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A New Fault-Location Method with High Robustness for Distribution Systems

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***Abstract*—This paper proposes a new single-end impedance based fault location method for power distribution systems. Based on direct three-phase circuit analysis, the authors have devised a generalized fault-location formulation in phase domain utilizing the fault admittance matrix. Newton-Raphson method is used for the solution of fault-location formulation. In order to eliminate the capacitive effect of feeders, the proposed algorithm adopts π model of line for the calculation of voltage and current in iterative process. The validity of the algorithm is tested with IEEE 34 Node Test Feeder using PSCAD-EMTDC. Simulation results have demonstrated that the method has high accuracy and good robustness.**

***Index Terms*—Power distribution lines, fault location, iterative method, fault admittance matrix**

I. INTRODUCTION

In electric power systems, distribution networks are susceptible to faults. Prompt and accurate fault location can reduce outage time, decrease losses and improve power supply reliability and continuity. However, the complexity of distribution system characteristics makes fault location quite a challenge, which can be explained as follow [1]–[3]:

1) Heterogeneity of feeders for various line configurations;
2) Unsymmetrical due to the untransposed lines;
3) Unbalances caused by the presence of single-, double-, and three-phase loads and the single-phase lines;
4) Presence of laterals along the main feeder;
5) Presence of load taps along the main feeder and laterals.

Due to the characteristics of distribution networks, the impedance based fault-location methods in distribution systems differ in analysis approaches (sequence component or phase component) and line models.

Because the transmission lines are transposed and symmetric, impedance based methods for transmission network are based on sequence analysis, such as the reactive component method and its variation in [4]–[6].

Several methods with apparent impedance approach which is a variation of reactive component method for rural distribution feeders were proposed in [7]–[9]. However, the sequence analysis approach will cause extra errors in fault location for the untransposed lines. Hence, more fault-location methods with phase components instead of sequence components for distribution network were proposed in [10]–[13].

A one-end single-line-to-ground (SLG) fault location method based on Direct Circuit Analysis (DCA) was proposed in [10]. The fault distance is obtained by iterative process. In order to eliminate the effects of laterals and load taps, radial distribution network is transformed to equivalent multi-section circuit after fault diagnosis which can find out the lateral or main feeder where fault happens. The basic idea of fault location algorithm in multi-section feeder is: if the estimated distance exceeds the length of the calculated section, calculate the sending-end voltage and current of the next section, and estimate the fault distance in next section; if the estimated distance is less than the length of this section, the fault distance is the sum of lengths of sections before fault point and the estimated distance in the last analyzed section. The multi-section fault location algorithms in [11]–[16] were designed based on this idea.

Utilizing matrix inversion lemma, the fault location methods in [11] and [12] provide quadratic equations of fault distance by fault admittance matrix for SLG fault and line-to-line (LL) fault. The method can get a unique fault distance by the solution of the equation, avoiding the false-root problem of iterative method. The drawback of this method is not applicable for all types of faults, but only for the faults with one fault resistance variable like SLG or LL faults.

The fault-location formulations were extended in [13] for all types of faults which contain SLG fault, LL fault, line-to-line-to-ground (LLG) fault, three-phase (LLL) fault and three-phase-to-ground (LLLG) fault in distribution systems. The typical characteristics of distribution network, such as laterals and load taps etc., were taken into account in this DCA based method. But it was noted in [14] that convergence problem exist in iterative process in [13]. The other drawback of the method in [13] is the missing of the capacitive effect of line, which is not tolerable in fault location for long feeders.

Different line models are adopted in fault location methods.

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Because the length of each section in distribution feeders is just several kilometers, lumped parameter model is used in most fault location algorithms and differs from one model to other. The classical matrix impedance model (Z-matrix model) was used in [7]–[13] for overhead lines, while π model was used in [15], [16] to compensate the capacitive effect. The distribution line model was utilized in [14] for distribution systems. However, a very simple fault model which assumes that all fault resistances of phase-to-phase and phase-to-ground are equal was taken for the fault location algorithm in [14].

