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Voltage Sags Matching to Locate Faults for Underground Distribution Networks

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***Abstract*—A voltage sags matching to locate a fault for underground distribution network is presented in this paper. Firstly the method identifies the faulted section by matching a voltage sags measured at the primary substation during a fault with pre-developed voltage sag database. From the identified faulted section, the distance of a fault from sending-end is calculated. The problem of multiple sections is addressed by ranking approach. Test results on an underground distribution network shows most faults can be located by the first attempt within high accuracy distance. Only few faulted sections found by the second attempt. Since the method is using only voltage sag data, monitored at the primary substation, the method is considers economical to be implemented for a rural distribution network.**

***Index Terms*—fault location, power distribution faults, pattern matching.**

I. INTRODUCTION

Restructuring and deregulation of the energy sector in the early 80's has brought new challenges to the task of maintaining a reliable electricity system. Since then, quality and reliability of power supply had become main objectives of power utilities in improving their services. These objectives may not be achieved fully since electrical system always subjected to unavoidable interruption such as short circuit fault in the system. Nevertheless, the interruption time could be minimized if fault can be located fast. This will improve reliability indexes such as system average interruption duration index (SAIDI).

In the past, fault locating in distribution system is time consuming since a trial and error approaches were applied. Usually, a suspected faulted feeder will be inspected to find the fault upon receiving complain from customer. For underground cable system, switching technique was often being practiced. This technique however, is time consuming and exposed additional stress on the equipment due to switching process. For that reasons, various automated fault location methods for distribution networks were introduced in the past [1]-[14].

Although these methods may assist fault location, some of the methods may not be effective due to complexity of distribution system such as mix of different type of cables and tapped with branches along a feeder. Hence, the impedance is not distributed equally along the system. As a result, method that is based on travelling wave may not be effective [1]-[2]. Distribution system also often has limited monitoring, mainly in a rural area. Thus, not much information can be utilized to assist fault location. As consequence, method that based on Intelligence techniques such as Expert System, Neural Network and Fuzzy Logic [3]-[5] may not be applicable due to insufficient data. Considering the aforementioned problems, fault location methods that require only limited data is preferable to be used for rural distribution networks.

A most popular type of method for network with limited data is by using voltage/current measured at the primary substation [6]-[8]. The calculated apparent impedance (as seen from a monitoring point) is used to estimate the distance of a fault. Due to single measurement, multiple fault locations are frequently obtained. The most likely fault location is identified based on the operation time of protective device such as re-closer and fuses upon fault occurrence.

Matching technique also has been applied for fault location for distribution networks [9]-[14]. Basically, the technique work by comparing specific data obtained from actual fault event with a simulated data. The match will lead to the possible fault location. Different types of data were reported to be applied. In [9], a reactance value obtained from a distance relay was matched with simulated reactance to locate a faulted section. Voltage sag data also was reported to be used [10]-[14]. In [10], voltage sag measured from different locations is matched with the simulated vulnerable voltage sag's contours. In [11], voltage sag waveform from measurement is matched with the simulated one using genetic algorithm.

Matching technique using voltage sag data was also reported in our previous works [12]-[14]. In [12], voltage sag pattern characteristic was used to locate a faulted section in distribution networks. Latter, the method was improved by determining the fault distance [13]. Further improvement was conducted to address the non-linearity of voltage sags profile [14]. All of these previous reported works were focusing on the fault location equations. None of them discuss in details how the computing process takes place. Hence, the main objective of this paper is to present the computing aspects mainly the algorithm of the method. The background of the method and its basic formulation will also be reviewed in this paper. A details test result of three-phase to ground fault, which not presented before will also be discussed to show the effectiveness of the proposed method.

This paper is organized as follows. In the following section, the basic principle of the proposed method is described. Section III is describing the algorithm of the

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method. Meanwhile Section IV is discussing the establishment process of database. Finally, the performance of the proposed method is presented in Section V.

