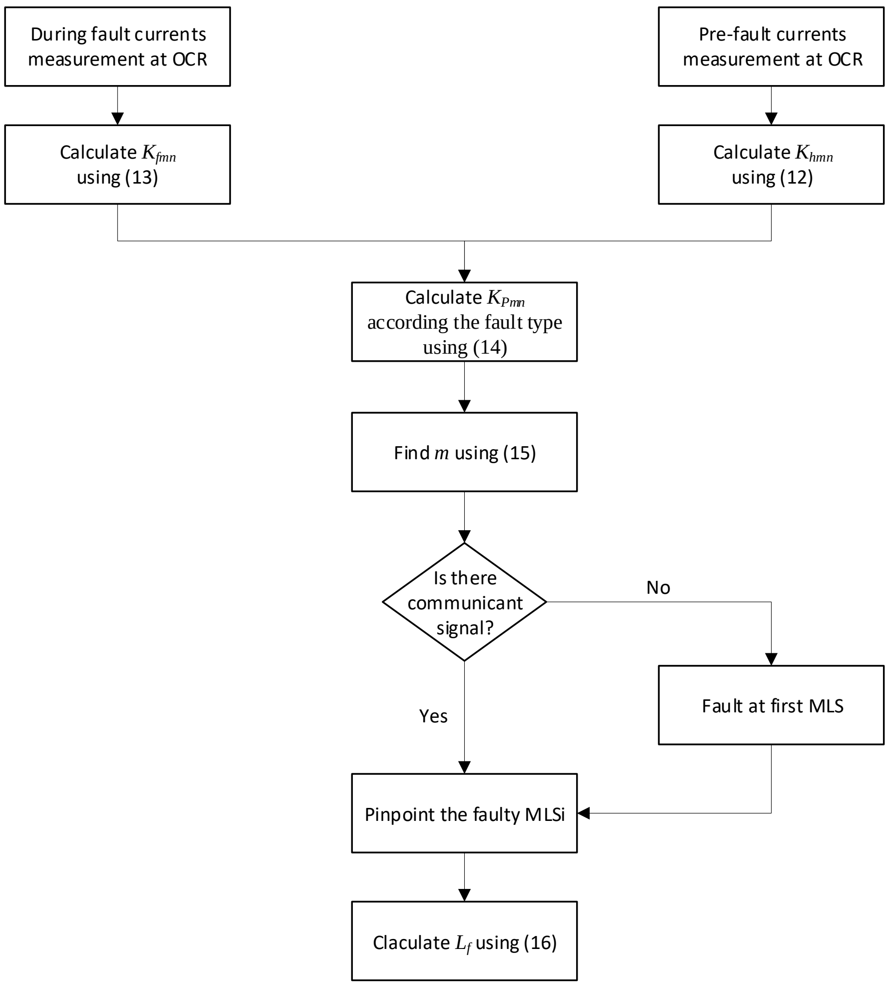


Figure 7. Flow-chart of the suggested approach using FLA2

3. TESTS AND RESULTS

The performance of the proposed approach is validated by considering two different PDSs. We have examined it initially on a standard IEEE network with 13 busbars. Then on a real PDS from the Algerian distribution network.

3.1. Case 1

For this case, the IEEE 13 Node test feeder is elected as a case study [27]. SLG, LLG and LLL fault at different positions were simulated using the Simulink/MATLAB environment [28]. Figure 8 shows the possible MLSs partitions of the analyzed feeder.

