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Voltage Sags Pattern Recognition Technique for Fault Section Identification in Distribution Networks

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Abstract—**This paper presents a method to identify a faulted section in a distribution network using voltage sags pattern characteristics. The method starts with fault analysis to establish analytical voltage sags database. When a fault occurs, the voltage sag at the monitored node is compared with the established voltage sags in the database to find all the possible faulted sections. Finally, the method applied rank reasoning analysis to prioritize all the possible faulted sections. The method has been tested on an urban distribution network feeder. The results show that the most fault sections in the tested distributed network feeder can be located by the first attempt. All remaining faulted sections can be found by the second attempt.**

Index Terms— **Faulted section, voltage sag pattern characteristics, voltage sag database, rank reasoning, distribution networks**

I. INTRODUCTION

Fault in distribution system is inevitable and caused by various factors such as adverse weather condition, equipment failure and ageing factors. When fault occurs, utilities are urged to locate and isolate fault as quickly as possible so as more efficient repair works and restoration of the system can be done. To achieve this, an automated fault location technique could be applied.

Basically, fault locating in distribution network can be divided into three approaches. The first approach depends on equipment to locate fault. Traveling wave and fault indicator are two well-known methods that based on this approach [1]-[3]. Traveling wave method requires sophisticated devices such as high speed data acquisition device, sensor and Global Positioning System (GPS) to capture transient waveform. On the other hand, fault indicator is simpler than traveling wave technique. It can be installed at few locations along the feeder. When fault occurs, it will give an indication such as light to indicate the faulted section. However, visual inspection needs to be conducted to check the signal. It can also be costly if the signal needs to be transmitted to the control centre since communication link will involve.

The second approach uses real time monitoring data with other information such as operator's experience and historical fault data. Fault location that depends on these data and information is using artificial intelligence method such as Expert System, Fuzzy Logic and Artificial Neural Networks to locate fault [4]-[6]. The successfulness of these methods is highly depending to the amount and quality of the supplied data. Unfortunately, not all distribution networks have such data. In most of 11 kV or lower voltage distribution networks, the only available data is from the measurement at the primary substation.

The third approach uses voltages and currents measured at the primary substation to locate fault. Method based on this approach is describes in [7]-[9]. In these methods, a developed mathematical equation is used to calculate fault location. Due to consideration of single measurement, multiple locations will be produced. The final location is determined based on the respond time of protective equipments when fault occurs. By knowing the location of all the protective equipments and its respond time setting, the most probable location can be selected.

Under the same approach, there are fault location through matching between simulated data and actual measurement data [10]-[12]. In [10], fault location is determined by comparing the actual reactance value measured from distance relay with simulated reactance value from short-circuit analysis. Reduction of multiple possible locations is achieved by using fault indicators. Similar method is also describes in [11], but voltage sag waveform is used. A recorded voltage waveform due to fault is compared with a list of simulated waveform based on fault at different locations and types. The method in [12] uses voltage sag magnitude to locate fault. Voltage sags measured at various nodes are compared with the simulated one. The matching will provide the fault location. However, the method is expensive since requires more than one voltage meters and the reading needs to be transmitted to central location.

Based on the same matching approach, the proposed method uses voltage sag to locate fault. In this method, pattern recognition technique is applied. In this method, voltage sag features that are voltage sag magnitude and phase shift captured at the primary substation are compared with the

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simulated ones. When fault occurs, the method searches and matches the captured voltage sags with the analytical voltage sags in the database. The match will give the corresponding faulted section. Due to limited measurement, multiple sections might be produced as faulted sections. The sections are ranked for the process of identifying the actual faulted section.

II. DESCRIPTION OF THE PROPOSED METHOD

The proposed method is utilizing the pattern characteristic of voltage sags variation between two adjacent nodes as seen at the primary substation. This is possible since one of the factor that influence the severity of the voltage sags at a primary substation is the distance of fault [13]. The used voltage sags data are voltage sag magnitude and phase shift (the phase different between before and after fault at the monitored node).