II. OVERVIEW OF THE PROPOSED METHOD

A. Voltage Sag Profile

To illustrate the proposed fault location method working principle, a distribution system with 2 laterals and one main line as shown in Fig.1 is used. A power quality measurement device is installed at the primary substation (node *a*) to monitor and record voltages sag event due to fault at any location.

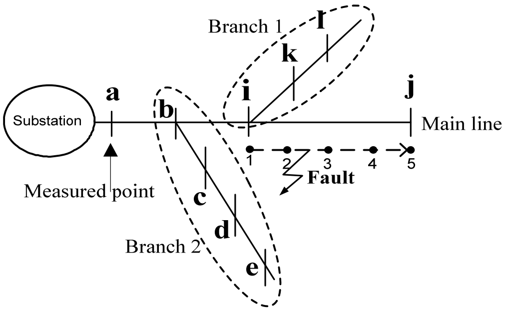

Figure 1. An example of simple distribution network

Assume that a short circuit fault occurred at any points between node *i* and node *j* (section i-j). For any type of fault, the relationship between voltage sags and fault distance on a section (from sending node) can be represented in the form of voltage sag as a function of fault distance as follows:

$$V_{sag}(d) = \mathrm{V}_{\text{i-j}}(d)\angle\varphi_{\text{i-j}}(d) \quad (1)$$

where $\mathrm{V}_{i-j}(d)$ and $\varphi_{i-j}(d)$ are the voltage sag magnitude and phase angle as a function of fault distance respectively for a section *i* - *j*. Since each section has different line impedance per-unit length, the voltage sag magnitude/phase angle function would be different for each section.

Based on the changes of the voltage magnitude/phase angle over fault distance as describes in [15], the changes of voltage magnitude and phase angle over a distance can be represented in a form of quadratic equations (1) and (2) :

$$\mathrm{V}_{\mathrm{a,F}} = a_2\mathrm{d}_{\mathrm{F}}^2 + a_1\mathrm{d}_{\mathrm{F}} + a_0 \quad (2)$$

$$\varphi_{\mathrm{a,F}} = b_2\mathrm{d}_{\mathrm{F}}^2 + b_1\mathrm{d}_{\mathrm{F}} + b_0 \quad (3)$$

Where a_0, a_1, a_2 and b_0, b_1, b_2 are coefficients of the voltage magnitude and phase angle profile respectively. d_{F} is the distance of fault from the sending node *i*. These coefficient can be obtained by simulated fault various location between node *i* and node *j* as shown in Fig. 1. The voltage sag measured at node *a* are then used to estimate the coefficients using curve fitting technique.

B. Faulted Section Identification

If the voltage sag magnitude and angle lies between the voltage sags of section *i-j* (*i* and *j* is any two adjacent nodes), that section will be considered as the possible faulted section. These conditions are shown by the following equation:

$$\mathrm{V}_{a,i}^{(\mathrm{dbase})} \le \mathrm{V}_{a,F}^{(\mathrm{meas})} \le \mathrm{V}_{a,j}^{(\mathrm{dbase})} \quad (4)$$

$$\phi_{a,i}^{(\mathrm{dbase})} \le \phi_{a,F}^{(\mathrm{meas})} \le \phi_{a,j}^{(\mathrm{dbase})} \quad (5)$$

Where ($\mathrm{V}_{a,i}^{(\mathrm{dbase})}, \phi_{a,i}^{(\mathrm{dbase})}$) and ($\mathrm{V}_{a,j}^{(\mathrm{dbase})}, \phi_{a,j}^{(\mathrm{dbase})}$) are simulated voltage sags in the database due to fault at node *i* and node *j* respectively.