Fixed point iterative method is used in most fault-location methods as in [7]–[10] and [13]–[16]. In [11] and [12], fault distance is directed solved by quadratic equation in one variable for SLG and LL faults. Reference [14] shows that the fixed point iterative method may cause divergence.

In this paper, a single-end fault location method for distribution systems is proposed. Using fault admittance matrix, a fault-location formulation in phase network for all types of fault has been derived for Newton-Raphson iterative method. The capacitive effect is considered in multi-section fault-location algorithm by using π model. A benchmark shows the proposed method has good performance in accuracy and convergence.

II. Derivation of Generalized Fault-Location Formulation

The following three-phase equations are obtained by Kirchhoff law from Fig. 1:

$$\mathbf{U_s} = x\mathbf{Z_l}\mathbf{I_s} + ((l-x)\mathbf{Z_l} + \mathbf{Z_r})\mathbf{I_L}, \quad (1)$$

$$\mathbf{U_s} = x\mathbf{Z_l}\mathbf{I_s} + \mathbf{Y_f}^{-1}\mathbf{I_f}, \quad (2)$$

$$\mathbf{I_s} = \mathbf{I_f} + \mathbf{I_L}, \quad (3)$$

where $\mathbf{U_s} = [U_{sa} \quad U_{sb} \quad U_{sc}]^T$ is phase voltage vector at substation end; $\mathbf{U_f} = [U_{fa} \quad U_{fb} \quad U_{fc}]^T$ is phase voltage vector at fault point; $\mathbf{I_s} = [I_{sa} \quad I_{sb} \quad I_{sc}]^T$ is phase current vector at substation end; $\mathbf{I_L} = [I_{La} \quad I_{Lb} \quad I_{Lc}]^T$ is phase current vector after the fault point; $\mathbf{I_f} = [I_{fa} \quad I_{fb} \quad I_{fc}]^T$ is fault current vector; $\mathbf{Z_l}$ is line impedance matrix per unit; $\mathbf{Z_r}$ is the load impedance matrix; $\mathbf{Y_f}$ is the fault admittance matrix; l is the whole length of the section; x is the fault distance.

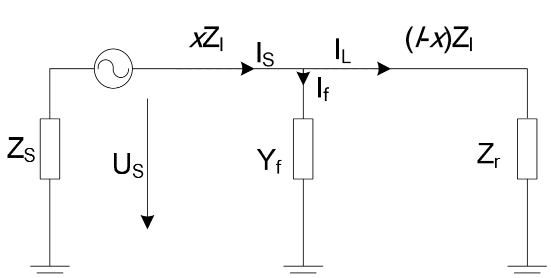

Fig. 1. A single section of distribution network with a fault.

By eliminating current vector $\mathbf{I_f}$ and $\mathbf{I_L}$ in (1)–(3), the generalized fault location formulation is derivate as (4)

$$\mathbf{U_s} - (\mathbf{Z_l} + \mathbf{Z_r})\mathbf{I_s} - ((l-x)\mathbf{Z_l} + \mathbf{Z_r})\mathbf{Y_f}[x\mathbf{Z_l}\mathbf{I_s} - \mathbf{U_s}] = \mathbf{0} \quad (4)$$

As shown in (4), the unknown parameters are fault distance x and fault admittance matrix $\mathbf{Y_f}$ which differs from the types of faults.

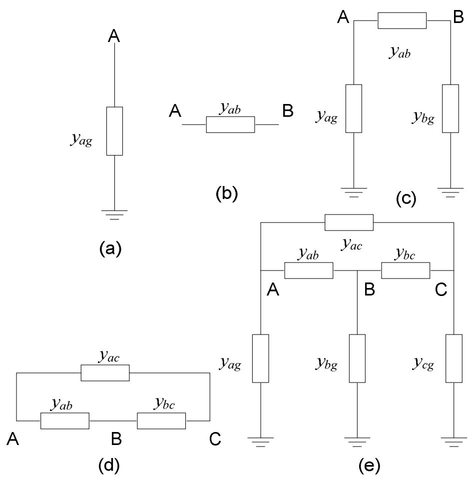

Fig. 2. Equivalent circuits for five types of faults: (a) LG fault, (b) LL fault, (c) LLG fault, (d) LLL fault, (e) LLLG fault.

