Comprehensive Distribution Network Fault Location Using the Distributed Parameter Model

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***Abstract*—A typical low- or medium-voltage distribution feeder consists of numerous branches as well as laterals and heterogenic conductor lines. The lack of measurement points and the presence of unbalanced loads make it more complicated for the construction of fault-location algorithms. In this paper, a brief and comprehensive review is presented which introduces and compares published papers in this area to date. In addition, the authors have devised a single-end fault-location algorithm using the distributed parameter model to overcome all of the aforementioned limitations in distribution feeders. The validity of the devised algorithm is studied within the PSCAD-EMTDC environment. This model provides more accurate results as the distributed nature of losses and capacitive effects are considered whereas in the available algorithms, these are ignored. A comparison which is made between the proposed method and two of the most complete available algorithms shows the superiority of our algorithm. Also, the proposed algorithm is able to locate various fault types in the network that has different phase laterals unbalanced loads and heterogeneity of the feeder line.**

***Index Terms*—Distribution feeder, fault location, single end.**

I. Introduction

A TYPICAL low- or medium-voltage distribution feeder consists of many branches as well as laterals and different types of conductors. The presence of one-phase or three-phase loads that are resistive, inductive, or dynamic, results in the distribution network exhibiting complicated characteristics. The difficulty is further pronounced in low-voltage feeders because of private customers as end users and, hence, the availability of one terminal for signal measurement. The acrimony of these feeders is summarized as follows:

- heterogeneity of feeders given by different size and length of cables, presence of overhead and underground lines, etc.;
- unbalances due to the untransposed lines and by the presence of single-, double-, and three-phase loads;
- presence of laterals along the main feeder [1];
- presence of the load taps along the main feeder and laterals;
- dynamic characteristics of the loads.

One of the earliest fault-location algorithms belongs to Srinivasan [2], who used the concept of simplified distributed parameters for fault location. The presence of load taps beyond the fault is treated by consolidating those load models with that of the remote end load. The fault distance is obtained by solving an implicit equation. Single-phase-to-ground, phase-to-phase, and three-phase-to-ground faults are treated. Taking the loads and their variable impedance behavior into account was the main contribution which caused noticeable error reduction of the fault-location algorithm.

Later on, the fault-location scheme presented by Girgis [3], [4] attempted to account for the multiphase laterals, the unbalanced conditions, and the unsymmetrical nature of the distribution feeders by continually updating voltage and current vectors at set locations within the system. The distance to the fault is then estimated by using a method based on the apparent impedance approach. Further consideration is the ability to determine the fault location on a lateral.

The algorithm introduced by Zhu *et al.* [5] searches among all possible sections to locate the fault. If the fault is found, the algorithm stops; otherwise, it will proceed to the next section for the calculation of voltage and current feed of the next section. In addition, a dynamic load model similar to [2] is adopted. In the aforementioned paper [5], based on statistical calculations, fault distance error bound is estimated to show how far the maximum distance of the actual fault is from the calculated fault for a worse case (maximum error). Furthermore, based on available data from fuses and reclosers in the network, a novel method has been proposed to solve the multiestimation problem. According to the proposed method, the reduced amount of loads after the fault has occurred, and the switching pattern of the reclosers can determine the possible faulty branches of the network. This information, plus the calculated distance, could provide the exact faulty section. The same technique was published later on by Lee [6].

One example of the most comprehensive works in the distribution fault location area belongs to Aggarwal [7], [8]. The introduced algorithm utilizes superimposed components (differences between before fault and after fault values) to identify the fault location. All of the distribution network features, except the capacitive effect of the lines, have been considered in this paper. According to the algorithm, the fault current in the healthy phases should be zero. The fault distance is systematically varying until the time when the fault path current(s) in the healthy phases attains the minima. For this minimal point, if the current of the phase(s) is not zero, it is assumed that faulty phases exist. According to the algorithm, the seen admittance of the left and right side of the assumed fault point are calculated. Then, using the calculated admittance, the superimposed fault current is estimated. By moving the fault point throughout the feeder, a place that attains the minimum fault current in healthy phases is identified as a fault location.