C. Fault distance

The distance of a fault from a sending-node (node *i*) can be calculated by incorporating the measured voltage sag during fault into (1) and (2). Suppose if the measured voltage sags are $\mathrm{V}_{\mathrm{a,F}}^{(\mathrm{meas})}$ and $\varphi_{\mathrm{a,F}}^{(\mathrm{meas})}$, the fault distance from sending-end is given by (6) and (7):

$$\mathrm{d}_{\mathrm{F}} = (-a_1 \pm \sqrt{a_1^2 - 4a_2(a_0 - \mathrm{V}_{\mathrm{a,F}}^{(\mathrm{meas})})})/2a_2 \quad (6)$$

$$\mathrm{d}_{\mathrm{F}} = (-b_1 \pm \sqrt{b_1^2 - 4b_2(b_0 - \varphi_{\mathrm{a,F}}^{(\mathrm{meas})})})/2b_2 \quad (7)$$

where $0.0 \le \mathrm{d}_{\mathrm{F}} \le L_{i-j}$ and $L_{i\text{-}j}$ is the line length of cable *i-j*.

Basically, both distance obtained from (6) and (7) should have the same value. However, due to error in the data measurement and/or in the calculation process, the values could be different. To differentiate between distance obtained from (6) and (7); the following notation will be used; d_{F1} for (6) and d_{F2} is for (7). The final fault distance is the average of both distances:

$$\mathrm{d}_{\mathrm{F}} = (\mathrm{d}_{\mathrm{F1}} + \mathrm{d}_{\mathrm{F2}})/2 \quad (8)$$

D. Ranking Reasoning

Due to single measurement and uncertainty of fault resistance, multiple fault location candidates will be produced. To address this issue, ranking reasoning is proposed to prioritise the inspection of the possible section. The mismatch between the two types of distance is used as a mean to rank the candidates:

$$\sigma = |\mathrm{d}_{\mathrm{F1}} - \mathrm{d}_{\mathrm{F2}}| \quad (9)$$

The matching is considered 100% accurate if $\sigma \approx 0.0$. The ranking will assign faulted section with the lowest σ as the first rank and followed by the second lowest as second. This step is repeated until all the candidates have been ranked.

III. ALGORITHM OF THE PROPOSED METHOD

The overall fault location estimation process of the proposed method is depicted in Fig. 2. The RMS value of the voltage magnitude is calculated once every cycle for each phase. When the magnitude is detected lower than threshold value of the nominal voltage for example 0.9 pu, the sags waveform is captured and stored until the magnitude recovers back to a nominal voltage value.

The captured voltage sags waveform is analyzed using Fast Fourier Transform (FFT) to extract the fundamental voltage components. The fundamental voltage components are used to identify fault type. This is necessary to narrow down the search domain, which in turn will reduce the overall processing time. Thus, only the respective database of the fault type needs to be checked.

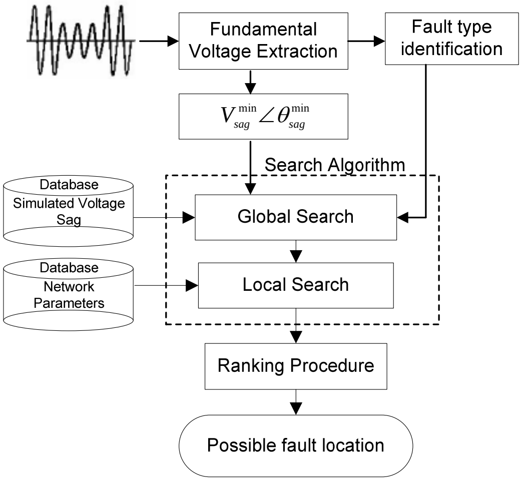

Figure 2. Flow chart of the proposed fault location

The fault type is identified based on the voltage sag magnitude pattern as follows:

i) Three phase fault to ground (LLLGF)– All the three phases has voltage magnitude that almost identical value.
ii) Single Line To Ground (SLGF)– One of the phases has voltage magnitude lower than 1.0 pu and the other two higher than 1.0 pu.
iii) Line to Line fault (LLF)– One of the phases has voltage magnitude the same as before fault, whereas the other two change.
iv) Double Line to Ground fault (LLGF)- One of the phases has voltage magnitude higher than 1.0 pu and the other two lower than 1.0 pu

The data input to this algorithm are the lowest voltage magnitude, and its corresponding phase angle. The search algorithm consists of global search and local search**.** In the global search, these data are compared with the simulated data of voltage sag magnitude in the database to find all the possible faulted section according to (4) and (5), and the possible fault resistance. The obtained candidates from the global search are then evaluated further in the local search to find the final fault distance and the rank of the possible fault location.