According to the equivalent circuits shown in Fig. 2, the fault admittance matrices of all types of faults are given as follow:

$$\mathbf{Y_f} = \begin{bmatrix} y_{ag} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$ – the fault admittance matrix of LG fault,

$$\mathbf{Y_f} = \begin{bmatrix} y_{ab} & -y_{ab} & 0 \\ -y_{ab} & y_{ab} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$ – the fault admittance matrix of LL fault,

$$\mathbf{Y_f} = \begin{bmatrix} y_{ag}+y_{ab} & -y_{ab} & 0 \\ -y_{ab} & y_{bg}+y_{ab} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$ – the fault admittance matrix of LLG fault.

$$\mathbf{Y_f} = \begin{bmatrix} y_{ab}+y_{ac} & -y_{ab} & -y_{ac} \\ -y_{ab} & y_{bc}+y_{ab} & -y_{bc} \\ -y_{ac} & -y_{bc} & y_{ac}+y_{bc} \end{bmatrix}$$ – the fault admittance matrix of LLL fault,

$$\mathbf{Y_f} = \begin{bmatrix} y_{ag}+y_{ab}+y_{ac} & -y_{ab} & -y_{ac} \\ -y_{ab} & y_{bg}+y_{bc}+y_{ab} & -y_{bc} \\ -y_{ac} & -y_{bc} & y_{cg}+y_{ac}+y_{bc} \end{bmatrix}$$

– the fault admittance matrix of LLLG fault.

III. Fault-Location Algorithm for Single Section

The coefficients in (4) can be calculated by the voltage and current data in substation end and relevant impedance data.

Six equations can be obtained from the real part and imaginary part in (4).

The vector of unknown variables which consists of fault distance and elements of the fault admittance matrix can be solved in (4) by Newton-Raphson method for all faults except LLLG fault.

According to the LLLG fault admittance matrix, there are seven unknown variables in six equations. The number of equations is not adequate for a solution. Utilizing the star equivalent circuit of LLLG fault in Fig. 3a, extra equations can be obtained by star-delta transform.

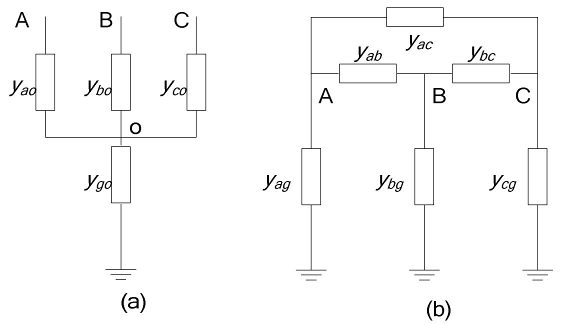

Fig. 3. Star-delta transform of LLLG fault: (a) star form, (b) delta form.

By the star- delta transforming, there is

$$y_{ij} = \frac{y_{io}\, y_{jo}}{\sum\limits_{k=a,b,c,g} y_{ko}}, i = a,b,c,g;\ j = a,b,c,g. \tag{5}$$

The extra equations are:

$$y_{ag}\, y_{bc} - y_{bg}\, y_{ac} = 0, \tag{6}$$

$$y_{ag}\, y_{bc} - y_{cg}\, y_{ab} = 0. \tag{7}$$

In the equation set of (4), (6) and (7), the fault distance of LLLG can be solved by Newton-Raphson method.

IV. Fault-Location Algorithm for General Feeders

The proposed method in previous section is a fault-location method for a single section, but it is practical for fault location in radial distribution system.

