Locating double and three phase fault to ground on a power distribution feeder using hybrid method

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Abstract— There are different branches in power distribution (PD) networks including load taps, laterals, and sub laterals. An accurate method in fault locating is used to improve reliability and efficiency of PD systems. In this paper, a new combined method is proposed for locating double and three phase faults to ground in PD networks. In addition, an impedance-based fault-location algorithm is used to find possible fault locations. Then, the new method using voltage sag matching algorithm is used to determine the faulty section. In this method, an impedance based fault location algorithm is used to determine possible fault locations after the possible fault locations are determined, after occurrence of double and three phase faults to ground. The same fault is simulated separately in possible locations. Then, the voltage at the input of a feeder is saved and the amplitude and angle of the voltage differences are determined. Accordingly, an online data bank is generated. Then, the obtained and recorded amplitude and angle of the voltage differences (at the beginning of the feeder) of the actual fault are compared with that data bank. Real location of fault is determined by matching value of each possible fault location. The proposed method outperforms its other counterparts in terms of locating faults and being less sensitive to the fault resistance.

Keywords- power distribution network; Impedance based fault location method; voltage sag.

1. Introduction

Generation, transmission, sub-transmission and distribution units are different sections of power systems. Since PD systems cover a geographically widespread area, one faces several problems in determining fault locations in distribution networks feeders such as cost, time and equipment. In order to overcome these problems, accurate and efficient methods should be developed to identify fault locations in PD networks. Several methods have been proposed for locating faults in PD including Traveling waves, impedance method and intelligent method, among which impedance-based fault location method is very simple and practical due to its high sampling rate, complete structure and that it only requires fundamental frequency components of current and voltage at the input of the feeder rather than a data bank [1-4]. In [5], for fault location in distribution networks, a new equation has been introduced. In this method, for each section, medium line model (π line model) is considered and a modified impedance based method is presented which improves the precision. As it has been reported, the maximum fault for 34-node IEEE network is 1.58% which equals to 1551m considering the total length of the network (98180m). An impedance based fault location method has been presented in [6], which uses fault location utilizing voltage and current registered at the beginning of the feeder. In [6], three impedance indicators have been introduced and the fault distance is determined in various types of faults. The results have shown that the mentioned method is sensitive to fault resistance.

In this paper, a new combined method is proposed for double phase and three phase faults to ground in order to determine faulty sections and fault distance in PD networks. For this purpose, first the improved impedance-based fault location method (IBFLM) is used to determine the possible fault locations; No approximation is applied to the distributed line model for any part of a PD network. Since IBFLM probably has multiple responses, the matching value, which is supposed to determine the fault section using voltage sag data, is defined. Consequently, two new algebraic equations for defining angle and amplitude of the voltage difference at the input of the feeder emerge, regarding the fault distance. Possible fault locations can be determined using improved IBFLM, once the fault occurs. Then voltage differences will be determined from the recorded voltage, at the input of the feeder. After that, the same fault is simulated in possible locations and an online data bank of magnitude difference and phase variations of voltage is generated. At this point, the recorded voltage differences are compared with the simulation results in order to find the matching one as the real location of the fault. Then, the modified type of IEEE 34 Node Test Feeder is selected for evaluating the proposed method. Simulink/MATLAB is used to simulate a test feeder and calculate different variables for different fault types, different fault inception algorithms and different fault resistances. The results show that the proposed method not only improves
accuracy (compared to previous IBFLM), but also its sensitivity to fault resistance is reduces (less than 0.42). Moreover, faulty section is determined using the proposed method, accurately.

In Section 2 of this paper, the proposed improved IBFLM is shown. Section 3 illustrates determining the faulty section and its applying on PD systems using the proposed method. The simulation results used to evaluate the accuracy of the proposed method are described in Section 4, and finally, conclusions are drawn in Section 5.

II. The Improved IBFLM

For the accuracy improvement of the IBFLM, in this method, distributed parameter line model is applied. In this method, all sections are investigated supposing that the fault has occurred in that section. Thus, investigated section consists of two circuits which is shown in Fig. 1. Now, by the first three terms of Taylor expansion, \( \cos kx(\theta) \) & \( \sinh kx(\theta) \). which are used in \( Z' \) and \( Y' \) are approximated. Consequently, fault point voltage is determined using Eq. 1. Moreover, according to Fig. 1, it can be seen that \( V_f \) is determined by Eq. 2.

\[
v_f = k_0 + k_1 x + k_2 x^2 + k_3 x^3 + k_4 x^4 + k_5 x^5
\]

\[
\begin{bmatrix}
V_{F_a} \\
V_{F_b} \\
V_{F_c}
\end{bmatrix} =
\begin{bmatrix}
Z_{f_a} + Z_{f_g} & Z_{f_g} & Z_{f_g} \\
Z_{f_g} & Z_{f_b} + Z_{f_g} & Z_{f_g} \\
Z_{f_g} & Z_{f_g} & Z_{f_c} + Z_{f_g}
\end{bmatrix} \begin{bmatrix}
I_{F_a} \\
I_{F_b} \\
I_{F_c}
\end{bmatrix}
\]