The method in identifying faulted section consists of two independent processes *A* and *B* as shown in Fig.1.

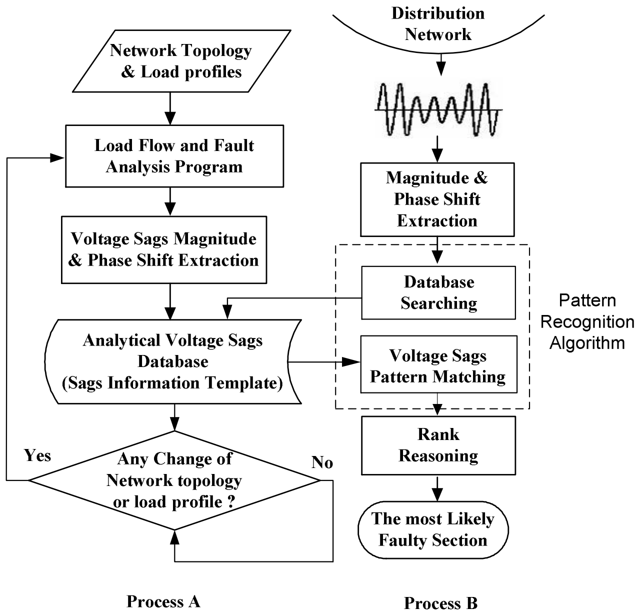

Fig. 1. Overview of the proposed fault section identification system

Process *A* uses three-phase load flow and unbalanced fault analysis to generate analytical voltage sags for all types of faults on all nodes for a network prior a fault. Process *B* performs fault section identification. It consists of (a) Voltage sags feature extraction, (b) Pattern recognition algorithm and (c) Rank reasoning process. When a fault occurs, process B firstly captures the voltage sag. Then the voltage sag feature extraction uses Fast Fourier Transform to calculate the captured voltage sag magnitude and phase shift. The pattern recognition algorithm uses a voltage sag pattern matching criteria to select all possible faulted sections from the database that matches the measured voltage sag pattern. The rank reasoning process prioritizes all selected possible faulted sections. In the rank reasoning process, the highest score is selected as the 1st faulted section finding attempt. If the 1st attempt makes incorrect fault section identification, the 2nd high score is selected and checked. The process continues until the correct fault section is found.

IV. PATTERN RECOGNITION ALGORITHM

The pattern recognition algorithm involves two sequential procedures (i) database search and (ii) voltage sag pattern matching. In searching the database, it compares the measured voltage sag with all analytical voltage sags and selects all possible faulted sections associated the analytical voltage sags. In the voltage sag pattern matching, it applies the trigonometry equation to measure the shortest distance between the measured voltage sag and the analytical voltage sags associated selected possible faulted sections.

A. Database Searching

Consider a typical distribution feeder with two lateral branches as shown in Fig.2.

