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Substation-centric Impedance-based Fault Location for Multi-Terminal Electric Distribution Networks

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Abstract

Automated and accurate fault location was attempted by many researchers employing various types of classical deterministic and modern stochastic algorithms. While modern knowledge-based algorithms are emerging as excellent alternatives for an accurate pinpointing of fault location in power networks, classical impedance-based algorithms are still struggling to compete and compute accurate fault location. The main advantages of the impedance-based algorithms are that they are simple, direct, economical and easy to equip into standard protective devices. In this work, Impedance-based algorithm is applied to an IEEE 13 node distribution network. The results of the work are encouraging despite the algorithm's drawback of multi-estimations for multi-terminal distribution network. The central substation fundamental components of fault currents and voltages were used for the estimation of fault location on any of the line-sections of the distribution network. The fault location estimation of the algorithm guides the power restoration crew in speedily reaching the fault site. Consequently, the power can be restored quickly to the connected customers, and the power drainage into faults can be reduced, which directly contributes towards power system reliability and economy.

Keywords: fault location; electric power distribution lines; impedance-based algorithm; power system reliability.

INTRODUCTION

Background

Fault location in power networks today cannot be relied on manual methods [1,2] of patrolling by road or air, for they are onerous and extremely time-consuming exercises. The automated and accurate fault location plays a great role in enhancing the power system reliability and economy. The valuable information about fault location enables the substation maintenance crew to quickly rush to the faulted site, repair and restore power supply to affected customers. The faster process of power restoration reduces customer interruption duration and loss of generated electrical energy. The researchers have explored many automated methods/techniques for accurately pinpointing the fault position. The fault location methods can be classified into four categories - Fundamental frequency methods, Traveling wave method, High frequency method and Knowledge-based techniques. Every method has its inherent merits and demerits.

A simple and economical way of determining the fault location is by employing the fundamental frequency methods, which are popularly called as Impedance-based methods. In these methods, fundamental voltages and currents, and the line parameters, are used to calculate the apparent impedance of the faulted line. The calculated impedance is a measure proportional to the fault distance. These methods are further classified as one-end or two-end algorithms depending on the availability of fault voltage and current data at the ends of the faulted line. The two-end impedance-based algorithms are inherently more accurate and robust than one-end impedance-based type, for the two-end fault data is complete and sufficient for building more deterministic circuit equations for the calculation of fault location. Yet, one-end fault-location algorithms were worked out by many researchers with adequate accuracy for most of the real time applications. Despite data insufficiency, the one-end algorithms are more economical and popular, for they obviate the need for costly communication equipment. More so, they can be easily equipped into protective relays or disturbance recorders. However, the two-end algorithms are more accurate than one-end type. Hence, if the low-speed communication channels are pre-existing, two-end algorithms are technically more preferred.

Distinctiveness of Fault Location in Distribution Networks [3]

Fault location in medium voltage distribution networks is more complex compared to that of high voltage transmission networks. Fault locators are equipped into every line of transmission networks. The algorithms employed in these locators simply include mathematical circuit equations for the calculation of distance to a fault by utilizing the voltage and current signals. But, the distribution line conductors are typically heterogenous, having highly ramifying branches and multiple load taps distributed along the line, which makes the fault location algorithm more complex [4]. Since it is uneconomical to dedicate a device to every feeder or line-section, the fault locators are typically substation-centric monitoring the voltages and currents at the substation. Therefore, the estimation of fault location in distribution networks involves more complex mathematical expressions.

Besides the above cited reasons, some more specific reasons, viz. non-availability of current in a faulted line, compensation inaccuracy of pre-fault load current in a faulted line, multi-terminal nature of networks, inadequate compensation of load variations, etc., also contribute towards to complexity.

Impedance-Based Algorithms

In distribution networks fault devices are centrally located, which lead to errors for reasons cited in the previous section. Various algorithms were developed to minimize the errors. The block diagram of the Apparent-impedance based algorithms is presented in Figure 1. These algorithms have following fundamental steps/stages in common.