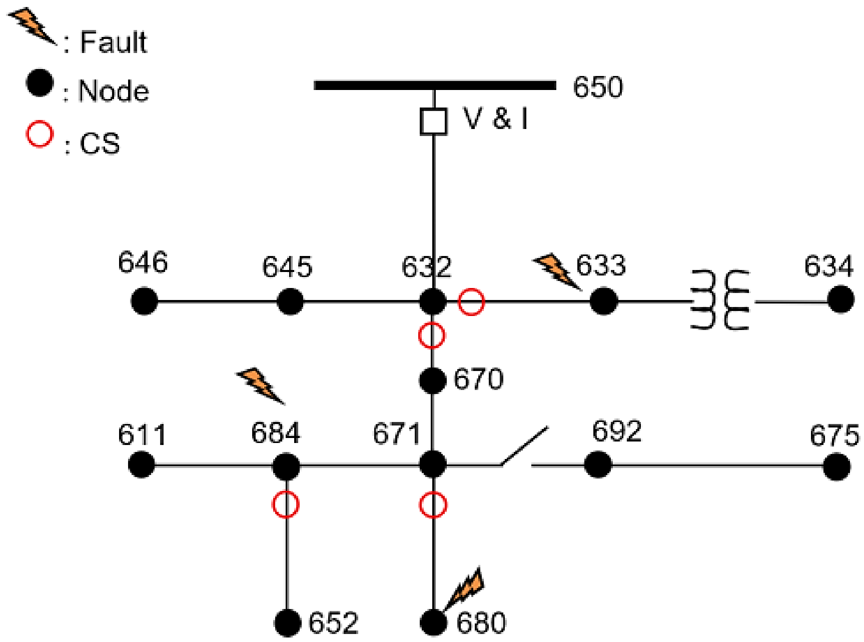


Figure 8. Possible MLSs for the IEEE 13 Node test feeder

Figure 9(a) shows the recorded currents at the sending extremity before and during a SLG fault case. The fundamental currents and voltage are analyzed using Fourier transform and employed to feed the FL process as input data. From Figure 9(b) we can see that, in order to distinguish between the inrush and the fault current a time delay is using. In this study a delay of (0.05 S) after the fault time (0.4 S) is set. Figure 10(a) shows that the approach proposed in [23] gives a fair accuracy. This means that the FL estimations depend strongly on the number of feeder's branches. However, Figure 10(b) results present a superior accuracy by using the new proposed approach. In this case, the healthy MLSs impedances (Z_{L1}, Z_{L2}) are evaluated and the FL process is employed only at the defective MLSi; this reduces the number of iterations and results unique FL candidate. In Figure 11, the results confirm the accuracy and feasibility of the novel approach for different types of faults. Errors are computed by (20) and grouped in Table 2 and Table 3.

$$Error(\%) = (|L_{real} - L_{est}|/L_t) * 100 \quad (20)$$

Where L_{real} is the real distance from the measurement position to the fault; L_{est} is the estimated fault, and L_t is the total length of the test feeder.

3.2. Case 2

To test the approach in the real world, a real radial PDS from the Algerian distribution network is selected. Its topology is showed in Figure 12. The elected feeder has 51 nodes, 30 kA, underground, and spread over a distance of 18,357 km with a total power of 15,933 MVA; for more details about the feeder characteristics readers can return to article [29]. Based on the selected PDS design, it has been partitioned into four (4) MLSs by inserting three CSs, as depicted in Figure 12.

Three real SLG fault cases are deliberately caused. These faults occurred at various load profiles and different distances throughout the PDS length (F1 at 3220 m, F2 at 5927 m, and F3 at 10290 m). Figures 13(a) and 13(b) represent a SLG fault components (current and voltage respectively) captured from the installed digital relay, at the sending extremity.

In Figures 14(a) and 14(b), experimental results confirm the reliability of the novel method by providing a high accuracy at different fault distances and different load profiles while giving unique FL compared to the previous method. Errors estimations are computed by (20) and represented in Table 4. From Tables 3 and 4, we can see that the second proposed approach (FLA2) is less accurate than the first proposed approach. However, it can be used in the absence of line parameters and when only currents measurements from one terminal-end are available.