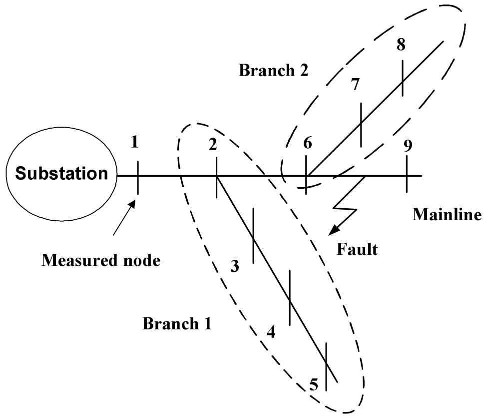

Fig. 2. A simple distribution feeder with two lateral branches

The feeder is divided into three main fault detection areas: (i) Mainline area, (ii) Branch 1 and (iii) Branch 2 areas. The mainline has three sections 1-2, 2-6 and 6-9. Branch 1 has also three sections 2-3, 3-4 and 4-5, and branch 2 has two sections 6-7 and 7-8. Assuming that a fault occurs at point *F* in the network, process B firstly measures the fault generated voltage sag at node 1 (i.e. at the substation) and calculates the measured voltage sag magnitude, $\mathrm{V}_{1,F}^{(\mathrm{meas})}$, and phase shift, $\phi_{1,F}^{(\mathrm{meas})}$. It then compares $\mathrm{V}_{1,F}^{(\mathrm{meas})}$ and $\phi_{1,F}^{(\mathrm{meas})}$ with the analytical voltage sag magnitudes, V_{1-p}, V_{1-q} and phase shifts, ϕ_{1-p}, ϕ_{1-q} for the fault analysis at any two adjacent nodes *p* and *q*, respectively by (1) and (2):

$$\mathrm{V}_{1-p} \le \mathrm{V}_{1,F}^{(\mathrm{meas})} \le \mathrm{V}_{1-q} \tag{1}$$

$$\phi_{1-p} \le \phi_{1,F}^{(\mathrm{meas})} \le \phi_{1-q} \tag{2}$$

Where p =1,…,9 and q =2, … ,9. If the measured voltage sags $\mathrm{V}_{1,F}^{(\mathrm{meas})}$ and $\phi_{1,F}^{(\mathrm{meas})}$ fulfill both (1) and (2), the search algorithm selects the line between the two adjacent nodes *p* and *q* as the possible faulted line section.

Since the network in Fig. 2 has two lateral branches 1 and 2, the electrical distance between node *1* and the fault point *F* could be the same as the electrical distance between node *1* and a point along branch 1 or a point along branch 2. Supposed there are three sections 6-9, 3-4 and 7-8 which satisfy (1) and (2), the search algorithm would select three possible faulted sections. Hence the following voltage sag pattern matching algorithm is used to find the most likely the actual faulted section.

B. Voltage Sag Pattern Matching

Since analytical voltage sags database for all types of faults analysis only on the network nodes is generated in the proposed method, voltage sag phase shift and magnitude pattern along a selected possible faulted section needs to be estimated. For short distance lines or cables, both voltage sag magnitude and phase shift can be considered as a linear function for a fault distance [13]. Therefore for most urban distribution networks, the voltage sag phase shift vs. magnitude may be considered as linear. The linear relationships of voltage sag phase shift vs. magnitude for the three selected possible faulted sections from database searching in section A are shown in Fig.3.

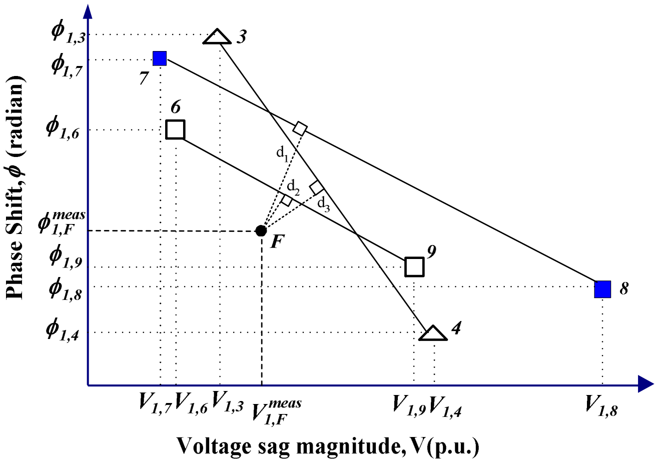

Fig. 3. Phase shifts versus magnitudes for the measured voltage sag due to the fault at *F* and the analytical voltage sags due to faults at 3, 4,6, 9, 7 and 8, *respectively.*