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TABLE I
COMPARISON BETWEEN DIFFERENT FAULT-LOCATION METHODS

	Fault location methods											
	Srinivasan (1989)	Girgins (1993)	Zhu (1997)	Aggarwal (1997)	Das (2001)	Saha (2001)	Choi (2004)	Jamali (2004)	Lee (2004)	Yang (2008)	Salim (2009)	This paper
Distribution system												
Line model	SDPM*	Z matrix	Z matrix	Z matrix	SDPM	Z matrix	Z matrix	SDPM	Z matrix	DPM**	Z matrix	DPM
Load model	Dynamic	Static	Dynamic	Dynamic	Dynamic	Static	Static	Static	Dynamic	Static	Dynamic	Static
Load value	known	known	estimated	estimated	estimated	known	known	known	estimated	estimated	estimated	estimated
Non homogeneity	--	--	--	✓	--	--	--	✓	--	--	✓	✓
Unbalanced System	--	✓	✓	✓	✓	--	✓	--	✓	--	✓	✓
Laterals	--	✓	✓	✓	--	--	--	✓	✓	--	✓	✓
Load taps	✓	✓	✓	✓	✓	✓	--	✓	✓	✓	✓	✓
Fault type	all	all	all	all	L-G	all	L-G	all	all	L-G	all	all
Calculation domain												
Sequential domain	✓	✓			✓		✓			✓		✓
Phase domain		✓	✓	✓		✓		✓	✓		✓	

* Simplified Distributed Parameter Model
** Distributed Parameter Model

The algorithm of Srinivasan [2] has been further developed by Das *et al.* [9], [10]. Their method makes use of prefault data to estimate the load's value when the fault occurs and then uses the simplified distributed parameter model for the construction of the fault-location algorithm. In general, the value of the impedance and admittance per meter for a cable or transmission line is small, hence $\cosh(\gamma x)$ is approximated to 1 and similarly $\sinh(\gamma x)$ with γx. Furthermore, Das [9], [10] assumes that all loads beyond the fault point are lumped together and placed at the end of the line and the intermediate loads (the loads between the substation and fault point) are ignored. Also, their solution to fault distance uses a noniterative equation in which the higher orders of possible fault distances are ignored. Their presented results show good accuracy within the computer simulation environment.

The method introduced by Jamali *et al.* [11] is also based on the distributed parameter model and similar assumptions to the Das [9], [10] method, such as $\tanh \gamma x$ being equal to γx are made. In addition, they have assumed there is no phase difference between fault current and branch currents feeding the fault. Moreover, for any chosen path, the laterals and loads are modelled with lumped R-L-C elements and their algorithm searches over all possible routes in the network. In order to reduce the computation time, a pre-estimated fault-location point is sought which roughly approximates the fault distance. This approximation is feasible if the impedance characteristics of different sections are the same.

Yang *et al.* [12] have developed a new algorithm based on distributed parameters for locating single-phase-to-sheath-to-ground cable faults. The effects of sheath and sheath grounding are also considered in their method. According to their results, the algorithm is robust against fault distance and fault resistance variations. However, the error is relatively significant when loads are different from the nominal or the rated values. Furthermore, there is a stability problem, and the algorithm cannot converge to the solution for multisection networks.

Filomena *et al.* [13] have attempted to extend the concept of the π model fault location to underground distribution systems. The self and mutual impedance and admittance of cables are calculated according to Carson's equation. The application of the derived expressions in their proposed algorithm yields the distance to fault point. Laterals and loads are considered as lumped elements at relevant buses. Filomena *et al.* [13] have also demonstrated the importance of the capacitive effect in cable fault location which is ignored in most works reported to date.

In one of the latest works in the distribution system fault-location area, which is published by Salim [14], a fault diagnosis method based on artificial neural networks (ANNs) for fault section determination and the wavelet technique for fault detection and classification are presented. In continuation of the work, an extended impedance-based fault-location formulation for generalized distribution systems was introduced [15]. The method is based on the apparent impedance calculation and fundamental quantities. The formulation considers load variation effects and different fault types using only local voltages and currents as input data. The formulation is also suitable for large distribution systems containing laterals and sublaterals. Table I compares all of the aforementioned methods in terms of the ability to address the various characteristics of the distribution systems and the employed line model.

From publications reported to date, one paper [1] has been written for the purpose of comparison between different available algorithms in which authors have simulated and justly compared 10 different well-known methods on the same network. Of these, three methods are identified to be adaptable or applicable to feeders of various characteristics. Among these identified methods, the method proposed by Das *et al.* [9], [10] presents the most precise algorithms for locating faults in distribution feeders. Although the simple approaches proposed by Warrington and Novosel [16], [17] are suitable for most fault-location purposes, they fall short of being applicable to more complicated networks. Also, another review of different methods is available in [18].