The lateral or main feeder where fault occurs can be found out using the fault diagnosis methods in [10], [17], [18]. Then, as can be seen in Fig. 4, the power consumption beyond the power flow path with fault is considered as load taps, and an equivalent multi-section feeder of radial distribution network can be developed.

By dividing power flow path with fault into multi-sections as Fig. 4, the effect of some factors, such as nonhomogeneous lines, laterals, and unbalances by the presence of single-phase line and load taps, can be eliminated [10].

The principle of dividing feeders into section is [14]:

1) The point with load taps;
2) The junction where the number of phases or the configuration of line changes.

Then, the impedance of loads can be obtained by the pre-fault power flow data and is considered as constant.

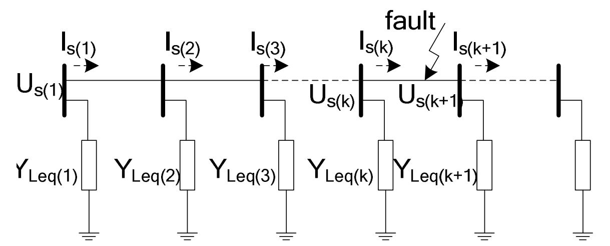

Fig. 4. The equivalent circuit of multi-sections line with a fault.

At last, whether feeders are symmetrical or not, it does not affect the proposed algorithm developed in phase network.

For the very short sections in distribution network, the Z-matrix model is taken in the single-section fault-location algorithm illustrated in Section II. But the whole length of distribution feeder is long enough, it is necessary for the multi-section fault-location algorithms to compensate the effect of shunt capacitance by using π line model.

The process of multi-section fault-location algorithm can be explained as follows.

Step 1) Establish the equivalent multi-section circuit for fault location, using the information of the topology of distribution network and the equivalent loads calculated by pre-fault power flow data.

Step 2) Measure the fundamental frequency components of voltage and current at the substation end.

Step 3) Start the fault investigation for a section (beginning with the first section in substation) by the single-section fault location algorithm.

Step 4) If estimated fault distance x is negative or within the length of the section, stop the algorithm; otherwise, calculate the sending-end voltage and current for the next section; then go to Step 3).

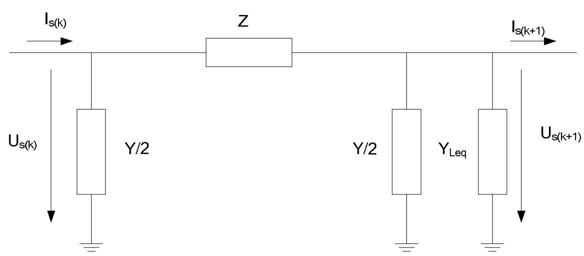

Fig.5. A section in π model of line.

Using π model of line, the equivalent circuit of a health section is showed in Fig. 5. There are

$$\mathbf{U_{S(k+1)}} = \mathbf{U_{S(k)}} + (l_{(k)}{}^2 \mathbf{Z_{(k)}} \mathbf{Y_{(k)}} / 2)\mathbf{U_{S(k)}} - l_{(k)} \mathbf{Z_{(k)}} \mathbf{I_{S(k)}}, \tag{8}$$

$$\mathbf{I_{S(k+1)}} = \mathbf{I_{S(k)}} - l_{(k)} \mathbf{Y_{(k)}} (\mathbf{U_{S(k)}} + \mathbf{U_{S(k+1)}}) / 2 - \mathbf{Y_{Leq(k+1)}} \mathbf{U_{S(k+1)}}, \tag{9}$$

where k is the number of analyzed section; $l_{(k)}$ is the length of analyzed section; $Z_{(k)}$ is the line impedance matrix per unit at analyzed section; $Y_{(k)}$ is the line shunt admittance matrix per unit at analyzed section;

Step 5) Calculate the total fault distance x_{total}, especially, if estimated fault distance x is negative, set x to zero

$$x_{total} = x_{sr} + x, \tag{10}$$

where x_{sr} is the distance between the substation end and the sending-end of the last analyzed section.

