A Generalized Fault Location Method Based on Voltage Sags for Distribution Network

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An enhanced fault location method based on voltage sag profiles for distribution networks is presented in this paper. In other previous methods, only a single measurement has been used. The proposed method can be used with any number of measurements in the network, making it more general. A new ranking approach that addresses multiple possibilities of the faulted section is proposed. Different case studies with various numbers of measurements are performed on a large 11-kV network with the main feeder consisting of 42 buses to validate the method. The test results show that there is an improvement in terms of accuracy in detecting the faulted section in the first attempt for each additional measurement. Therefore, by utilizing the average value of each measurement, a better accuracy of fault location can be achieved. © 2013 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

Reliability of a power system service can be interrupted by the occurrence of faults. Power supply to the customers will also be affected. Hence, it is crucial for the fault to be located as accurately as possible so that the maintenance crew can be immediately dispatched to the appropriate location. However, accurate fault location is not easy because of various factors such as the complexity of power distribution systems, namely nonhomogeneity of lines, unbalanced network, lateral branches, and distributed loads.

Since fault location research studies are important, various methods have been developed to identify fault location. In general, fault location methods can be classified into four: impedance-based, fundamental-frequency, traveling-wave, and knowledge-based methods. However, the complexity of distribution networks, mainly nonhomogenous lines/cables, makes the impedance-based [1–11] and traveling-wave high-frequency-component methods [12–15] ineffective. Both methods are more suitable and widely used for fault location in homogenous transmission line systems.

Knowledge-based method, such as artificial neural network [16–18], genetic algorithm [19], and hybrid methods [20–22], are also being applied in the area of fault location. These methods require information such as substation and feeder switch status, real-time feeder measurement, and atmospheric conditions. For distribution network with limited real-time measurements, these methods may not be suitable.

Considering such limitation, in our previous work [22, 23], a knowledge-based method, which uses only voltage sag data at primary substation, was proposed. A fault that is close to the measurement location can be identified because it causes more severe voltage sags than a fault that is further from the measurement location. The pattern of the voltage sags between the database and actual data can be matched. In the initial work, a faulted section was identified by matching the actual data with the database of the obtained voltage sags [22]. Improvement from the initial work was done to determine the fault distance from the sending node of the identified faulted section [23].

This paper presents an improvement of the previous methods from single voltage sag measurement to multiple numbers of measurements. The improvement is important because, nowadays, distribution network are not only monitored at one point but there is possibility at multiple points, especially for smart-grid applications [24]. The improvements include new ranking reasoning and fault distance estimation. The improved method has been tested with a large 1-kV network consisting of two feeders and five branches with a total of 42 buses, which was never considered earlier.

This paper has been organized as follows. In the following section, an overview of the previous methods is presented. Section 3 presents the description of the improved method. The results of the proposed method are presented and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. Overview of the Previous Method

The method is based on the principle of the voltage sag profile as seen from a primary substation. A fault occurring near the measurement location causes more severe voltage sags than a fault that is further from the measurement location. Basically, the
algorithm of the method consists of three main tasks: fault section identification, fault distance determination, and ranking procedure. The details of these tasks are presented in [22, 23].

2.1. Faulted section identification Identification of a faulted section is conducted by matching the voltage sag magnitude and phase angle at the measured node with the voltage sag magnitude and phase angle in the database. A faulted section is identified when the voltage sag magnitude and phase angle lie between any voltage sags of two adjacent node values, such that

\[
V_p^{\text{(dbase)}} \leq V_F^{\text{(meas)}} \leq V_q^{\text{(dbase)}} \quad (1)
\]

\[
\phi_p^{\text{(dbase)}} \leq \phi_F^{\text{(meas)}} \leq \phi_q^{\text{(dbase)}} \quad (2)
\]

where \(\phi_p^{\text{(dbase)}}\), \(\phi_q^{\text{(dbase)}}\), \(V_p^{\text{(dbase)}}\), \(V_q^{\text{(dbase)}}\), \(V_p^{\text{(meas)}}\), and \(V_q^{\text{(meas)}}\) are the simulated phase angle and voltage sags due to the fault at node \(p\) and node \(q\) which is stored in the database. Since there are many lateral nonhomogeneous networks, it is possible to obtain multiple faulted sections. To overcome this problem, a ranking reasoning algorithm has been applied.