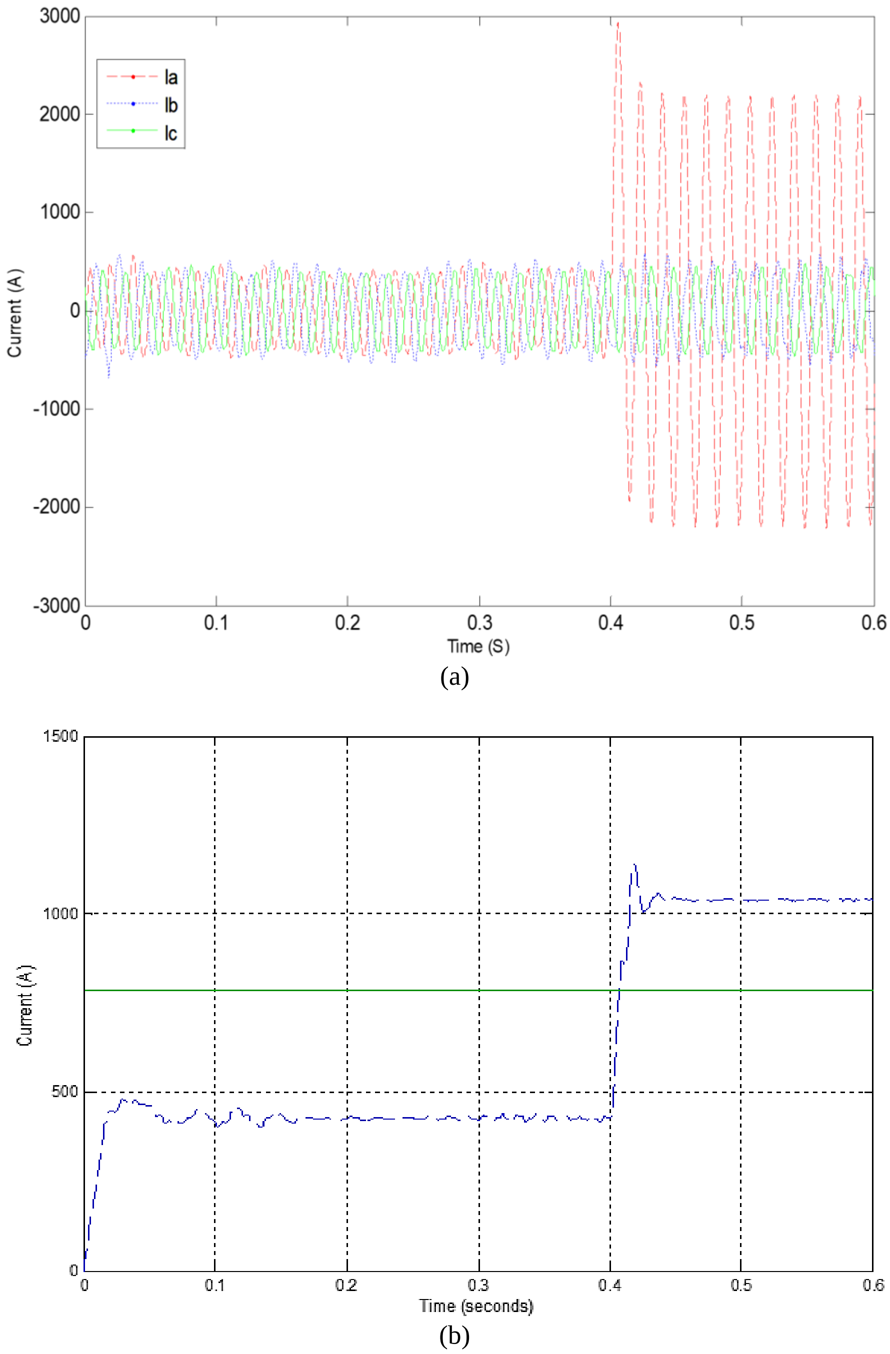
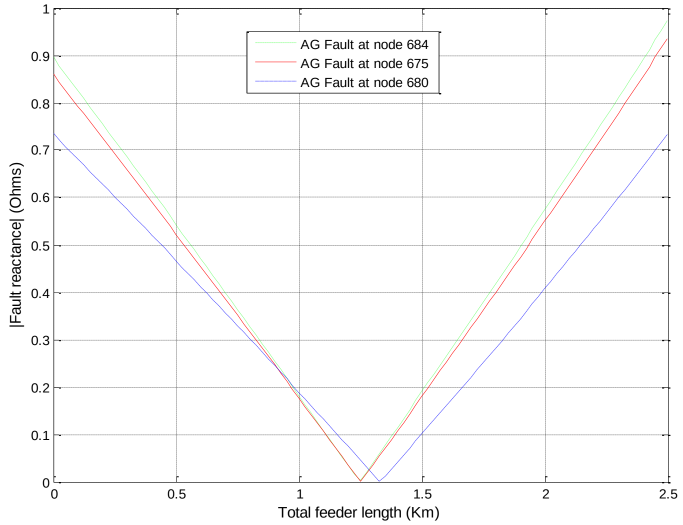
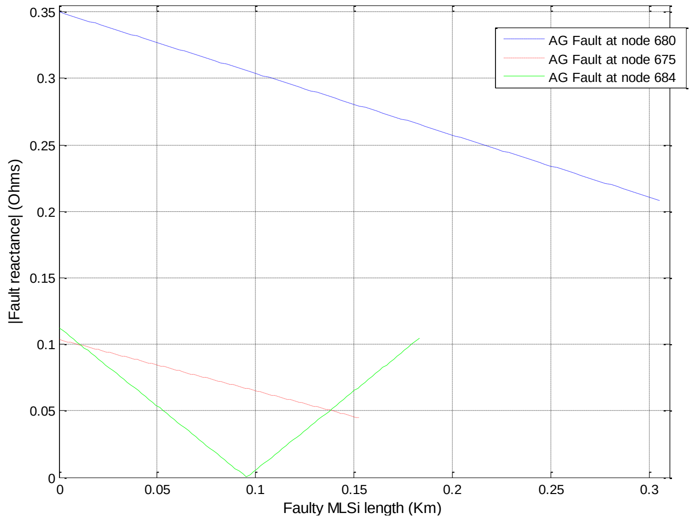