(i) Pre-fault steady state condition - Calculation of positive and zero-sequence impedance in all nodes of the network using the existing feeder topology and load profile.

(ii) Fault condition – Calculation of specific fault-loop parameters for every fault type and the place of measurements (either at transformer or faulty-feeder), which enables to find fault position.

(iii) Final estimation of fault location - by the elimination of unlikely fault locations using consistent logic or procedure or technique.

The final stage is paramount, more particularly for fault location on distribution lines. It is highly imperative to employ an advanced tool or technique to arrive at an accurate estimation. The current research trends are more inclined towards artificial intelligence tools and techniques [5, 6]. The accuracy of the algorithms can be enhanced with the accuracy of system data. These methods involve calculation of apparent impedance and fundamental quantities. If dynamic load variations are duly compensated, accuracy can be improved.

Classical Impedance-based algorithms [7-11] have evolved, and they remain as popular fault location methods till to this day. The research is still in progress to upgrade and uplift the accuracy offered by these algorithms, and they still stand competitive and leave scope for further development. To cite one such is the work by Salim R.H. et al. [12], where line shunt admittance (LSA) effect is considered to improve the accuracy of the existing impedance-based methods. The results of this work demonstrated that even in overhead power distribution lines this effect should not be neglected since it can significantly increase the error in the existing methods. A paper by Yanfeng Gong et al. [13] presents a new impedance-based method that gives all possible fault locations by using an elaborate feeder model and fault event reports, supported with data from other intelligent electronic devices deployed in the field. This method provides automated fault location within a minute after the inception of fault. In another paper by Hassan Nouri et al. [14], a single-end fault location algorithm used a distributed parameter model, which yielded more accurate results due to the distributed nature of line losses and capacitive effects.

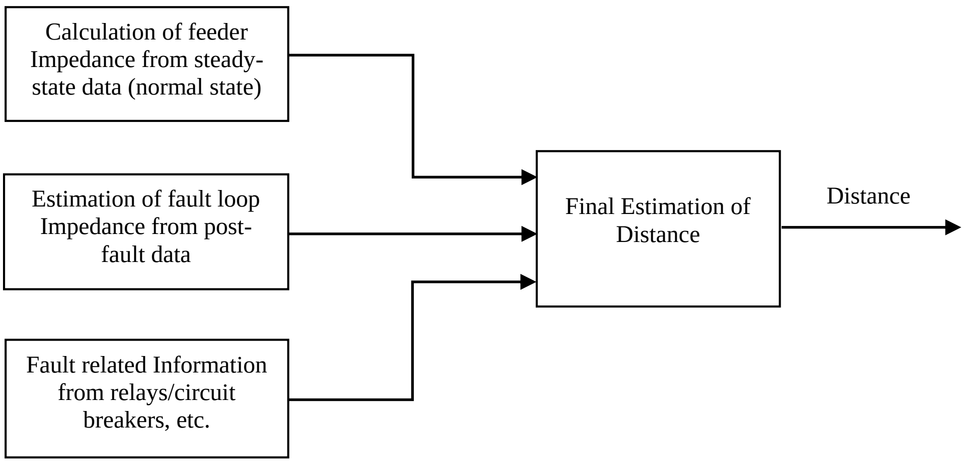

Figure 1. Block diagram of the Apparent-impedance based algorithm [3].

MATERIALS AND METHODS

Impedance-based method

In DN networks, Fault locators (FLs) become economically viable if they are located at a centralized substation. The fault data (voltages and currents) is available only from the substation, which greatly stipulates the accuracy of the fault location. The Impedance-based algorithm used in this work is as per the flow chart presented in Figure 2. After running a power flow study on IEEE 13 node DN [15] (Figure 3) (simulated in MATLAB) under pre-fault (normal) conditions, equivalent impedances at all nodes are calculated using node voltages and currents. Then, for every identified power flow path (Table 1), equivalent systems were developed after determining net equivalent impedance (by combining parallels between existing loads and laterals at each node) at all nodes of the path. Assuming that there are no load variations during the first cycle upon the inception of fault, the lines and loads, which are falling out of the power flow pathway under consideration, are represented by constant impedances. But, before this, it is necessary to run a power-flow algorithm to record voltages and currents during pre-fault conditions. Knowing this power-flow data, equivalent impedances,