2.2. Ranking reasoning process For rank reasoning process, the voltage sag magnitude and phase angle are assumed as a linear function of the fault distance. This assumption is for a short distance cable, which is always true for a rural distribution system [23]. The linear relationship of the voltage sag phase angle versus its magnitude is illustrated in Fig. 1.

Referring to Fig. 1, it is assumed that there are three possible selected faulted sections; section 6–9, section 3–4, and section \(p–q\). To rank the faulted section among these selected sections, the rank reasoning algorithm calculates the shortest distances \(d_1\), \(d_2\), and \(d_k\) between the measured voltage sags \(V_p^{\text{(meas)}}\) and \(\phi_p^{\text{(meas)}}\).

Using a trigonometric equation, the shortest distance \(d_k\) for the \(k\)th selected possible faulted section can be calculated. The rank reasoning compares the calculated distance \(d_k\) between the measured voltage sag pattern for all possible faulted sections, i.e. \(k = 1, \ldots, n\). The rank is based on the distance of the line section \((d_1, d_2,\) and \(d_{\text{closest}}\)). The closest will be ranked as the first possible, followed by the second closest, and so on. Based on the ranking of the section, the first rank faulted section will be inspected first. In case the first section is incorrect upon inspection, the second possible section will be inspected. The process is repeated for the next section until the actual faulted section is found.

2.3. Fault distance The fault distance is determined by assuming that the length of a faulted section \(p–q\) (any two adjacent nodes of a section) corresponds to the distance between point \(p\) and \(q\) of the voltage sag data as shown in Fig. 1. For the purpose of derivation of the fault distance equation, only section \(p–q\) is considered, as shown in Fig. 2.

The fault distance is derived on the basis of the intersection of line \(d_k\) (the shortest distance) to the line \(p–q\); given the fault distance \(d_f\) from node \(p\). The distance \(d_f\) can be calculated using the cosine rule. The shortest distance \(d_k\) and fault distance \(d_f\) (from node \(p\)) are given by

\[
d_k = |\sin \theta_{BC} \times C| \quad (3)
\]

\[
d_f = \sqrt{A^2 - d_k^2} \quad (4)
\]

and the actual length \(F_{d_k}\) can be calculated using

\[
F_{d_k} = |d_f \times l_{p–q}|/B \quad (5)
\]

where

\[
\theta_{BC} = \cos^{-1}[(B^2 + C^2 - A^2)/(2 \times B \times C)] \quad (6)
\]

\[
A = \sqrt{(\phi_p^{\text{(dbase)}} - \phi_F^{\text{(meas)}})^2 + (V_F^{\text{(meas)}} - V_p^{\text{(dbase)}})^2} \quad (7)
\]

\[
B = \sqrt{(\phi_q^{\text{(dbase)}} - \phi_F^{\text{(meas)}})^2 + (V_F^{\text{(meas)}} - V_q^{\text{(dbase)}})^2} \quad (8)
\]

\[
C = \sqrt{(\phi_F^{\text{(meas)}} - \phi_q^{\text{(dbase)}})^2 + (V_q^{\text{(dbase)}} - V_F^{\text{(meas)}})^2} \quad (9)
\]

\(l_{p–q}\) is the length of cable/line for section \(p–q\) in kilometres.

3. The Improved Method

In the previous method, only one measurement at the primary substation is used to locate the fault. The main problem of using a single measurement is that the voltage sag might be unobservable for a fault occurring far away from the measurement location. Therefore, the method could be ineffective for a large-scale network with a long feeder. This fact has been shown and discussed in details in Ref. [21]. Considering this limitation, the method is improved to make it adaptable for any number of measurements. This section describes the improvements in details.
be considered. Equations (1) and (2) therefore can be written as

where

In this paper to address this problem by considering two criteria:

Another database. Thus, a new ranking approach is proposed in

The whole steps are repeated for all other types of fault. The

The probability of being a faulted section is higher when more

The same equations as (1) and (2) are applied in the improved method. The difference

The databases and the network parameters database will be

The same equations as (1) and (2) are applied in the improved method. The difference

3.3. Ranking analysis Since the faulted section identification

3.4. Fault distance estimation Since the improved

3.5. Overall algorithm The flowchart of the proposed algorithm is shown in Fig. 4.

The algorithm can be divided into two parts: matching and ranking. In the matching process, voltage sag measurements from various locations are compared with the simulated database to obtain possible faulted sections, the total numbers of sections i selected ($NSIS$), the fault distance $d_f$, and the shortest distance $d_i$.