Figure 9. A pre and during fault currents case (a) fundamental current component using fourier transform and (b) using IEEE 13 Node test feeder



(a)



(b)

Figure 10. The absolute values of faults reactance on the IEEE 13 Node test feeder using (a) previous approach [23] and (b) the new proposed approach

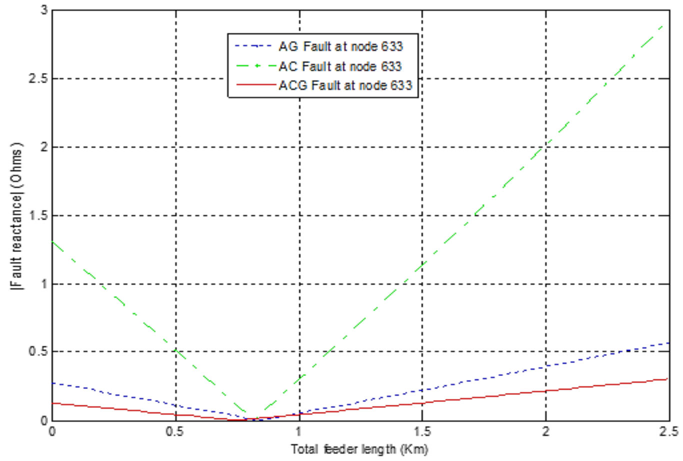


Figure 11. Fault reactance values on the IEEE 13 Node feeder using the novel methodology for different faults type

Table 2. Results of the proposed approach vs the approach [23] on the IEEE 13 node test feeder

Fault position	Fault type	Proposed approach errors (%) using FLA1	Approach of ref [23] errors (%)	Candidate fault location estimations	
				Proposed approach	approach of ref [23]
Node 684	AG	0.146	2.426	1	2
Node 680	AG	2.900	4.865	1	2
Node 675	AG	0.000	7.962	1	2

Table 3. Result comparisons between the FLA1 and FLA2 on the IEEE 13 node test feeder