V. SIMULATION STUDY AND RESULT ANALYSIS

In this paper, error is calculated by (11)

$$error[\%] = \frac{|x_{estimated} - x_{actual}|}{l_{total}} \times 100, \qquad (11)$$

where $x_{estimated}$ is estimated fault distance; x_{actual} is actual fault distance; l_{total} is the total line length.

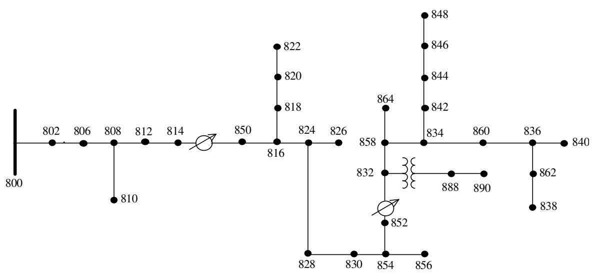

Fig. 6. IEEE 34 Node Test Feeder [19].

TABLE I. OVERHEAD LINE CONFIGURATIONS (CONFIG.).

Config.	Phasing	Phase	Neutral	Spacing ID
		ACSR	ACSR	
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

TABLE II. LOAD MODEL CODES.

Code	Connection	Model
Y-PQ	Wye	Constant kW and kVAr
Y-I	Wye	Constant Current
Y-Z	Wye	Constant Impedance
D-PQ	Delta	Constant kW and kVAr
D-I	Delta	Constant Current
D-Z	Delta	Constant Impedance

To validate the proposed method, the IEEE 34 Node Test Feeder as shown in Fig.6 is modeled using PSCAD-EMTDC. This feeder has 8 laterals, 5 types of untransposed overhead lines whose configurations are shown in Table I, 2 regulators and 6 types of loads which are illustrated in Table II.

Simulation studies are implemented to evaluate the performance of the proposed method. Additionally, the tests also evaluate:

1) The effect of shunt capacitances of line.

2) The convergence of the method in comparison with methods proposed in [13], [15], [16], among which [13] does not compensate the capacitive effect.

The following conditions were considered in the simulations:

3) 8 fault points along the main feeder of 800-802-806-812-814-850-816-824-826-828-830-854-852-832-858-834-860-836-862-838, this total line length L_{total} is 58.9819 km.

4) 4 fault types (LG, LL, LLG and LLLG fault);

5) 3 different fault resistances (0Ω, 10Ω, 300Ω).

Four methods are tested as a benchmark. Besides the method proposed in this paper, there are other three methods proposed in [13], [15] and [16]. These four test methods are all capable for all types of fault and various fault resistances. Also there are differences among them. Salim's method in [13] ignores the capacitive effect by using Z-matrix line model, Filomena's method in [15] considers the capacitive effect by using π model based on [13], and Salim's method in [16] takes π line model for fault distance calculation. The three methods all get a solution by fixed point iterative method, and the proposed method in the paper get a solution by Newton-Raphson method.

Table III shows the comparisons of these algorithms for 8 fault points, 4 fault types and 3 different fault resistances. It is found in the benchmark for four methods, the proposed method has better convergence than the other three methods which may be diverged in high fault resistances. The error is increasing with the increase of fault resistance. And when fault distance increases, the accuracy is decreasing. But there is not clear evidence to support that the accuracy is related to fault types.

As can be seen in Table IV, Salim's method in [16] has better performance in low fault resistance; Salim's method in [13] has the worst performance. The errors between Salim's method in [13] and other methods explain the effect of shunt parameters of line. At the meantime, the proposed method has nearly equal accuracy with Salim's method in [16], while the proposed method has better robustness than Salim's method in [16] in high fault resistance.