In the ranking process, the obtained values from the matching process are used to rank the possible faulted sections according to its inspected priority. In this process, the average of fault distance $d_i'(average)$ and average of the shortest distance $d_i$ (average) are also calculated. The average of the shortest distance $d_i'(average)$ is utilized as the main criterion of the ranking if the total number of $NSIS$ belonging to section $i$ is equal to the other selected sections. Otherwise, the ranking will be based on the number of $NSIS$. The highest $NSIS$ of a section will be selected as the first rank. This is followed by the next highest value of the shortest distance.

Finally, the end results of the algorithm are the faulted section (that has been ranked) $NSIS$, the average of the shortest distance $d_i'(average)$, and the actual fault distance $F_d$.

4. Testing of the Proposed Method

4.1. Test distribution network Different from the previous paper, in this paper a large-scale nonhomogeneous distribution network is used to test the capability of the proposed method.

The diagram shows the process of the proposed method. The real-time measurement includes voltage magnitude and phase angle. The fault type identification is done using a database. The voltage sag simulated is also used for matching. The ranking process is based on the highest $NSIS$. The most possible faulted section is determined using the equation (13).
A single-line diagram of the network is shown in Fig. 5. The system consists of one source 132 kV representing the grid, a unit of step-down 132/11 kV transformer, and four branches. The network is divided into four branches with a total of 41 line sections and 43 buses.

The tested network was modeled using PSCAD power system simulator software. The cables were modeled using the PI model with constant impedance load. The sources were the three-phase voltage source model. Since the studied distribution network is an underground cable system, faults are normally caused by permanent insulation breakdown. Hence, in the voltage sag pattern simulation, only faults with zero impedance were considered.

For this case study, three possible measurement locations were considered, called sections 1, 2, and 3. To show the proposed method adaptability for any number of measurements, three cases were considered in the tests: (i) single measurement at location 1, (ii) two measurements at locations 1 and 2, and (iii) three measurements at locations 1, 2, and 3. For practical implementation of the proposed method, the chosen measurement location should be able to detect voltage sags at any location.

4.2. Test case: single line-to-ground fault (SLGF) at the midpoint of the line section

In this case, the performance of multiple measurements is investigated. An SLGF is simulated at the midpoint of all the lines between two adjacent nodes or a section. It should be noted that SLGF is applied since it is the most frequent fault occurrence in the actual distribution systems [1].

Table I shows the test results of the proposed method for a single up to three measurement points. The yellow background color in the column of section is the correct answer of the faulted section selection. Even though the simulation is performed on each section of the test network, only results of certain sections are presented to show the performance of the proposed method.

In Table I, the first column shows the tested section. The second column presents the selected possible section. The third column shows the number of sections found in different databases (NSiS). Meanwhile, fourth and fifth column show the shortest distance \( d_k \) and actual fault distance (measured from a sending node). The following columns represent two and three measurements, respectively.

Taking section 3–4 as an example for discussion; when a fault is created at the midpoint of section 3–4, three possible sections were found, that is, 3–4, 25–26, and 39–40. The respective shortest distance \( d_k \) and the actual fault distance are shown in the same row. For one measurement, the NSiS always has one value. Since the real measurement will be matched with the single database, the shortest distance \( d_k \) is considered as the main criterion in determining the ranking of the possible faulted section.

It can be seen in Table I that section 3–4 has the lowest shortest distance \( d_k \), which makes it to be the first rank. For two and three measurements, the significant different is on the NSiS. This is because section 3–4 was found more than once at different databases corresponding to one, two, and three measurements. In this condition, the average of the shortest distance \( d_k \) (average) and the average of the actual fault distance \( d_k \) (average) are considered.

In case several sections have the same value of NSiS, the ranking process will consider the average of the shortest distance \( d_k \) (average). This condition is applicable to subsequent measurements up to \( n \) measurements. For example, for a fault at the midpoint of section 23–24 on the three measurements, the first NSiS is 3 and the value of the average of the shortest distance \( d_k \) (average) is 0.00041. The second NSiS and the following is 1, with the value of the average of the shortest distance \( d_k \) (average) increased from the smallest value until the largest value. The sequence value of the average actual fault distance, \( d_k \) (average), will follow ranking based on NSiS and \( d_k \) (average).