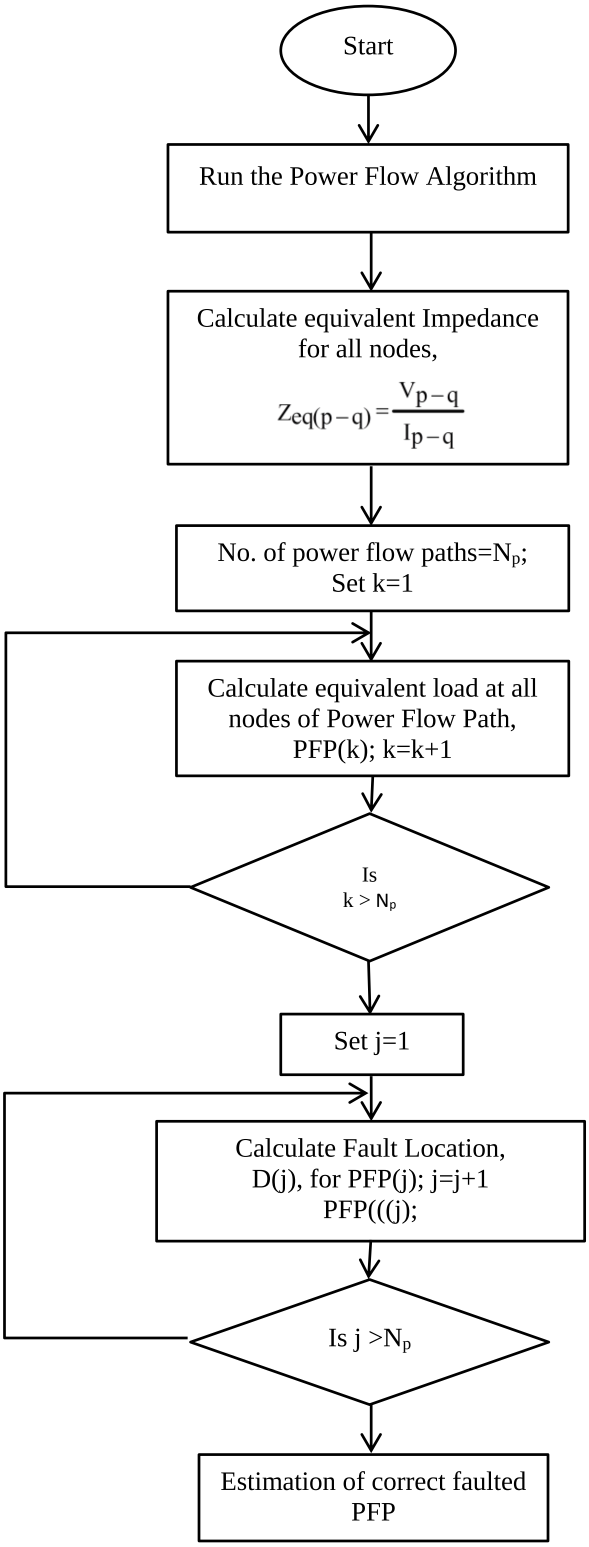

Figure 2. Flowchart of Impedance-based algorithm

and therefore the equivalent systems for each power-flow path can be modelled. Then, the fault-location algorithm is executed for each equivalent system, and accordingly multiple no. of fault locations corresponding to all prevailing power-flow paths can be estimated. The number of fault locations estimated equals the total number of equivalent systems. It is unique with the issue of fault location in distribution systems, wherein the multiple fault locations are estimated. These estimations must be properly diagnosed using various tools and techniques to arrive at a final correct and accurate one.