Fault position	Fault type	Actual distance (p.u)	Proposed approach			
			FLA1		FLA2	
			Estimated distance (p.u)	Errors (%)	Estimated distance (p.u)	Errors (%)
Node 684	AG	0.524	0.550	0.146	0.422	17.44
	AC	0.524	0.460	6.400	0.332	18.64
	ACG	0.524	0.590	6.600	0.455	10.14
Node 680	AG	0.609	0.580	2.900	0.555	17.44
	AC	0.609	0.540	6.900	0.630	18.64
	ACG	0.609	0.530	7.900	0.843	10.14
Node 675	AG	0.340	0.340	0.000	0.360	08.99
	AC	0.340	0.330	1.000	0.302	12.09
	ACG	0.340	0.300	4.000	0.396	06.61

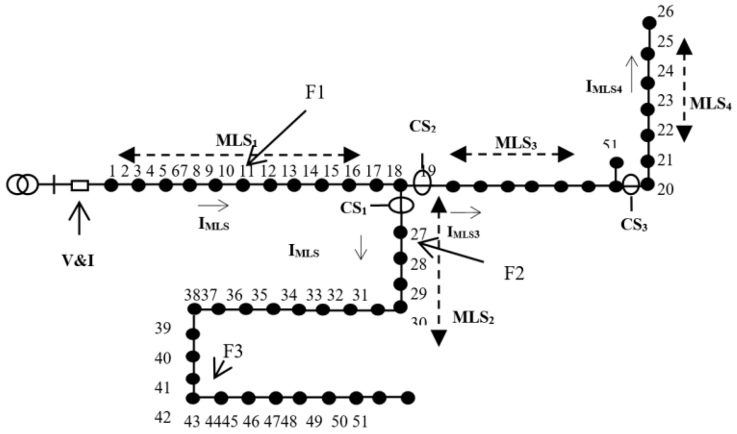
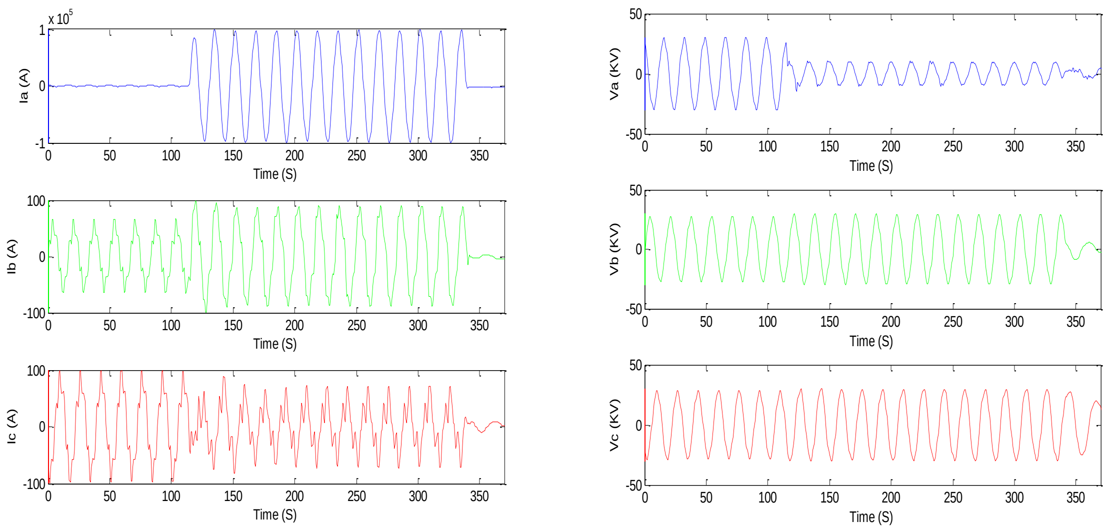
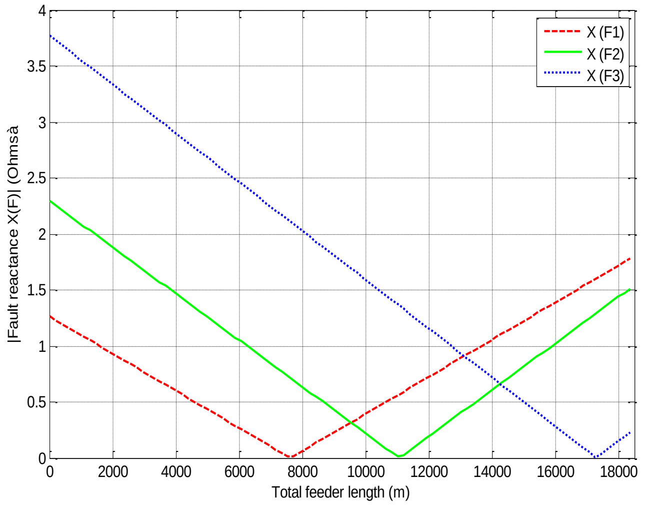