There are a small number of published articles which have considered other aspects of fault location in distribution systems. Jarventausta [19] utilizes the fuzzy sets theory to model the uncertainty in the fault-location process of distribution networks. Darvish [20] made use of ANN for error correction of the computed fault distance. Han [21] introduced a new method for solving the multiestimation problem by injecting two sinusoidal signals with different frequencies and measuring the sending-end voltage and current. This method is applicable for locating single-phase-to ground faults on overhead lines. And, finally, the use of Bayesian networks on the basis of expert knowledge and historical data for fault location and diagnosis on distribution feeders has been introduced in [22].

In this paper, attempts are made to devise a single-end impedance-based fault-location algorithm for combined overhead lines and underground cables, which is based on the distributed parameter model. This model provides more accurate results since the distributed nature of losses and capacitive effects is considered which are ignored in the lumped model. A comparison between the proposed method and two of the most complete available algorithms shows the superiority of our proposed algorithm. Also, the algorithm is able to locate various fault types in the network that have different phase laterals, unbalanced loads, and heterogeneity of the feeder line.

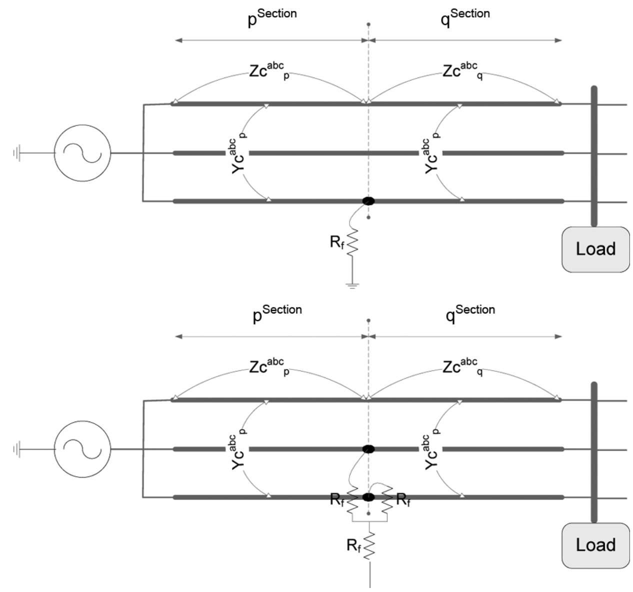

Fig. 1. Equivalent circuit section for the fault model.

II. Fault-Location Algorithm

A. Fault-Location Concept

In the proposed algorithm, the fault location is identified in two steps.

The first step includes an algorithm that suggests there is a fault in a section of the network.

The second step contains an algorithm that determines the next possible section and computes the voltage, current, and load values, which are necessary for fault-location purposes. After a thorough search over all possible routes/ branches, the possible fault location can be estimated.

Fig. 1 shows simulated faults in a section between the sending-end and the receiving-end buses. In the proposed method, the distributed parameter model is used to devise a fault-location algorithm. The distributed parameter model is derived from the well-known expressions

$$\begin{aligned}\partial V &= -Iz\partial x\\ \partial I &= -Vy\partial x\end{aligned} \tag{1}$$

where

- ∂V incremental voltage through the line;
- ∂I incremental current due to the capacitive effect of the line.

In the single-end fault-location method, the voltage and current values are measured only at one terminal. Here, the distributed parameters, propagation constant, and characteristic impedance are found through the EMTDC cable constant routine solution in the fundamental frequency domain. Therefore, the voltage and current values at the power system frequency are extracted from the measured waveforms using the fast Fourier transform technique. Furthermore, because different phases are coupled to each other in the phase domain, modal transform is applied by the transformation matrix to decouple the circuit equations. In this paper, the PSCAD modal transformation matrix is used to decouple the circuit equations. In the modal domain, each mode can be treated as a separate phase without coupling any other modes. Hence, the proposed algorithm is applied for each mode.