IV. DATABASE ESTABLISHMENT

There are two types of databases that need to be developed in order for this method to work. The first database consists of simulated voltage sag magnitude and phase angle monitored at the measured node. The second database consists of an equation of voltage magnitude and phase angle as a function of fault distance for all section in the network. Fault resistance is considered in fault location by incorporating it in the fault analysis. Since the fault resistance value is uncertain, a set of discrete values are used for the database.

A. Database 1- Simulated Voltage Sags at Node

The first type of database is developed using the following steps:

i) The pre-fault voltage is determined for all the nodes in the system using three phase load flow program.
ii) A fault resistance value is first set to 0.0 pu.
iii) Single Line to Ground Fault is simulated using fault analysis program at all nodes.
iv) The lowest magnitude of the three phases obtained from the fault is chosen together with the corresponding phase angle.
v) These voltage magnitude and phase angle are stored in database.
vi) Step (ii) to (v) is repeated for all the nodes in the system.
vii) Steps (ii) to (vi) are repeated for other fault resistance value such as 5 ohm and 10 ohm etc.

The whole steps are repeated for all other type of faults and the results are stored into different databases according to the fault type.

B. Database II- Simulated Voltage Sags Equation

The second type of database is developed using the following steps:

i) The pre-fault voltage is determined for all the nodes in the system using three phase load flow program.
ii) A fault resistance value is set to 0.0 pu.
iii) The first section is chosen to create the voltage sags equation of the magnitude and phase angle.
iv) The section is divided into *n* sections of equal distances as illustrated in the Fig. 3.

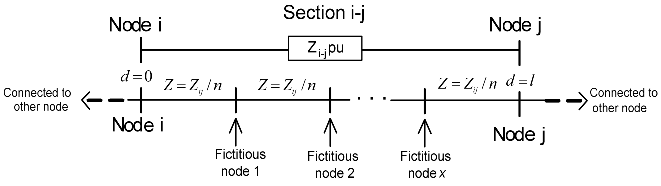

Figure 3. Subsections for section *i-j*

v) The pre-fault voltage for the fictitious nodes can be calculated using the following equation:

$$V_x = (1-l)\times V_i + (l \times V_j) \qquad (10)$$

where V_x is a complex quantity of voltage of the fictitious node x and l is the distance of the node measured from sending node i. By using (10), any pre-fault voltage at any location between two adjacent nodes can be calculated provided that the voltages are known at both nodes. Thus, load flow analysis does not need to be used to calculate the pre-fault voltage at the fictitious nodes.

vi) The chosen locations of the section are simulated with SLGF.
vii) The resulting voltage magnitudes and phase angle at each node are used to create the equation of voltage magnitude and phase angle as a function of fault distance.
viii) The same steps are repeated for all the sections and different type of fault. All the obtained equations are stored into the databases.

The above steps are repeated to consider different value of fault resistance. For example, if the minimum fault resistance is assumed to be 0 ohm and the maximum is 50 ohm with resistance increment 5.0 ohm, there will be a total of 44 databases, which represent four types of fault and 11 different values of fault resistance, as illustrated in Fig. 4.