The loads in simulation consist of constant impedance loads, constant power loads, and constant current loads. When a fault happens, impedances of constant power loads and constant current loads change. So it can be inferred from the fault-location formulation in the proposed algorithm that relation between errors and fault resistances or fault points is just outward phenomenon, in essential, the errors may be caused by the uncertainty of load impedances for the load variations in fault period.

If the impedance of all loads is correct, the proposed method can get the exact result. But it is difficult to identify the type of every load in distribution network to estimate load impedance in fault period.

Additionally, the solution in proposed method is a vector which consists of fault admittances and fault distance. Hence, the validity of estimated fault distance can be evaluated by the value of fault resistances, because the proposed method provides a very accurate fault distance in low fault resistance. When the fault resistances are enough big, estimated distance has a large error, just for reference.

TABLE III. A BENCHMARK OF FOUR METHODS.

Fault distance	Fault type	Estimated error [%]											
		$R_f = 0\Omega$				$R_f = 10\Omega$				$R_f = 300\Omega$			
		Proposed Method	Salim [13]	Filomena [15]	Salim [16]	Proposed Method	Salim [13]	Filomena [15]	Salim [16]	Proposed Method	Salim [13]	Filomena [15]	Salim [16]
0.9181	a-g	0.0003	0.0003	0.0003	0.0003	0.0352	0.0327	0.0322	0.0300	1.5566	3.5921	1.5566	1.5566
	a-b	0.0003	0.0005	0.0005	0.0005	0.0117	1.0363	1.0390	0.2161	1.5566	Diverge	1.5566	Diverge
	a-b-g	0.0003	0.0003	0.0003	0.0003	0.0603	0.0606	0.0614	0.0638	0.3187	0.4472	0.6707	0.6707
	a-b-c-g	0.0003	0.0003	0.0003	0.0003	0.1452	0.1460	0.1468	0.1490	1.0480	0.5828	1.1604	5.2448
24.8328	a-g	0.1209	0.1100	0.1209	0.1211	0.0278	0.0759	0.0057	0.0063	2.4726	0.6939	8.1864	10.7144
	a-b	0.1569	0.1340	0.1162	0.1476	0.2412	2.0227	2.1141	0.2810	1.5471	Diverge	Diverge	13.1570
	a-b-g	0.0906	0.1116	0.0906	0.0903	0.0243	0.1181	0.0180	0.0038	0.2423	4.4388	1.4922	4.4734
	a-b-c-g	0.1512	0.1653	0.1498	0.1517	0.0843	0.1749	0.0802	0.0715	9.7281	0.3858	10.1384	11.6880
36.6522	a-g	0.2483	0.1905	0.2483	0.2486	0.2106	0.0393	0.2150	0.2232	6.6609	6.8380	7.1616	9.7513
	a-b	0.3585	0.3091	0.2475	0.3375	0.2120	2.0554	2.2262	0.2532	6.5501	Diverge	Diverge	22.0057
	a-b-g	0.2963	0.3894	0.2963	0.2960	0.2428	0.4950	0.2420	0.2322	3.2920	10.4844	3.5989	5.7709
	a-b-c-g	0.4044	0.4718	0.3978	0.4044	0.3940	0.6186	0.3847	0.3855	8.1908	3.8601	8.1908	10.3687
44.2896	a-g	0.0120	0.1173	0.0117	0.0126	0.2287	0.0663	0.2393	0.2543	5.3774	5.2808	7.6396	10.9758
	a-b	0.4704	0.4674	0.3473	0.4456	0.5831	1.9403	2.2036	0.0172	3.1968	Diverge	Diverge	18.1009
	a-b-g	0.5446	0.7427	0.5449	0.5441	5.2459	5.5921	5.2429	5.2230	3.8352	7.3018	4.2472	8.1185
	a-b-c-g	0.6439	0.7989	0.6344	0.6437	0.6478	1.0352	0.6352	0.6325	10.3204	8.4366	10.7619	14.2746
53.0855	a-g	0.2347	0.5389	0.2347	0.2347	0.2906	0.8158	0.2906	0.2890	7.3406	8.9218	7.4855	7.4855
	a-b	0.7427	0.8232	0.6330	0.6980	0.5383	1.2524	1.7806	0.0401	7.3406	Diverge	Diverge	Diverge
	a-b-g	1.0745	1.4510	1.0745	1.0551	1.2568	1.8947	1.2538	1.2038	7.3406	5.2557	Diverge	Diverge
	a-b-c-g	1.1337	1.4448	1.1222	1.1198	1.2030	1.7779	1.1894	1.1602	7.3406	6.4729	Diverge	Diverge
54.6499	a-g	0.4772	0.8137	0.4772	0.4772	0.5730	1.1697	0.5741	0.5722	4.6882	11.5166	4.8331	4.8331
	a-b	0.7359	0.9823	0.6491	0.7135	0.4655	1.2655	1.8281	0.1299	4.6882	Diverge	Diverge	Diverge
	a-b-g	1.2772	1.7656	1.2772	1.2770	1.3973	2.2339	1.3973	1.3959	4.6882	12.6012	Diverge	Diverge
	a-b-c-g	1.3001	1.7092	1.2862	1.3001	1.4131	2.1722	1.3965	1.4123	4.6882	9.2795	Diverge	Diverge
56.8026	a-g	0.8707	1.2382	0.8707	0.8707	0.9921	1.6802	0.9926	0.9907	1.0385	8.2486	1.1834	1.1834
	a-b	0.7173	1.0778	0.6679	0.7012	0.2235	0.7094	1.0385	0.4540	1.0385	Diverge	Diverge	Diverge
	a-b-g	1.8426	2.1337	1.5831	1.5831	2.1244	2.6025	1.6827	1.6805	5.4497	14.5709	Diverge	Diverge
	a-b-c-g	1.4412	1.9053	1.4270	1.4412	1.6358	2.4745	1.6178	1.6344	1.0385	10.7144	Diverge	Diverge
57.8709	b-g	2.4691	2.9869	2.4691	2.4688	3.1255	3.9567	3.1223	3.1195	18.1423	Diverge	13.5185	10.8710