As mentioned before, the cable or line constant routine of PSCAD is used for deriving the impedance (in ohms per meter) and admittance (Mho/m) values of the cable or overhead line. Equation (2) shows the relation of voltages and currents for different points of a section in the modal domain. A^k, B^k, E^k and F^k are equation constants and have to be solved iteratively from boundary condition equations. γ^k is equal $\sqrt{Z^k \Upsilon^k}$ and k shows the zero, positive, and negative sequences, respectively. C^k is equal to $-\Upsilon/\gamma$

$$\begin{aligned}\begin{pmatrix} V_p^k(x_p) \\ I_p^k(x_p)\end{pmatrix} &= \begin{pmatrix}\cosh(\gamma^k x_p) & \sinh(\gamma^k x_p)\\ C^k\sinh(\gamma^k x_p) & C^k\cosh(\gamma^k x_p)\end{pmatrix}\begin{pmatrix}A^k\\ B^k\end{pmatrix}\\ \begin{pmatrix} V_q^k(x_q) \\ I_q^k(x_q)\end{pmatrix} &= \begin{pmatrix}\cosh(\gamma^k x_q) & \sinh(\gamma^k x_q)\\ C^k\sinh(\gamma^k x_q) & C^k\cosh(\gamma^k x_q)\end{pmatrix}\begin{pmatrix}E^k\\ F^k\end{pmatrix}.\end{aligned} \tag{2}$$

x_p stands for a distance between the fault point and the sending end of a section and x_q represents the distance from the fault point to the receiving end.

B. Boundary Conditions

1) Phase-to-Ground Fault: The solution of (2) provides the voltage and current values at any point in a section. However, first, the value of all constants must be determined by boundary conditions. A^k and B^k can be obtained by using (3), where $\mathrm{V_s}$ and $\mathrm{I_s}$ are the measured values at the sending end of the line or cable

$$\begin{aligned}V_p^k(0) &= A^k = V_s\\ I_p^k(0) &= C^k B^k = I_s.\end{aligned} \tag{3}$$

Boundary equations between the p and q sections are used for obtaining a constant value for E^k. Here, it is assumed that the voltage at the end of section p is equal to the voltage at the beginning of section q, and (4) gives the value of E^k. In the following formulas, x represents the fault point

$$\begin{aligned} V_p^k(x) &= V_q^k(0) = E^k \\ I_p^{b,c}(x) &= I_q^{b,c}(0). \end{aligned} \tag{4}$$

Since the fault produces discontinuity in the current flow at the fault point, (4) is not valid for a faulty phase. Hence, the value of the current should be obtained in conjunction with the boundary condition at the load points. According to Ohm's law, (5) is held for current and voltage values of the load at the end of the line. Z_{load} is the load impedance value for the faulty phase and l is the length of the entire line

$$Z_{\text{load}}^{\text{eq}^a} I_q^a(l-x) = V_q^a(l-x). \tag{5}$$

By assuming a pure resistive fault, the fault distance can be calculated by equalizing the imaginary part of fault resistance to zero in (6). The fault distance for single phase to ground is solved with the Newton–Raphson method

$$\begin{aligned} &F_{\text{PhaseToGround}}(x) \\ &\quad = \text{imag}(R_f) = \text{imag}\left(\frac{V_p^a(x)}{I_p^a(x) - I_q^a(0)}\right) = 0. \end{aligned} \tag{6}$$

2) Phase-To-Phase Fault: The preceding concept described in the previous section can be applied for finding the phase-to-phase fault (the phase A to B fault is used here as an example). However, in this case, (4) should be replaced by the following equations:

$$\begin{aligned} V_p^k(x) &= V_q^k(0) = E^k \\ I_p^c(x) &= I_q^c(0) \\ I_p^a(x) + I_p^b(x) &= I_q^a(0) + I_q^b(0). \end{aligned} \tag{7}$$

By applying the Newton–Raphson iterative method to the following equation, the fault distance for the phase-to-phase fault will be solved:

$$\begin{aligned} &F_{\text{PhaseToPhase}}(x) \\ &\quad = \text{imag}(R_f) = \text{imag}\left(\frac{V_p^a(x) - V_p^b(x)}{I_p^a(x) - I_q^a(0)}\right) = 0. \end{aligned} \tag{8}$$

3) Phase-to-Phase-to-Ground Fault: A similar concept to that shown in Section II-B-1 with some changes is used here for determining the boundary conditions in the case of phase-to-phase-to-ground faults. In an instant, in a phase-a-to-b-to-ground fault, (4) and (5) should be replaced with (9) and (10), respectively

$$\begin{aligned} V_p^k(x) &= V_q^k(0) = E^k \\ I_p^c(x) &= I_q^c(0) \end{aligned} \tag{9}$$

$$\begin{aligned} Z_{\text{load}}^{\text{eq}^a} I_q^a(l-x) &= V_q^a(l-x) \\ Z_{\text{load}}^{\text{eq}^b} I_q^b(l-x) &= V_q^b(l-x). \end{aligned} \tag{10}$$

By applying the Newton-Raphson iterative method to (11), the fault distance for the phase-to-phase-to-ground fault will be solved

$$\begin{aligned} &F_{\text{PhaseToPhaseToGround}}(x) = \text{imag}(R_f) \\ &\quad = \text{imag}\left(\frac{V_p^a(x) - V_p^b(x)}{\left(I_p^a(x) - I_q^a(0)\right) - \left(I_p^b(x) - I_q^b(0)\right)}\right) = 0. \end{aligned} \tag{11}$$

The previously presented fault-location methods can cover all different types of faults. However, an equivalent set of boundary conditions should be used for other fault types. Due to the similarity and brevity, the boundary conditions for other fault types have not been presented in this paper.