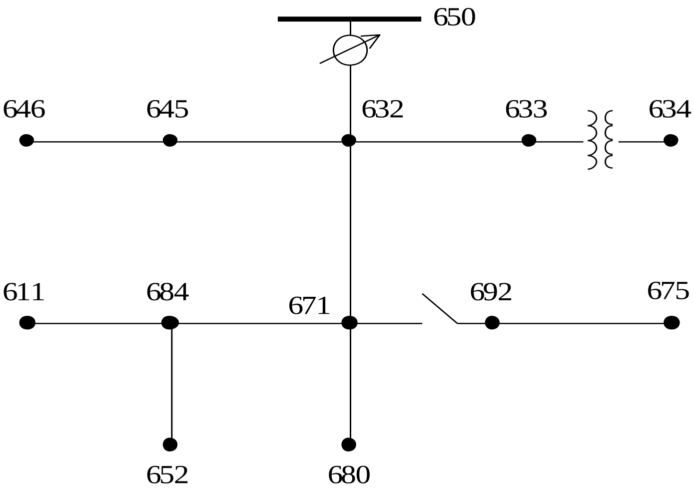

Figure 3. IEEE (13 node) distribution network

Table 1: Power flow paths

S.No.	Power Flow Path	Nodes with laterals and/or loads
1	650-632-633-634	632
2	650-632-645-646	632
3	650-632-671-692-675	632, 671
4	650-632-671-684-652	632, 671, 684
5	650-632-671-684-611	632, 671, 684
6	650-632-671-680	632, 671

Fault Location Algorithm [16]

Considering a single line-to-ground fault on phase 'a' of IEEE 13 node DN

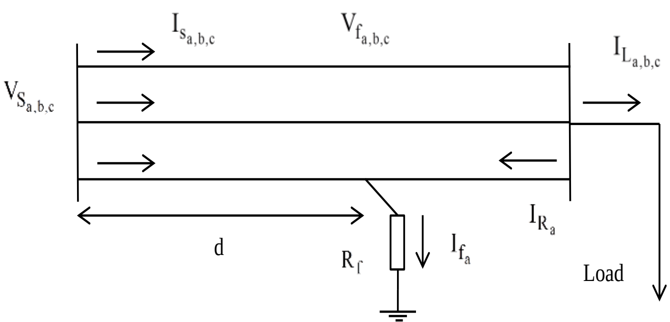

Figure 4. Single line-to-ground fault on phase 'a'

The fault location algorithm using a single line-ground fault on phase a:

Step 1: Load current during the fault is assumed to be the pre-fault load current.

Step 2: Considering a single line-to-ground fault (Figure 4), the fault current is estimated using following formula:

$$I_{f_a} = I_{S_a} + I_{R_a} = I_{S_a} - I_{L_a} \quad (1)$$

where,

I_{f_a} is fault current in faulty phase

I_{S_a} is sending end current in faulty phase

I_{R_a} is remote end current in faulty phase

I_{L_a} is load current

Step 3: Fault location is calculated using following formulae:

$$d = \frac{\{Im(V_a)\, Re(I_a) - Re(V_a)\, Im(I_a)\}}{\{M_{1_a}\ Im(I_{f_a}) - M_{1_a}\ Re(I_{f_a})\}} \quad (2)$$

$$M_{1_a} = \sum_k \{Re(Z_{ak})Re(I_{f_k}) - Im(Z_{ak})Im(I_{f_k})\} \quad (3)$$

$$M_{2_a} = \sum_k \{Re(Z_{ak})\, Im(I_{f_k}) - Im(Z_{ak})\, Re(I_{f_k})\} \quad (4)$$

V_a is Sending-end voltage in faulty phase

I_a is Sending-end current in faulty phase

Z_{ak} is Impedance between faulty phase and three phases

' d ' is the estimated distance from the reference point under consideration.