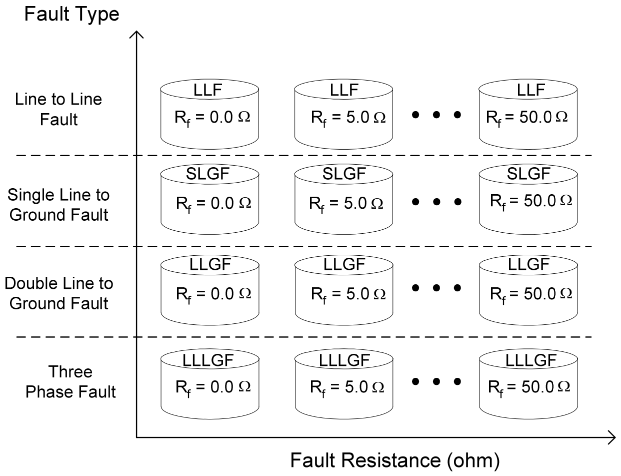

Figure 4. Illustration of analytical databases

These databases, and also the network parameters database, will be updated whenever necessary. For example, if there are changes in the system such as reconfiguration of the network or loading variation.

V. CASE STUDY

The proposed method was evaluated using the same underground rural distribution network in [12]-[13]. The one-line diagram of the tested network is shown in Fig. 5. The system is simulated using PSCAD/EMTDC software. Loads were modelled as constant impedance. At the monitoring node 2, the lowest value voltage magnitude is taken as an input to the method together with its corresponding phase angle.

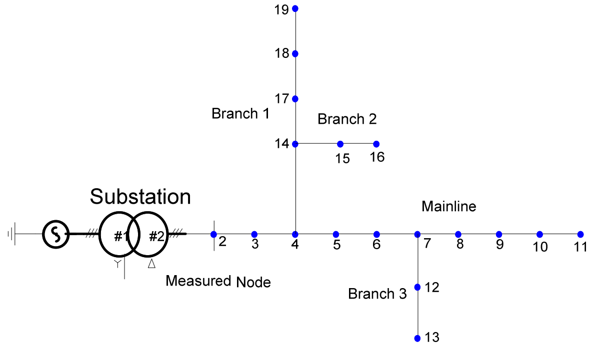

Figure 5. Subsystem of 11 kV distribution network

The performance of the algorithm is analysed by simulating a fault at the middle of each line for all section in the system. In this paper, test result of LLLFG will be presented in details since in our previous paper [13], a test on SLGF has been presented. However, overall test result for all type of fault will also be discussed. Since the test network is an underground cable, where faults are normally caused by permanent insulation breakdown system, fault resistance is considered zero for all test cases.

A. *Voltage Sags Profile Characteristic*

The overall pattern of the voltage sag profile for LLLGF is depicted in Fig. 6(a) and Fig. 6(b). The close up look of the area in the dash line of Fig. 6(a) is shown in Fig. 6(b). This profile was constructed by creating fault at five different locations between two adjacent nodes of a section. The lowest magnitude and corresponding phase angle is used to construct the voltage profiles.

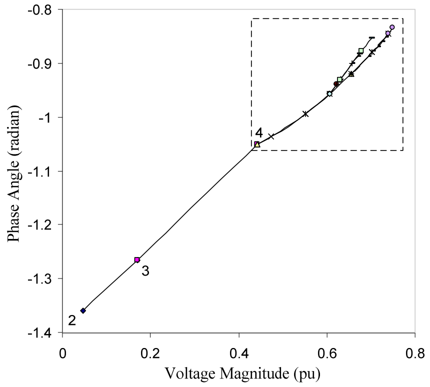

Figure 6(a). Voltage sag profile as seen at monitored node due to LLLGF

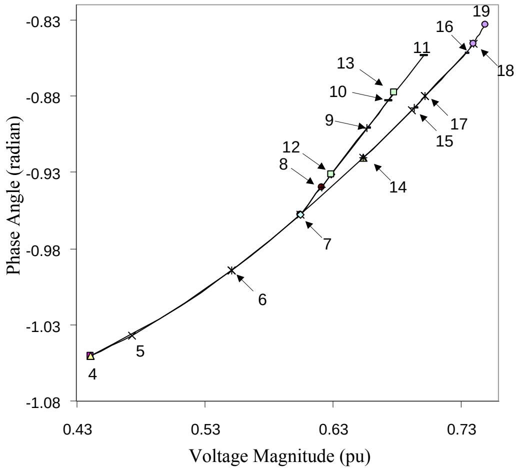

Figure 6(b). Close up look of voltage profile as seen at monitored node due to LLLGF

The voltage sag profile shows that the voltage sag magnitude increases as LLLGF moves away from the primary substation of node 1. As the fault location moving occurs close to the primary substation, voltage sag magnitude becomes deeper.