4.3. Analysis of the ranking performance

The overall performance of multiple measurements in this method is presented in Fig. 6. The \( x \)-axis represents the number of measurements, while the \( y \)-axis represents the number of candidates at the first, second, and third rankings.

From Fig. 6, there are significant improvements for the section selected in the first rank with the higher number of measurements.
For a single measurement, the total number of sections in the first rank is 39% (16 sections). This number increases tremendously to 73.2% (30 sections) and 97.6% (40 sections) for two and three measurements, respectively. A significant improvement in term of successful selected section can also be observed. Based on one measurement, there is 46.3% (19 sections) undetected cases. However, with additional measurement, all the faulted sections were successfully located.

The result of the second rank of a single measurement is 12.2% (five sections) and decreases to the 4.9% (two sections) for the third and fourth ranks on the single measurement increase slightly for two measurements. The third and fourth ranks on the single measurement increase slightly for two measurements. However,
these values increase as a result of the reduction of 46.3% (nondetected faulted section) of the single measurement to the zero value (nondetected faulted section) of two measurements. Otherwise, the second, third, and fourth ranks decrease until remaining at 2.4% (one section) of the third rank on three measurements.

The improvement using this method is possible because a fault near the measurement location induces more severe voltage sag than a fault occurring far away from the measurement location. Therefore, if more measurements are made in the distribution systems, a fault that is closer to the measurement nodes will likely generate more accurate results. Another reason is that considering the total number of sections \( i \) selected (NSiS) from severe measurements will contribute to a better accuracy of fault location detection.

### 4.4. Analysis of fault distance error based on multiple measurements

The accuracy of the obtained fault distance is also presented in this section.

The estimation error distance is calculated without considering the error measurement. The percentage error of fault distance can be calculated from the difference between the actual distance \( d_{\text{actual}} \) and the calculated actual fault distance \( d_a \) over the length of main feeder

\[
\% \text{ distance error} = \frac{d_{\text{actual}} - d_{\text{calculated}}}{\text{length of main feeder}} \times 100 \quad (14)
\]

The analysis of the fault distance error for SLGF at the midpoint of the main feeder is summarized in Table II. This table presents the correct fault section estimation for three measurements.

From Table II, it can be observed that the maximum error of 1.047848% is obtained at test section 10–11. In terms of length, the error is around 0.54 km or 537.55 m, which is considered acceptable in practice. However, it is important to point out that the location of the fault is correctly done at section 10–11 in the first attempt.

In order to present a detailed analysis on fault distance error for various measurements numbers, a fault is simulated at various distances across two adjacent nodes. The effect of multiple measurements to the accuracy of the fault distance is analyzed on the basis of the simulation results of sections 3–4, 16–17, which represent subsection A, and sections 28–29, 31–32 at subsection B, as shown in Figs 7–10, respectively.