III. Generalized Algorithm for the Multisection Distribution Feeder

A. Heterogeneity

A distribution feeder is composed of many sections with unbalanced laterals and loads as well as heterogenic lines. Each section could consist of the overhead line and cable or be composed of different types of underground cable with possible unbalanced (one, two, or three phase) loads. The proposed algorithm for networks of such characteristics searches each section individually for fault points, and the search starts from the first section or distribution substation. If the calculated fault point is within the length of the section, the fault distance can be found. Otherwise, the sending-end voltage and current values for the next section are calculated before the algorithm proceeds to the next section.

This method of investigating network sections individually enables different line parameters, and characteristics are set for each section. Setting different parameters for each section enables the algorithm to take the heterogeneity of the lines into account.

B. Load Values Estimations

Considering accurate estimations of load values is really important to develop a precise fault-location algorithm [23]. This is achieved through a three-phase power-flow approach, using the prefault data. As a result, the equivalent impedance of all branches as well as loads are calculated in normal conditions. By considering resistive and inductive loads, and assuming the impedance value of loads remains constant after the fault, then the amount of current flowing in all healthy branches can be calculated according to (12). Subtracting the fault current from load current in each section will provide the exact value of feeding fault current for the next section. The more precise the fault current, the more precise the fault distance estimation.

C. Load Taps and Laterals

Due to the presence of unbalanced loads and laterals before the fault point, the sending-end current of the next section will be calculated as shown in (12) from the receiving-end current of the previous section. The sending-end voltage is equal to the receiving-end voltage of the previous section

$$\begin{aligned} Is_{\text{NextSection}} &= Ir_{\text{PreviousSection}} - (I_{\text{Load}} + I_{\text{Latelal}}) \\ I_{\text{Load}} &= \frac{V_{abc}}{Z_{\text{Load(estimated)}}} \\ I_{\text{Lateral}} &= \frac{V_{abc}}{Z_{\text{Lateral(equivalent)}}} \end{aligned} \tag{12}$$

where

Z_{Load}	load impedance which is estimated from the prefault data by three-phase power flow; it can be a balanced load (three phase) or unbalanced (one or two phase);
Z_{Lateral}	equivalent lateral impedance which is again estimated from the prefault data by three-phase power flow; it can be a balanced load (three phase) or unbalanced (one or two phase);
$Is_{\text{NextSection}}$	sending end of the current section;
$Ir_{\text{PreviousSection}}$	receiving end of the previous section.

In general, when the fault resistance is small in comparison with loads, the loads can be neglected. This means that one can assume there is no current flow in the healthy laterals or branches. But in the case of a higher resistance fault (5 Ω and over), this assumption leads to a noticeable error in the results. Therefore, for the calculation of the high-resistance fault point, the amount of current flow into the healthy laterals and branches should be calculated or, in other words, the effect of loads must be considered.

Despite the branch impedance being small in comparison with the loads (which is less than 0.01 Ω), assuming the line of the branch has ideal connections, hence neglecting the line resistance will still produce conspicuous errors in the results. Therefore, to prevent these errors, the voltage and current of all nodes and, hence, all loads are estimated through a three-phase power-flow calculation using the prefault data. The estimated current of each branch is subtracted from the fault path for assessing the exact value of fault current feeding the fault point.