The voltage sag profile of different sections can be seen overlapped on particular section. Some of the pattern also quite closes to each other. Overlap profile is caused by parallel line sections with the same type of cable. For example, section 4-5, 5-6 and 6-7 overlapped with section 4-14. These parallel line sections can also be clearly seen in Fig. 5 of the network. The overlapped pattern causes multiple sections to be selected as a faulted section. Hence, if voltage sag values lie on the section 4-5, section 4-14 will also be selected. This is according to Eq. (4) and Eq. (5).

Besides overlapping pattern, a linear variation and non-linear pattern can also be observed. The non-linear pattern is like sections 2-3 and 3-4 and a non-linear variation is section 4-14. The linear pattern occurs for a short line section, whereas the non-linear is for long line section. This characteristic is important in determining the correct fault distance as discussed in [13].

B. *Test Result of Three Phase Fault*

Fault was simulated at the middle of each line section of the test network. The obtained results are presented in Table I with the tested section and the actual fault distance shown in column 1. The selected faulted section together with the fault resistance, estimated distance (d_{F1} and d_{F2}) and the final fault distance (d_F) are presented in the following columns.

TABLE I Test Result of LLLGF (0 Ohm Fault Resistance)

Test Section	Result				
	Candidates	R_F (ohm)	d_{F1} (km)	d_{F2} (km)	d_F (km)
2-3 (0.25km)	2-3 √	0	0.2501	0.2501	0.2501
3-4 (0.627km)	3-4 √	0	0.6269	0.6269	0.6269
4-5 (0.07km)	4-5 √	0	0.07	0.07	0.07
	4-14 √	0	0.0709	0.0658	0.0684
5-6 (0.2km)	5-6 √	0	0.2	0.2001	0.2
	4-14	0	0.3452	0.3306	0.3379
6-7 (0.175km)	6-7 √	0	0.175	0.175	0.175
	4-14	0	0.7133	0.7206	0.717
7-8 (0.1km)	7-8 √	0	0.1	0.1	0.1
	7-12	0	0.1	0.1001	0.1
	4-14	0	0.9449	0.9925	0.9687
8-9 (0.25km)	8-9 √	0	0.25	0.2501	0.25
	12-13	0	0.1505	0.1508	0.1507
	4-14	0.25	0.0163	0.9253	0.4708
9-10 (0.135km)	12-13	0	0.5347	0.5346	0.5346
	9-10 √	0	0.135	0.1349	0.135
	14-17	0	0.1061	0.3462	0.2261
	14-15	0	0.106	0.3464	0.2262
	4-14	0.25	0.2383	1.2319	0.7351
10-11 (0.25km)	10-11	0	0.2499	0.25	0.25
7-12 (0.15km)	7-12 √	0	0.15	0.15	0.15
	7-8	0	0.15	0.1499	0.15
	4-14	0	0.9752	1.0379	1.0065
12-13 (0.375km)	12-13 √	0	0.3749	0.3749	0.3749
	8-9	0	0.4748	0.4747	0.4747
	14-17	0	0.0098	0.208	0.1089
	14-15	0	0.0099	0.2081	0.109
	4-14	0.25	0.1471	1.1017	0.6244
4-14 (0.645km)	6-7	0	0.1048	0.104	0.1044
	4-14 √	0	0.6448	0.6472	0.646
14-17 (0.25km)	14-17	0	0.25	0.2501	0.25
	14-15	0	0.25	0.2501	0.2501
	4-14	0.25	0.3736	1.1406	0.7571
17-18 (0.25km)	17-18 √	0	0.25	0.2501	0.25
	15-16	0	0.3549	0.3553	0.3551
18-19 (0.125km)	18-19 √	0	0.1251	0.125	0.125
14-15 (0.1975km)	14-15 √	0	0.1975	0.1976	0.1975
	14-17	0	0.1976	0.1975	0.1976
	12-13	0	0.6888	0.3629	0.5259
	4-14	0.25	0.3245	1.092	0.7083
15-16 (0.26km)	15-16 √	0	0.255	0.2549	0.255
	17-18	0	0.15	0.1497	0.1499