Step 4: Fault-point voltages are calculated using the following formulae:

$$\begin{bmatrix} V_{f_a} \\ V_{f_b} \\ V_{f_c} \end{bmatrix} = \begin{bmatrix} V_{s_a} \\ V_{s_a} \\ V_{s_a} \end{bmatrix} - d \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_{s_a} \\ I_{s_b} \\ I_{s_c} \end{bmatrix} \quad (5)$$

Step 5: The load current is updated by using the above fault point voltages using the formulae:

$$I_{L_a} = [Y_{aa} \quad Y_{ab} \quad Y_{ac}][V_{f_a} \quad V_{f_b} \quad V_{f_c}]^T \quad (6)$$

where $$Y_{ab} = [(l-d)\, Z_{ab} + Z_{L_{ab}}]^{-1} \quad (7)$$

Z_{ab} is the line impedance per unit length between phases

$Z_{L_{ab}}$ is the load impedance between phases

' l ' is the total length of the faulted line

Step 6:

The fault distance was calculated again using the updated load current. Then, the incremental difference (Δd) between the present and previous estimation was checked for convergence criteria:

$$\Delta d = | d(i+1) - d(i) | \quad `(8)$$

$\Delta d < \delta$, where δ is previous defined error tolerance.

Step 7: If convergence criteria is fulfilled the algorithm stops, else next iteration continues from step 2.

Fault location equations for other types of faults

Double line-to-ground fault

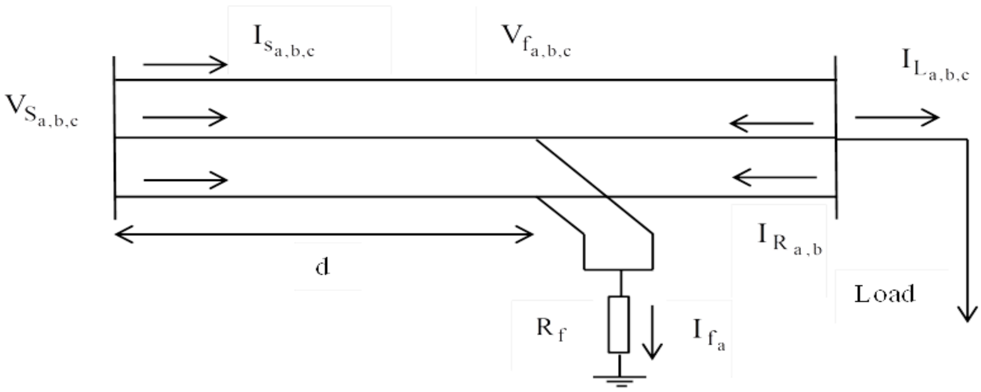

Figure 5. Double line-to-ground fault on phases a and b

$$\begin{bmatrix} d \\ 0 \\ 0 \\ R_f \end{bmatrix} = \begin{bmatrix} M_{1_a} & Re(I_{f_a}) & 0 & \{Re(I_{f_a}) + Re(I_{f_b})\} \\ M_{2_a} & Im(I_{f_a}) & 0 & \{Im(I_{f_a}) + Im(I_{f_b})\} \\ M_{1_b} & 0 & Re(I_{f_b}) & \{Re(I_{f_a}) + Re(I_{f_b})\} \\ M_{2_b} & 0 & Im(I_{f_b}) & \{Im(I_{f_a}) + Im(I_{f_b})\} \end{bmatrix}^{-1} \begin{bmatrix} Re(V_{s_a}) \\ Im\,V_{s_a}) \\ Re(V_{s_b}) \\ Im(V_{s_b}) \end{bmatrix} \quad (9)$$