D. Faults on a Single-Phase Lateral

The single-phase-to-ground fault-location algorithm with some modifications is used here. Instead of three matrixes for zero, positive, and negative sequences, just a single-phase distributed parameter line model is used. And instead of solving 12 unknowns, only 4 unknowns should be solved from boundary conditions. After calculating the sending-end voltage and current of the lateral from (12), the unknowns of the matrix below should be solved

$$\begin{aligned} \begin{pmatrix} V_p(x_p) \\ I_p(x_p) \end{pmatrix} &= \begin{pmatrix} \cosh(\gamma x_p) & \sinh(\gamma x_p) \\ C\sinh(\gamma x_p) & C\cosh(\gamma x_p) \end{pmatrix} \begin{pmatrix} A \\ B \end{pmatrix} \\ \begin{pmatrix} V_q(x_q) \\ I_q(x_q) \end{pmatrix} &= \begin{pmatrix} \cosh(\gamma x_q) & \sinh(\gamma x_q) \\ C\sinh(\gamma x_q) & C\cosh(\gamma x_q) \end{pmatrix} \begin{pmatrix} E \\ F \end{pmatrix} \end{aligned} \tag{13}$$

The constants are $C = -y/\gamma$ and $\gamma = \sqrt{zy}$. The coefficients A and B can be found by considering the following boundary conditions:

$$V(0) = V_S, I(0) = I_S.$$

By solving the aforementioned boundary conditions, we have

$$A = V_S, B = \left(\frac{-y}{\gamma}\right) I_S.$$

Similarly, the constant E and F can be solved. Applying (6) with the Newton–Raphson method will give us the fault distance.

Algorithm Flowchart and Assumptions

In the presence of laterals in complicated networks, multiple estimations will be provided by the algorithm. The number of estimates for a fault depends on the system configuration and the location of the fault. Various methods can be used to overcome this problem, such as fault indicators, customer calls, or intelligent fault diagnosis schemes, such as current pattern-matching rules [5], [6] and the artificial neural networks (ANN) method [14]. Information from these techniques is combined with multiple estimates to arrive at a single estimate for the location of a fault.

The iterative processes for finding the fault distance can be explained as follows.

- Step 1) Measure the voltage and current from the substation node (first node of the network).
- Step 2) Extract the fundamental frequency from the measured data.
- Step 3) Start the fault investigation for the first section.
- Step 4) Start with an initial guess for the fault distance X_1.
- Step 5) Find all constants by solving boundary condition equations.
- Step 6) Determine the voltage and current of the faulted point.
- Step 7) Calculate the distance X_{i+1} from (6), (8), or (11).
- Step 8) If $|X_{i+1} - X_i| < \varepsilon$, the fault is found; otherwise, repeat from Step 7).
- Step 9) If the estimated distance is within the length of the section, stop the algorithm; otherwise, calculate the sending-end voltage and current for the next section from (12); then go to Step 4).
- Step 10) Stop the algorithm when all sections have been investigated.

IV. Result and Discussion

In order to test the proposed method, a modified real underground distribution feeder of the Electric Energy State Company of Rio Grande do Sul (CEEE), Brazil [13] is simulated with PSCAD-EMTDC. Fig. 2 shows the network configuration, and the relevant data are presented in Tables II and IV. As a result of modification, the laterals are changed from three phase to one phase to show the ability of the algorithm to find the fault point in unbalanced systems. Also, cable data are modified [12] according to Table III due to the unavailability of cable data in [13]. Utilizing the EMTDC cable constant program, the

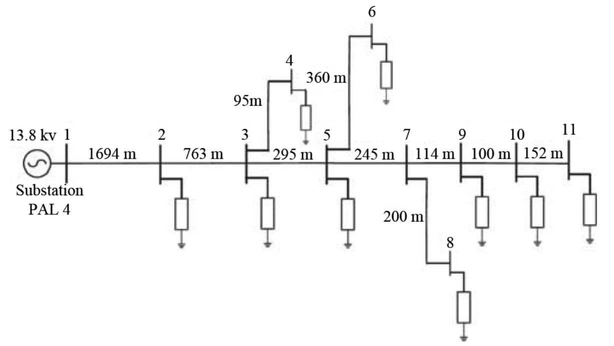

Fig. 2. Equivalent circuit network for the fault model [13].

TABLE II
BRANCH DATA

BUS FROM	BUS TO	DISTANCE	TYPE
1	2	1694	*3 Phase*
2	3	763	*3 Phase*
3	4	95	*Phase A*
3	5	295	*3 Phase*
5	6	360	*Phase B*
5	7	245	*3 Phase*
7	8	200	*Phase C*
7	9	114	*3 Phase*
9	10	100	*3 Phase*
10	11	152	*3 Phase*

TABLE III
CABLE PARAMETERS DATA

CABLE PARAMETERS	VALUE
Core inner radius	0.007
Core outer radius	0.02895
Core resistivity	1.7241E-8
Insulator 1 outer radius	0.04245
Sheath outer radius	0.04515
Sheath resistivity	2.84E-8
Insulator 2 outer radius	0.04965
Relative permeability for all conductors	1
Relative permeability for all insulators	1
Relative permittivity for all insulators	3.4

impedance and admittance of the conductors are obtained. It is assumed that the sheath is perfectly grounded and cross bonded.