<table>
<thead>
<tr>
<th>No</th>
<th>Tested section</th>
<th>Actual distance (km)</th>
<th>Calculate average distance (km)</th>
<th>% error distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2–3</td>
<td>2.5</td>
<td>2.946428</td>
<td>0.870230</td>
</tr>
<tr>
<td>2</td>
<td>3–4</td>
<td>2.375</td>
<td>2.433814</td>
<td>0.114647</td>
</tr>
<tr>
<td>3</td>
<td>4–5</td>
<td>1.7</td>
<td>1.943999</td>
<td>0.475632</td>
</tr>
<tr>
<td>4</td>
<td>5–6</td>
<td>2.4</td>
<td>2.710476</td>
<td>0.605216</td>
</tr>
<tr>
<td>5</td>
<td>6–7</td>
<td>2.5</td>
<td>2.691601</td>
<td>0.373491</td>
</tr>
<tr>
<td>6</td>
<td>7–8</td>
<td>1.75</td>
<td>1.767460</td>
<td>0.034025</td>
</tr>
<tr>
<td>7</td>
<td>8–9</td>
<td>1.25</td>
<td>1.227042</td>
<td>0.044752</td>
</tr>
<tr>
<td>8</td>
<td>9–10</td>
<td>1.9</td>
<td>1.838139</td>
<td>0.120587</td>
</tr>
<tr>
<td>9</td>
<td>10–11</td>
<td>1.375</td>
<td>0.837454</td>
<td>1.047848</td>
</tr>
<tr>
<td>10</td>
<td>11–12</td>
<td>0.05</td>
<td>0.026716</td>
<td>0.045388</td>
</tr>
<tr>
<td>11</td>
<td>12–13</td>
<td>0.1</td>
<td>0.181129</td>
<td>0.158146</td>
</tr>
<tr>
<td>12</td>
<td>13–14</td>
<td>0.25</td>
<td>0.135966</td>
<td>0.222288</td>
</tr>
<tr>
<td>13</td>
<td>2–25</td>
<td>2.5</td>
<td>2.828783</td>
<td>0.602299</td>
</tr>
<tr>
<td>14</td>
<td>25–26</td>
<td>2.42</td>
<td>2.885373</td>
<td>0.852519</td>
</tr>
<tr>
<td>15</td>
<td>26–27</td>
<td>2.42</td>
<td>2.694328</td>
<td>0.502543</td>
</tr>
<tr>
<td>16</td>
<td>27–28</td>
<td>2.2</td>
<td>2.301026</td>
<td>0.185070</td>
</tr>
<tr>
<td>17</td>
<td>28–29</td>
<td>2.08</td>
<td>2.119025</td>
<td>0.071490</td>
</tr>
<tr>
<td>18</td>
<td>29–30</td>
<td>1.1</td>
<td>1.101387</td>
<td>0.002541</td>
</tr>
<tr>
<td>19</td>
<td>30–31</td>
<td>1.6</td>
<td>1.663254</td>
<td>0.115875</td>
</tr>
<tr>
<td>20</td>
<td>31–32</td>
<td>2.5</td>
<td>2.497952</td>
<td>0.003752</td>
</tr>
<tr>
<td>21</td>
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<td>1.931604</td>
<td>0.070338</td>
</tr>
<tr>
<td>22</td>
<td>35–36</td>
<td>0.454</td>
<td>0.400486</td>
<td>0.098033</td>
</tr>
<tr>
<td>23</td>
<td>36–37</td>
<td>0.3</td>
<td>0.253599</td>
<td>0.085002</td>
</tr>
<tr>
<td>24</td>
<td>37–38</td>
<td>0.25</td>
<td>0.194336</td>
<td>0.101971</td>
</tr>
</tbody>
</table>

From the plots shown in Figs 7–10, it is obvious that they have a similar pattern. The percentage of error decreases with the increase in the number of measurements in between two adjacent nodes. A large reduction in the percentage of error can be observed from one measurement to two measurements. These indicate that single measurement alone may not produce accurate faulted section and fault distance. For each section, the highest error for each measurement can be seen at a particular distance across the section.

A unique observation can be seen in Fig. 8, where only two and three measurements are presented. The reason is that section 16–17 cannot be detected. This section is located far away from the measurement 1, which is not able to detect voltage sags. Another interesting observation is a fault occurs near a node and the error is almost zero. This is because the voltage sag and phase angle magnitudes are almost the same with the values in the database.
Overall, it can be seen that the highest error is found for fault at test section 28–29. However, with the increase in the number of measurement, the error decreases. This analysis has shown that the proposed method has successfully achieved higher accuracy of fault distance. The analysis of the proposed method has also shown that multiple measurements can reduce the fault distance error.

4.5. Analysis measurement error  The effect of measurement error of voltage sags on multiple measurements is represented by sections 3–4, 19–22 at subsection A and by 39–40, 42–43 at subsection B. The measurement error is varied between ±0.1% and −1% in order to investigate its effect on the distance estimation error.

From the Figs 11–14, it can be seen that an increase in the percentage of measurement error causes the fault distance estimation error to be higher. Negative and positive measurement errors have the same effect on the distance estimation error. However, when multiple measurements are applied, the percentage of the distance estimation error is lower. Therefore, this shows that a larger number of measurements can yield a better result.

5. Conclusion

An improved fault location method based on voltage sags has been proposed in this paper. The improvement has made the algorithm adaptable to any number of measurements in the system to locate a fault. A new ranking approach has been also proposed to cater to multiple faulted sections. Tests revealed that when the number of measurements increases, the fault distance error decreases. This shows that the proposed method can successfully achieve a higher accuracy of the fault distance. The analysis has also shown that multiple measurements can reduce the fault distance estimation error for different errors of measurement. Therefore, this clearly shows that a larger number of measurements can yield a better result.
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References


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