Line-to-line fault

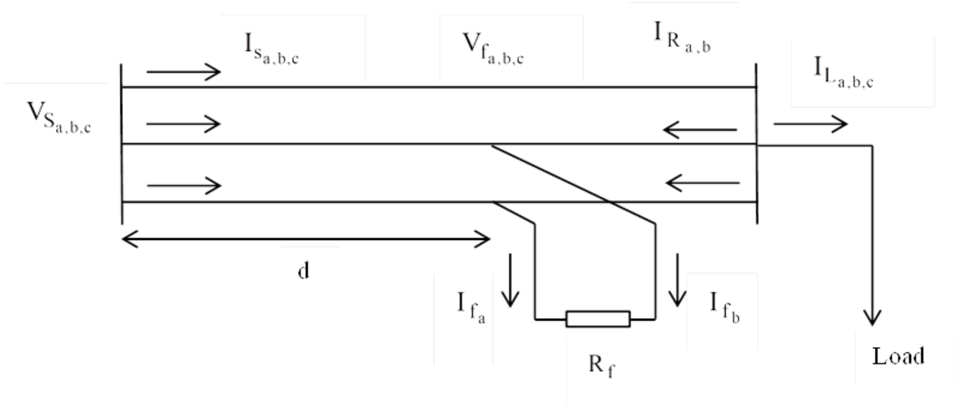

Figure 6. Line-to-line fault on phases a and b

$$\begin{bmatrix} d \\ R_f \end{bmatrix} = \begin{bmatrix} M_3 & Re(I_{f_a}) \\ M_4 & Im(I_{f_a}) \end{bmatrix}^{-1} \begin{bmatrix} \{Re(V_{s_a}) - Re(V_{s_b})\} \\ \{Im(V_{s_a}) - Im\,V_{s_b})\} \end{bmatrix} \quad (10)$$

$$M_3 = \sum_k [\{Re(Z_{a_k}) - Re(Z_{b_k})\} Re(I_{s_k}) - \{Im(Z_{a_k}) - Im(Z_{b_k})\} Im(I_{s_k})] \quad (11)$$

$$M_4 = \sum_k [\{Re(Z_{a_k}) - Re(Z_{b_k})\} Im_{s_k}) - \{Im(Z_{a_k}) - Im(Z_{b_k})\} Re(I_{s_k})] \quad (12)$$

Three phase-to-ground fault:

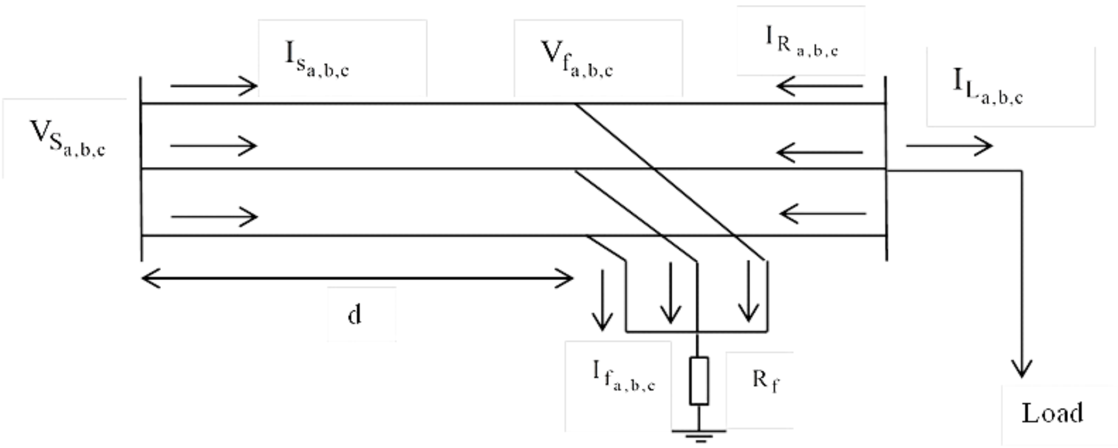

Figure 7. Three phase-to-ground fault

$$I_{f_T} = I_{f_a} + I_{f_b} + I_{f_c} \tag{13}$$

$$\begin{bmatrix} d \\ 0 \\ 0 \\ 0 \\ R_f \\ 0 \end{bmatrix} = \begin{bmatrix} M_{1_a} & Re(I_{f_a}) & 0 & 0 & Re(I_{f_T}) & -Im(I_{f_T}) \\ M_{2_a} & Im(I_{f_a}) & 0 & 0 & Im(I_{f_T}) & Re(I_{f_T}) \\ M_{1_b} & 0 & Re(I_{f_b}) & 0 & Re(I_{f_T}) & -Im(I_{f_T}) \\ M_{2_b} & 0 & Im(I_{f_b}) & 0 & ImI_{f_T}) & Re(I_{f_T}) \\ M_{1_c} & 0 & 0 & Re(I_{f_c}) & Re(I_{f_T}) & -Im(I_{f_T}) \\ M_{2_c} & 0 & 0 & Im(I_{f_c}) & ImI_{f_T}) & Re(I_{f_T}) \end{bmatrix}^{-1} \begin{bmatrix} Re(V_{s_a}) \\ Im(V_{s_a}) \\ Re(V_{s_b}) \\ Im(V_{s_b}) \\ Re(V_{s_c}) \\ Im(V_{s_c}) \end{bmatrix} \tag{14}$$

Matlab Simulation of IEEE 13 node distribution network

The algorithm developed in this work was applied to a typical IEEE power distribution network with 13 nodes and 10 line-segments/sections with its specification [17] (Tables, 2 to 5). The Simulink model for the above network was developed using the SimPowerSystem toolbox in a MATLAB Simulink environment. Faults considered for testing the algorithm are ten types - three phase-to-phase faults, three single-line-to-ground faults, three double-line-to-ground faults, one three-phase-short circuit fault.

Table 2. Line Segment Data

Node A	Node B	Length in meters	Config.
632	645	151.54	603
632	633	151.54	602
633	634	0	XFM-1
645	646	90.9	603
650	632	606.1	601
684	652	242.4	607
632	671	606.1	601
671	684	90.9	604
671	680	303.0	601
671	692	0	Switch
684	611	90.9	605
692	675	151.54	606

Table 3. Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Table 4. Spot Load Data

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
	Model	kW	kVAr	kW	kVAr	kW	kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTAL	1158	606	973	627	1135	753

Table 5. Distributed Load Data

Node A	Node B	Load Model	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
			kW	kVAr	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

RESULTS AND DISCUSSION

Multi-estimations of Impedance-based Algorithm

Impedance-based method suffers from the drawback of multi-estimation issue, when applied to multi-terminal distribution networks, since it searches through all possible power flow paths and estimates multiple fault locations. The final fault location can be estimated/ranked only if certain information is available from the status of deployed protective devices. In the absence of such information, artificial intelligence based methods are the suggested alternatives.

Power Flow Study on IEEE Distribution Network

Initially, the equivalent impedances at all nodes of the network are calculated. The line currents and node voltages available from the power flow study are used for calculating the equivalent impedances. The results of the power flow study are given in Table 6.

Table 6: Results of Power Flow Study

Node	Phase A		Phase B		Phase C	
	Voltage (p.u.)	Current (Amps)	Voltage (p.u.)	Current (Amps)	Voltage (p.u.)	Current (Amps)
650-632	1.0 ∟0^0	558.4∟-28.6^0	1.0∟-120^0	414.9∟ -141^0	1.0∟120^0	586.6∟ 93.6^0
632-633	1.021∟ -2.5^0	81.33∟ -37.7^0	1.04∟-121.7^0	61.1∟ -159.1^0	1.02∟117.8^0	62.70∟ 80.5^0
632-645	1.021∟ -2.5^0	-	1.04∟-121.7^0	143 ∟-142.7^0	1.02∟117.8^0	65.21∟ 57.8
645-646	-	-	1.03∟-121.9^0	65.2∟ -122.2	1.02∟ 117.9^0	65.21 ∟ 57.8
632-671	1.021∟ -2.5^0	478.29∟ -27^0	1.04∟-121.7^0	215.∟ -134.7^0	1.02∟117.8^0	475.5∟ 99.9^0
692-675	.990 ∟ -5.3^0	205.3∟ -5.2^0	1.05∟-122.3^0	69.6∟ -55.2^0	.978∟ 116^0	124∟ 111.8^0
671-684	.990∟ -5.3^0	63.07∟ -39.1	1.05∟-122.3^0	-	.978∟116^0	71.2∟ 121.6^0
684-652	.988∟ -5.3^0	63.07∟ -39.1^0	-	-	.988∟ -5.32^0	-
684-611	.988∟ -5.3^0	-	-	-	.98∟ -5.32^0	71.2∟ 121.6^0
671-680	.990∟ -5.3^0	-	1.05∟-122.3^0	-	.98∟116^0	-