TABLE IV. THE AVERAGE ERROR AND MAX ERROR OF FOUR METHODS.

Error type	$R_f = 0\Omega$				$R_f = 10\Omega$				$R_f = 300\Omega$			
	Proposed Method	Salim [13]	Filomena [15]	Salim [16]	Proposed Method	Salim [13]	Filomena [15]	Salim [16]	Proposed Method	Salim [13]	Filomena [15]	Salim [16]
Average error[%]	0.6143	0.7890	0.5855	0.5995	0.8150	1.3626	1.1397	0.7629	4.8523	Diverge	Diverge	Diverge
Max error[%]	2.4691	2.9869	2.4691	2.4688	5.2459	5.5921	5.2429	5.2230	18.1423	Diverge	Diverge	Diverge

VI. CONCLUSIONS

A new single-end fault-location method in radial distribution systems is proposed in this paper. The typical characteristics of distribution networks have been taken into consideration in proposed method. Furthermore, the method is suitable for all types of fault and various fault resistances.

A generalized fault-location formulation is devised in phase domain by utilizing fault admittance matrix. The fault distance can be solved from the formulation by Newton-Raphson iterative method. In order to eliminate the capacitive effect of feeders, the proposed algorithm adopts π model of line for the calculation of voltage and current in iterative process. The evaluation studies based on PSCAD/EMTDC simulation data have demonstrated that the proposed method has high accuracy and better robustness than methods in [13], [15] and [16] which use fixed point iterative method.

The results of simulation also show that proposed method has higher accuracy in low resistance faults. However, because the load impedances in high resistance faults have a remarkable discrepancy from the load impedances calculated by pre-fault power flow data, errors increase with fault resistance. The effect of load variation in fault period will be furthered in future work.

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