A. Effect of Fault Resistance and Fault Distance Variation

The percentage error shown in Figs. 3 and 4 is calculated from the following expression:

$$\text{Error}(\%) = \frac{\text{Estimated Location - Actual Fault Location}}{\text{Actual Fault Location}} \times 100. \tag{14}$$

TABLE IV
LOAD DATA

BUS NUMBER	RESISTANCE (Ω)	REACTANCE (Ω)
2	646.5	131.3
3	129.3	26.3
4	646.5	131.3
5	215.5	43.8
6	538.8	109.34
8	215.5	43.8
9	538.8	109.4
10	538.8	109.4
11	646.5	131.3

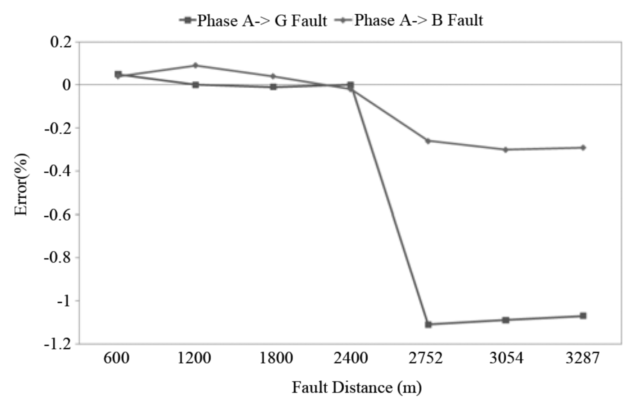

Fig. 3. Fault Location Error for $\mathrm{RF} = 10\ \Omega$.

TABLE V
FAULT ERROR IN THE UNBALANCED LATERALS

R_F (Ω)	ERROR (%)	ERROR DISTANCE (M)	FAULT LOCATION (M)	TYPE
1	1.79	45	2507	PHASE A
	-2.27	-68.1	3000	PHASE B
	2.54	78.7	3097	PHASE C
10	-1.58	-39.5	2507	PHASE A
	-3.34	-100.2	3000	PHASE B
	3.36	104	3097	PHASE C

As illustrated, there is no similarity between the fault distance and the estimated error profiles. However, the comparison of Figs. 3 and 4 suggests that if the fault resistance is increased, the error will also increase. For example, increasing the fault resistance from 1 to 10 Ω leads to an increase in error from less than 0.1% to around 2%.

B. Unbalanced Loads and Laterals

For demonstrating the ability of the algorithm to find fault points for an unbalanced feeder, three faults are produced on single phase laterals which is quite common in distribution systems. The laterals are single phase and respectively branched from phase A, B and C. The results are shown in Table V.

TABLE VI
FAULT ERROR COMPARISON IN METER AND PERCENTAGE (%)

FAULT LOCATION	FAULT RESISTANCE = 1Ω						FAULT RESISTANCE = 10Ω					
	PROPOSED METHOD		ZHU		SALIM		PROPOSED METHOD		ZHU		SALIM	
METER	METER	%	METER	%	METER	%	METER	%	METER	%	METER	%
600	0.2	-0.04	-54.9	9.15	52.2	-8.7	-0.3	0.05	488.9	-81.48	-16.1	2.68
1200	0.5	-0.04	-116.8	9.73	109	-9.08	0.0	0	420.5	-35.04	-30.3	2.53
1800	0.1	0	-7.7	0.43	169.9	-9.44	0.1	-0.01	355.5	-19.75	-243.5	13.53
2400	0.3	-0.01	-69.7	2.9	44.3	-1.85	0.1	0	175.4	-7.31	DIVERGED	--
2752	0.5	-0.02	-28.5	1.04	25.3	-0.92	30.4	-1.11	114.1	-4.15	DIVERGED	--
3054	0	0	-4.8	0.16	38.4	-1.26	33.4	-1.09	104	-3.41	DIVERGED	--
3287	0.1	0	-6.5	0.2	21.6	-0.66	35.1	-1.07	63.4	-1.93	DIVERGED	--