Table 7. Calculated values for Single line-to-ground fault on phase ‘a’ of line-section, 650-632

Phase	Pre-fault Currents	Fault values				Load Current
		Voltages	Currents	Fault point Voltage	Fault Current	
a	501∟-1.27 ^{0}	125.1∟-0.33 ^{0}	654.7∟-1.4 ^{0}	2.45∟-1.2 ^{0}	868.3∟-1.2 ^{0}	278.6∟2.5 ^{0}
b	485∟2.92 ^{0}	828∟-2.5 ^{0}	480.2∟-2.9 ^{0}	780.5∟-2.6 ^{0}	0	480.2∟-2.9 ^{0}
c	495∟0.83 ^{0}	772.4∟-1.7 ^{0}	489.4∟-0.8 ^{0}	710.8∟1.7 ^{0}	0	489.4∟-0.8 ^{0}

Table 8. Calculated values for Single line-to-ground fault on phase ‘a’ of line-section, 650-632

Constants			Fault Location (in meters)	
M1	M2	M12	Actual	Estimated
0.29	-0.09	-206	400.5	406.4

Fault locations estimated by Impedance-based Algorithm

The various types of faults were triggered on all the line-sections of the 13 node IEEE distribution network. The recorded fault voltages and currents at the substation were used for running the Impedance-based algorithm. The intermediate calculated quantities and constants of the algorithm for a single-line-to-ground fault on phase ‘a’, planted at 400.5 meters, on the line-section 650-632, are given in Tables, 7 to 8. The fault locations estimated by the algorithm for the faults triggered at various locations of the distribution network are given in Table 9.

Table 9. Results of Impedance-based Algorithm

S. No.	Faulted line segment	Type of fault	Fault Location in meters		
			Actual values	Estimated Values	Error(in m)
1	650-632	Phase-to-phase fault between A and B	350	345	-5
2	632-633	Phase-to-phase fault between B and C	75	71	-4
3	632-645	Phase-to-phase fault between A and C	110	101	-9
4	645-646	Three-phase faults (with & without ground)	50	46	-4
5	650-632	Single-line-to-ground fault on A	406.4	400	-6.4
6	684-652	Single-line-to-ground fault on B	64	59	-6
7	632-645	Single-line-to-ground fault on A	101	102	+1
8	650-632	Double-line-ground fault between A and B	406	403	-3
9	692-675	Double-line-ground fault between A and C	42.4	38	-4.4
10	632-633	Double-line-ground fault between A and C	80	134	-5
11	632-645	Phase-to-phase fault between B and C	101	110	+9
12	671-684	Phase-to-phase fault between B and C	27.3	35	+7.7
13	632-650	Three-phase faults (with and without ground)	406	407	+1

CONCLUSION

The Impedance-based algorithm was applied to an IEEE 13 node distribution network. The results of the work are encouraging despite the algorithm's drawback of multi-estimations for multi-terminal distribution network. The central substation fundamental components of fault currents and voltages are used for the estimation of fault location on any of the fault-sections of the distribution network. The fault location estimation of the algorithm supports the power restoration crew in quickly rushing to the fault site for repair work. The power can be restored quickly to the connected customers, and the power loss due to faults can be minimized. Thus, fault location directly contributes towards power system reliability and economy.

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