In appendix (A1) in [1], the calculated vectors \( k0 \) to \( k5 \) are propounded. Therefore, with equalization of Eq. 1, 2 and separating the imaginary and the real parts of these equations and eliminating the fault impedance, the following equation is determined, which is an algebraic equation of fifth order regarding to the fault distance.

\[
x^5 \left[ \sum_{mep} \text{Im}(k_{5m}l_{fm}) \right] + x^4 \left[ \sum_{mep} \text{Im}(k_{4m}l_{fm}) \right] + x^3 \left[ \sum_{mep} \text{Im}(k_{3m}l_{fm}) \right] + x^2 \left[ \sum_{mep} \text{Im}(k_{2m}l_{fm}) \right] + x \left[ \sum_{mep} \text{Im}(k_{1m}l_{fm}) \right] + \sum_{mep} \text{Im}(k_{0m}l_{fm}) = 0
\]

Where \( x \) is Fault distance, \( l_{fm} \) is fault current at \( m \)th phase which is the faulty phase and \( p \) is the faulty phases (a, b or c). In this equation, it is very important to determine the current of fault point. This is depended on the load model and the recorded current at the beginning of feeder. Thus, the accurate model of the load is used in this algorithm, which its value can be calculated by the method proposed in [1]. Now, five solutions are obtained by solving this equation. It is important to select the correct solution. For being selected as the correct solution, each solution needs to meet the following conditions [2]:

- It has to be a positive, real number,
- Its value needs to be less than the length of the considered section.

III. The proposed method for faulty section estimation and its Implementation

In this method, firstly all possible fault points need to be determined using recorded currents and voltages at the beginning of the feeder, due to limitations related to information of distribution systems. For this a method is presented in Section 2. Among all, just one of these possible fault points is the real fault location. Accordingly, in this section, a new faulty section estimation method is suggested to achieve the real fault point and the faulty section. For achieving this goal, the same kind of the fault will be simulated in the section of possible locations of the fault with 0.1 km steps and the phase angle variation and magnitude difference of voltages at the beginning of the feeder will be calculated based on the fault distance and stored for each one. Therefore, the data banks will be generated, online. Now, magnitude difference of recorded voltage and the phase angle variation are given on the new calculated curves (data banks). The nearest one to that will be selected as the real fault point. The details of each part of the proposed method for determining the faulty section will be explained in the following.

A. Generating the data bank

The data bank is generated from the simulated fault in the section of probable fault point with 0.1 km steps when the fault occurs. This data bank is formed of the magnitude difference of voltages and the phase angle variation at the beginning of the feeder. The database will be utilized for obtaining the general third-order algebraic equation of magnitude difference of voltage and the phase angle variation based on the distance. The behavior of phase and voltage variations has nonlinear relationship with the distance.

As the relationship could be described by two third-order polynomials in terms of the fault distance:

- 1. The phase angle variation of voltage at the beginning of the feeder - fault distance
- 2. The magnitude difference of voltage at the beginning of the feeder - fault distance

The global equations are as follows:

\[
\Delta V_i = a_1 x^3 + a_2 x^2 + a_3 x + a_0
\]

\[
\Delta \theta_i = b_1 x^3 + b_2 x^2 + b_3 x + b
\]

Where \( V \) is voltage magnitude, \( x \) is distance, \( \theta \) is phase variation and \( i \) is the section of equation which is employed.

- Voltage magnitude coefficient in the equation:
This coefficient is determined with curve fitting mathematic methods. These equations can be obtained from the simulated fault on the probable faulty sections, when the real fault occurs in PD feeders. These equations could be constant, linear and nonlinear, depending on the coefficients. Therefore, a set of two equations can be generated for each possible faulty section.

B. Matching Algorithm and Improving the Accuracy of the Determined Fault Distance

In this part, an algorithm is suggested to determine the real faulty section among the determined probable fault sections from IBFLM results. In this algorithm, after the fault occurrence and distinguishing it, the value of phase variation ($\Delta \theta$) and magnitude differences ($\Delta V$) of recorded voltage are extracted and saved simultaneously, the possible fault locations can be determined by using the improved IBFLM ($X_s$). Then, the same fault is simulated in each possible section by 0.1 km steps and the online database is created. According to each phase variation ($\Delta \theta$) and magnitude differences ($\Delta V$) of recorded voltage, there is a cubic equation related to the fault distance; so, the constant coefficients of these equations are determined by using this generated online database for each possible faulty section.