Figure 12. Real life feeder topology

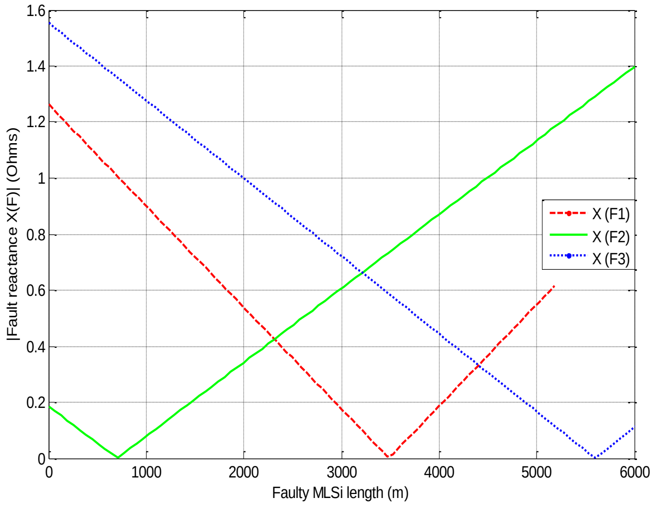


(a) (b)

Figure 13. The downloaded data from the OCR at the sending extremity during F1 fault (a) currents and (b) voltages



(a)



(b)

Figure 14. The absolutes values of faults reactance’s on the Algerian PDS using (a) the approach [23] and (b) proposed approach

Table 4. Proposed approach versus approach [23] on the Algerian PDS

Fault position	Fault type	Proposed approach errors (%)		Approach of ref [23] errors (%)	Candidate fault location estimations	
		Using FLA1	Using FLA2		Proposed approach	approach of ref [23]
F1	AG	2.879	15.97	6.460	1	2
F1	AG	0.855	16.24	3.715	1	2
F1	AG	0.119	12.40	0.054	1	2

4. CONCLUSION AND FUTURE WORK

In this article, the problem of multiple FL estimation in PDS is addressed using a new protocol. The approach is based on partitioning PDS into several possible MLS, and then combines different impedances calculation and measurements, in a predefined protocol to uniquely elect a faulty MLS, on which FL process is applied. This protocol offered a synergy to the legacy FL process and reduced the number of iterations, and hence speeded up the process which in turns will help operators to fix the fault and restore normal services with minimum delay. Two variants have been implemented, the first is an impedance-based algorithm (FLA1) that uses the serial line impedance of each homogeneous line-section, voltages, and currents measured at the sending extremity before and during the fault state. While the second, is used when lacking the line parameters (FLA2), which must use only the measurement of currents at a single extremity of the line. Real-world data have been feed to simulation and results obtained from the described approach were compared to real faults location, this demonstrated improvement in the precision in less time, thanks to the partitioning and candidate smart and genuine elections. The simulation results and the real-world experiments demonstrate that this work will improve fault location finding, and reduce the time required for the process and hence it will improve the overall service of the power distribution utilities, by reducing the complexity of such primordial challenge which is fault locating. However, the liberalization of the energy market and the integration of distributed generation (DG) resources units change the radial aspect of distribution systems to non-radial and multi-source systems. This new characteristic of the distribution system can affect the accuracy and the effectiveness of the FL method. Hence, there is a need more work in the future for the FL method to answer the issues due to the penetration of DG units.

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