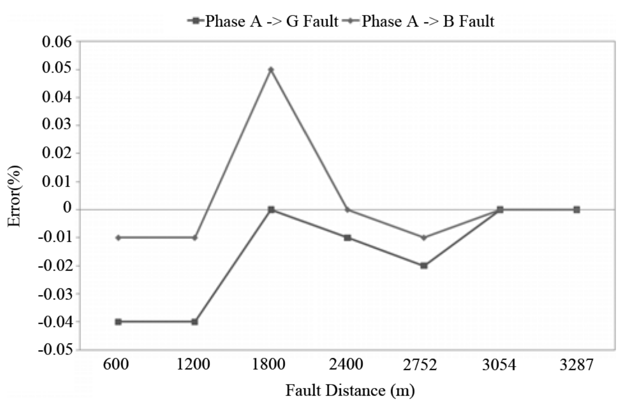

Fig. 4. Fault-location error for $\mathrm{RF} = 1\ \Omega$.

C. Comparison With Previous Methods

To demonstrate the superiority of this method over proposed methods to date, a comparison between the proposed method in this paper and the methods of Zhu [5] and Salim [15] is presented. These methods are deliberately chosen from the best algorithms introduced for distribution systems fault location until now (Table I). These algorithms cover all fault-location characteristics which are necessary for distribution systems.

Table VI shows the comparisons of the algorithms mentioned before and the proposed algorithm in this paper for a single-phase-to-ground fault at two different fault resistances. For calculating the voltage and current in each section (Section III-C), it is assumed that all methods are using same power-flow algorithm, whereas in the power-flow algorithm, the capacitive effect is not considered as is the case in the methods of Salim and Zhu. Furthermore, the Salim and Zhu methods will diverge for the faults placed after the second bus. Since their algorithms use a short line model, consequently the adapted power-flow method is based on a short line model as well. However, the same power-flow method for calculating the voltage and current of different nodes in a network, which consists of distributed capacitance, will produce considerable errors.

As illustrated, the difference even in low fault resistance is considerable. By increasing the length of the line section or fault resistance, the accuracy of their method will be dramatically decreased. In addition, Salim's method is unable to converge to the solution for higher fault resistances.

The main difference between the proposed method in this paper and the methods of Zhu and Salim is the line model where the effect of the Y-impedance matrix is not considered. Although the short line model gives good accuracy for calculating the line voltage and current, this is not enough for fault location, especially in underground cables where the capacitive effect should be considered to avoid a large amount of error.

D. Discussion

The method of confirming the algorithm is important; for example, it is possible to simulate a line with simple impedance, the exact π model, or more intricate methods, such as frequency-dependent models. These methods are available in all well-known and globally accepted packages, such as Electromagnetic Transient Program (EMTP) and PSCAD. Frequency-dependent models are not accurate enough for studies in the fundamental frequency range. On the other hand, the exact π, distributed parameters, and Bergeron models due to their accuracy in fundamental frequency are more suitable for fault location. Hence, many researchers have used simple impedance or π methods for confirmation of their algorithms. Simulating a line or feeder with simple impedance does not consider the effect of capacitance; furthermore, utilizing the exact π model neglects the nature of the distributed capacitive effect, both which can produce an error. This error is the simulation error and is not included in the reported errors by researchers to date. For example, an algorithm that neglects the admittance of the line is proposed. The estimated fault distances are compared with a simulation which again neglects the admittance of the line. This error is not reflected in the results reported by the authors. Therefore, the confirming simulation should be the most precise model as the distributed parameters here are chosen.

V. CONCLUSION

This paper has proposed a method for the location of faults in distribution feeders utilizing single-end measurements. Heterogeneity, the existence of unknown loads and unbalanced loads, and unbalanced laterals are the challenging characteristics of a distribution feeder. All mentioned characteristics are considered in the proposed fault-location algorithm.

Estimated fault distances show high accuracy in low resistance faults. However, because the fault current will be comparable with load currents in higher fault resistances, errors increase. Due to the important effect of load modelling on accuracy [23], [24], the effect of all loads (intermediate loads before the fault point as well as loads placed after the fault point) is taken into account by performing three-phase distribution system load flow.

The proposed algorithm is compared with two of the most complete methods published to date to confirm the superiority of the work in terms of accuracy. In distribution system fault location, taking into account the capacitive effect of lines plays an important role for precisely locating the fault. Although ignoring the capacitance might not be important in short overhead lines, when it comes to cables, it can have a great influence on accuracy. The result of the comparison furthermore reveals that methods, which ignore the capacitive effect, are unable to converge to a solution. Among reported papers to date, only [2], [9], [13], and [25] consider the capacitive effect in their algorithms and among them, the work done by [25] is the most comprehensive work considering the π model for fault location.

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