Thus, two fault distances will be determined as $X_{\Delta V}$ and $X_{\Delta \theta}$ in each possible section through the recorded actual $\Delta V$ and $\Delta \theta$ and calculating cubic equations for $\Delta V$ and $\Delta \theta$. This is done to obtain an equation for each determined possible fault section from IBFLM. Now, the matching index is defined for determining the main faulty section. It is calculated with (6). It should be calculated for each possible fault section. This method has two important notes rather than the same methods: at first, the online database generation and online faulty section and the fault distance detection and secondly, using two cubic equations for improving the accuracy of the faulty section estimation algorithm and enhancing the fault distance determination. Based on this defined match index, the ranking of the determined possible fault points is done. The one having the minimum index will be the real fault point. The matching value will be derived from the following formula.

$$\delta_j = \sqrt{\sum_{i \in P} \left( x_{\Delta V_{ij}} - x_{\Delta \theta_{ij}} \right)^2} \quad (6)$$

Where $\delta$ is the matching or the mismatching value, $\Delta V$ is the obtained distance from voltage magnitude difference equation and $\Delta \theta$ is the obtained distance derived from phase angle variation equation.

If $\delta<0.0$, then, the matching will be complete. Ranking and priority of possible points will be sorted based on the matching value. The procedure can be simplified using the following relations. The result will be a list of possible faulty section or sections which are sorted according to the matching degree. The one with the minimum value is the main faulty section. It can be understood better, if Fig. 2 is taken into account. This figure shows two curves obtained from the simulated fault in determined possible faulty section by IBFLM in 0.1 km steps. This demonstrates the curve of voltage magnitude difference equation related to the distance ($f_{\Delta V}(\Delta V, x)$) and phase angle variation related to the distance ($f_{\Delta \theta}(\Delta \theta, x)$). Both equations show a voltage sag diagram along with two adjacent buses for each probable faulty section. Therefore, the recorded magnitude difference and phase variation of voltage (actual values) are assigned on these figures and two distances $X_{\Delta V}$ and $X_{\Delta \theta}$ can be calculated as shown in Fig. 2.

These distances are close to each other for main faulty section which is known through matching index $\delta$. It is shown in this figure.

iv. The results of the simulation

A. Case Study

The modified IEEE 34 Node Network is selected as a case study, in order to evaluate the proposed method. This network is shown in Fig. 3 [7]. The length of the general data of the selected feeder is 98.18 km, has eight laterals and sub-laterals and the voltage regulators are removed. There is an assumption that the lines in modified IEEE 34 Node Network will be three phase and conductors number will be 300 MCM; all loads, assumed as spot loads. More information is available in [8].
The Simulink toolbox of MATLAB (MathWorks, Natick, MA, USA) software is used for simulating the modified IEEE 34 node network which is used to distribute the parameter line model. In the proposed method, the fault location is determined only using three phase voltages and currents at the beginning of the feeder.

The error percentage of fault location which is used in this paper is defined in the following equation:

$$\text{Error\%} = \frac{x_{\text{actual}} - x_{\text{calculated}}}{l_1} \times 100 \quad (8)$$

Where $x_{\text{actual}}$ is the real fault distance, $x_{\text{calculated}}$ is the calculated fault distance and $l_1$ is total length of the feeder.

B. Performance Evaluation

In the proposed method, firstly, the possible fault locations will be determined using IBFLM. As an example, a double phase fault has occurred in section 808-810, 11.979 km from the beginning of the feeder. Fault resistance is assumed to be zero ohm. The voltage and current wave forms of phase are shown in Fig. 4.

![Figure 4. Voltage and current of faulty phase at the beginning of feeder](image)

Now, sections 808-810, 11.979 km and 808-812, 12.051 km will be determined as the possible fault points using IBFLM. One of these sections will be the real fault section. Therefore, for the real faulty section determination, the same type of the fault will be simulated in each probable section of fault by 0.1 km step and the obtained voltages at the beginning of the feeder will be recorded. Then, the voltage difference of pre-fault and post-fault will be calculated for each simulated fault. Now, the coefficient of defined three order polynomial equations will be determined using recorded magnitude and phase variation of voltage difference, for magnitude and phase variation of the voltage difference of phase $a$. The values of matching index $\delta$ will be calculated for two possible fault locations as 0.008 for section 808-810 and 0.428 for 808-812. Among them, the calculated index for the faults in sections 808 and 810 at 11.979 km is minimum. Therefore, based on the proposed method, the fault will be located at 11.979 km from the beginning of the feeder in sections 808 and 810, for which the error is 0.0012%. It is run for some locations that the results are shown in Tables 1 to 5. From these tables, it can be concluded that the proposed method is accurate for determining the faulty section and distance. In the following, the effect of the influential parameters such as fault inception angle and the fault location, have been considered, in order to evaluate the accuracy of the proposed method.