*Note: Symbol (√) in the table indicate the correct section

The results shows that most faulted sections can be found in the first attempt while the remaining fault sections can be discovered at the second attempt. Out of 17 tested sections, only 2 locations were found at the second attempt (section 9-10 and section 4-14), while the remaining found in the first attempt. This is a great improvement as compared to searching fault by patrolling the feeder or switching section by section.

It can be seen that the method locates only one faulted section for fault at section 2-3, 3-4, 10-11 and 18-19. This can be explained based on voltage sag profile in Fig. 6. It can be seen the voltage pattern of section 3-4 and 18-19 does not overlap with any other line sections. Thus, the only one possible section was selected. However for a line section that overlapped with other sections, multiple faulted sections will be selected. This can be seen where two possible faulted sections for the fault at mid-point of lines 4-5, 5-6, 6-7, 4-14, 15-16, and 17-18. Three possible faulted sections are discovered for fault at mid-point of lines 7-8, 8-9, 7-12 and 14-17, four possible sections for lines 14-15 and five sections for section 9-10 and 12-13.

The final estimated distance (in km from sending node) is shown in the last column of Table I. For instance, fault at mid-point of section 2-3 produced fault distance of 0.2501 km from node 2. Another example is fault at mid-point of Section 15-16 produced fault distance of 0.255 km from node 15. The actual fault distance are 0.25 km and 0.26 km for section 2-3 and section 15-16 respectively. Although, the distance obtained from the method is not equal to the actual location, the difference is insignificant. Thus, it can be considered that the method able to produce accurate fault distance. The ability to locate the fault distance from a specific node would assist the maintenance crew to locate the fault much faster.

C. *Ranking Performance: All Types of Fault*

The overall performance of the method in term of identifying the correct faulted section is presented in Fig. 7. The *x*-axis presenting the test section and the *y*-axis is the number of candidates found and the rank number of the correct fault section found.

The results show that although some produced multiple section, majority faulted section can be found in the first attempt, which is in the first rank. Only few found in the second attempt. This proves the effectiveness of the method in locating a faulted section in underground distribution network for all type of faults.