Case 1: The impact of different fault locations on the accuracy of proposed method

In this part, double-phase and three phase faults to ground in different locations are simulated to verify the accuracy of this method. The fault parameters are two fault distances in two sections (808-810, 11.979148 km, 862-838, 58.392614 km) and fault inception angle is 45°. The results are shown in table 1 for double phase fault to ground and table 2 for three phase fault to ground. According to these tables, it can be seen that the number of possible locations can be different. For example, the number of possible locations is two for fault in 808-810 while it is three for fault in 862-838. Moreover, it can be understood that three fault distances are calculated for each possible fault point which are obtained by IBFLM ($x_{IBFLM}$) and two cubic equations ($x_a$ and $x_{01}$ explained in part 3.B).

<table>
<thead>
<tr>
<th>Actual section</th>
<th>Possible locations</th>
<th>$\delta$ index</th>
</tr>
</thead>
<tbody>
<tr>
<td>808-810, 11.9791 km</td>
<td>808-810, 11.9791 km</td>
<td>0.0086 (ok)</td>
</tr>
<tr>
<td>808-812, 12.051 km</td>
<td>808-812, 12.051 km</td>
<td>0.4283</td>
</tr>
<tr>
<td>862-838, 58.3926 km</td>
<td>862-838, 58.3926 km</td>
<td>0.0202 (ok)</td>
</tr>
<tr>
<td>862-840, 58.1633 km</td>
<td>862-840, 58.1633 km</td>
<td>0.0458</td>
</tr>
</tbody>
</table>

Case 2: The impact of different fault resistance on the accuracy of proposed method

The two and three phase fault can be occurred in two types (solidly and resistive). For example: 1- the fault is occurred...
through external things hitting such as tree branches, birds etc. This fault can be with constant or variable resistances. 2- The phase wires can be fallen on resistive ground such as asphalt, sand etc. according to the ground fault model, the RFI and RFg can have value and affect on fault location algorithm. Consequently, analysis of the fault resistance is very important in fault location algorithm. Different tests are performed in which the parameters are fault inception angle: 45, double phase fault to ground and three phase fault to ground at 11.979 km. The obtained results are shown in Tables 3 and 4. It can be seen that the minimum and maximum errors are 0.001% and 0.006%, respectively; in these two fault locations for different resistances. As the presented δ (index of fault section estimation) values in these tables, it could be found that the accuracy of this method in the faulty section estimation is good and all real faulty sections and locations are determined precisely.

TABLE III. RESULTS OF RUNNING THE PROPOSED ALGORITHM FOR DIFFERENT FAULT RESISTANCE (DOUBLE PHASE FAULT TO GROUND)

<table>
<thead>
<tr>
<th>Actual fault location (km)</th>
<th>Fault Resistance (Ω)</th>
<th>Possible fault location (km)</th>
<th>Error %</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>808.810</td>
<td>0</td>
<td>808.810 11.979</td>
<td>0.0012</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>808.810 11.977</td>
<td>0.0028</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>808.810 11.974</td>
<td>0.0057</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.812 11.572</td>
<td>0.4154</td>
<td>0.398</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actual fault location (km)</th>
<th>Fault Resistance (Ω)</th>
<th>Possible fault location (km)</th>
<th>Error %</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>808.810</td>
<td>50</td>
<td>808.810 11.976</td>
<td>0.003</td>
<td>3.9908</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.812 11.994</td>
<td>0.015</td>
<td>22.3723</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.810 11.976</td>
<td>0.003</td>
<td>0.0053</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.812 11.706</td>
<td>0.278</td>
<td>1.1322</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.810 11.9732</td>
<td>0.006</td>
<td>2.2082</td>
</tr>
<tr>
<td></td>
<td></td>
<td>808.812 11.575</td>
<td>0.418</td>
<td>11.1093</td>
</tr>
</tbody>
</table>

### Case 3: The impact of the fault inception angle on the accuracy of the proposed method

Different simulations have been conducted to evaluate this condition. The obtained results are shown in Tables 5.

### V. Conclusion

In this paper, an innovative combined method is proposed for determining online fault location in power distribution networks. For this purpose, probable fault locations are determined using the proposed impedance-based fault location method and the recorded current and voltage at the input of the feeder. Then, a novel faulty section estimation method is used to determine actual fault location and faulty section. For this purpose, first the same fault type is simulated in each probable fault location and the voltage sags are recorded for each of them. Then a third order polynomial is defined for magnitude and phase variation of voltage difference which is recorded at the input of the feeder for each probable faulty section. Next, matching index (|X_\text{AV} - X_\text{RF}|) is used to estimate real fault location and faulty section. Location with minimum index is determined as the real fault location and faulty section. The results verify that the proposed method outperforms its counterparts in terms of determining fault locations and sensitivity to fault resistance.

### REFERENCES