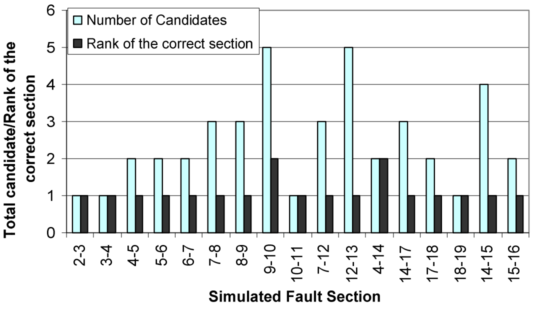

Figure 7(a). Ranking performance for LLLGF test

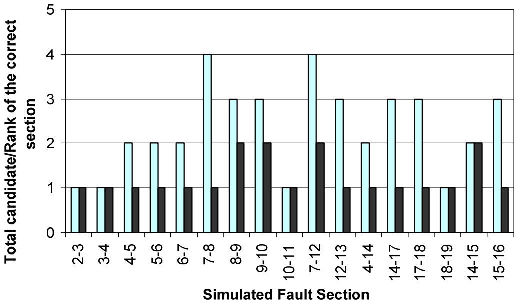

Figure 7(b). Ranking performance for SLGF test

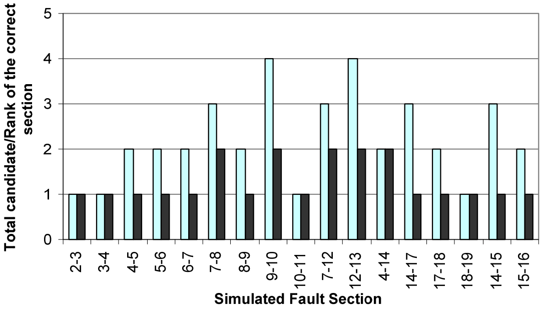

Figure 7(c). Ranking performance for LLGF test

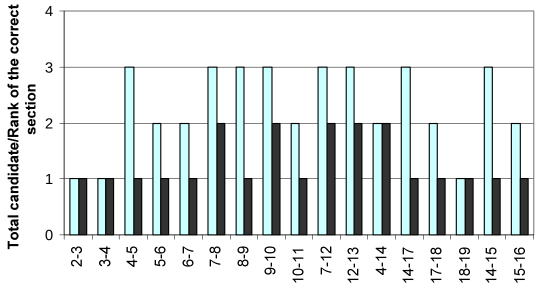

Figure 7(d). Ranking performance for LLF test

D. Fault Distance Performance: All Types of Fault

The accuracy of fault distance is calculated by comparing the actual distance (d^{Actual}) with the estimated one (d_F) from the proposed method. The difference would indicate the accuracy of the distance. The percentage fault distance error is calculated using (10):

$$\%\,\text{error} = \left|\frac{d^{Actual} - d_F}{\text{Total Lenght of faulted Section}}\right| \times 100 \qquad (10)$$

The graphs in Fig. 8 present the obtained error estimation of fault at the middle of the line section for the network.

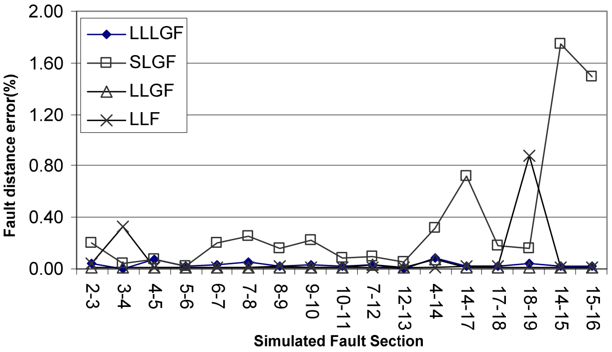

Figure 8. Fault distance error for test at mid-point of all section for all type of fault

It can be seen that LLLGF and LLF produced the most accurate fault distance. This can be seen by the small distance error, which is insignificant. The low error is believed to have been caused by computation error.

On the other hand, SLGF produced less accurate distance. The highest error occurred for test at middle of line section 14-15, which is around 1.7%. If this value is converted into actual distance it is around 6.75 m (1.7% x 0.395 km). However, this error is considered small. The main reason of this high error is due to complicated voltage sag pattern characteristic, which has many overlapping pattern as shown in our previous paper [12]. Thus, the method has difficulty in determining the correct fault distance accurately.

VI. CONCLUSION

This paper has presented a fault location method for underground distribution networks by using voltage sags matching. Any actual fault can be matched with the simulated one stored in database to determine the location of a fault. Since the method used pre-developed database, the whole process of the method is not consuming time. Load variation and uncertainty of fault resistance can be addressed by updating the database whenever there are changes in the system.

The method has been tested in a real time simulation environment by integrating it into PSCAD/EMTDC power system simulator software. An actual 11kV rural distribution system was used as the test system. Despite the present error in the real time simulation test, test results show that most of tested fault locations can be found by the first attempt and very few at the second attempt. Meanwhile, the estimated fault distance also shows high accuracy with insignificant error. Based on the test result, the method is considered promising for actual implementation. Furthermore, the method can be considered practical and economical since only require single measurement at the primary substation.

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