As it can be seen from Fig.3, the Process B sag pattern matching algorithm calculates the shortest distance d_1, d_2, and d_3 between the measured voltage sags $V_{1,F}^{meas}$ and $\phi_{i,F}^{meas}$ and the three selected possible faulted sections *7-8*, *6-9*, and *3-4*, respectively. Based on trigonometric equation, the shortest distance, d_k, for the k^{th} selected possible faulted section is calculated by (3):

$$d_k = \frac{\left| A \times V_{1,F}^{meas} + B \times \phi_{1,F}^{meas} + C \right|}{\sqrt{A^2 + B^2}} \tag{3}$$

Where $(V_{1,F}^{meas}, \phi_{1,F}^{meas})$ are the measured voltage sag magnitude and phase shift at the measurement node *1* due to a fault at *F* ; $A = \dfrac{\phi_{1,q} - \phi_{1,p}}{V_{1,q} - V_{1,p}}$; $(V_{1,p}, \phi_{1,p})$ and $(V_{1,q}, \phi_{1,q})$ are the analytical voltage sags magnitude and phase shift at node 1 for the fault analysis at two adjacent nodes *p* and *q*, respectively; $B = -1$ and $C = \phi_{1,q} - A \times V_{1,q}$.

C. Rank Reasoning Process

Finally, the rank reasoning compares the calculated distance d_k between the measured voltage sag pattern for all possible faulted sections, i.e. , k=1, .., n. In the rank reasoning, it selects the least distance between the measured voltage sag and the selected faulted section as the 1st faulted section finding section. The second minimum will be the 2nd faulted section finding section. The process continues for all other possible faulted section.

Based on the rank reasoning process, the 1st faulted section will be inspected first. In case the first section is incorrect upon inspection, the 2nd possible faulted section will be inspected. The process is continuous for the next section until the actual fault section is found.

V. TESTS OF THE PROPOSED METHOD

A. Distribution Network

The proposed method was evaluated and tested using one of Malaysia urban distribution networks as shown in Fig.4. The network consists of a 132 kV source, two units of step down 132/11kV transformer and 8 11kV feeders. All cables in the network are three-phase balanced underground system. The tested feeder in the dotted line area is divided into 4 branches with total 17 line sections and 18 nodes. There are two normally open switching nodes, NO1 and NO2, which can provide the network reconfiguration options in case of faults occur in the tested feeder.

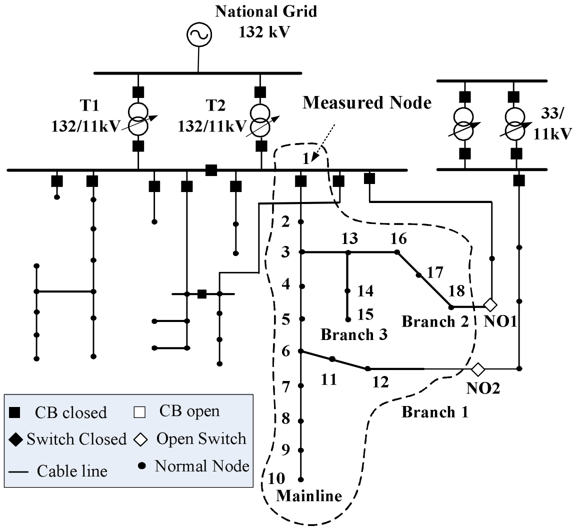

Fig. 4. Subsystem of 11kV distribution network

The network was implemented using power system Electromagnetic Transient Direct Current (EMTDC) software. The cables use PI-model, the loads use constant impedance and the source is 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 waveform simulations, only faults with zero impedance were considered. The simulated voltage sags waveforms were then measured by the computer. The computer then compares the measured sag waveform with the analytical voltage sags pattern database.

B. Analytical Voltage Sags Patterns of the Network

1) Single Line Fault to Ground: Since Single Line to Ground Fault (SLGF) is the most frequent fault type in the network, the tests started with SLGF. It can be seen from Fig.4 that the lateral branch 2 starts from node 3. Hence the voltage sag pattern due to any fault between nodes 1-2 or 2-3 is unique. Thus only the analytical voltage sag patterns due to SLGFs beyond node 3 are examined and shown in Fig.5.

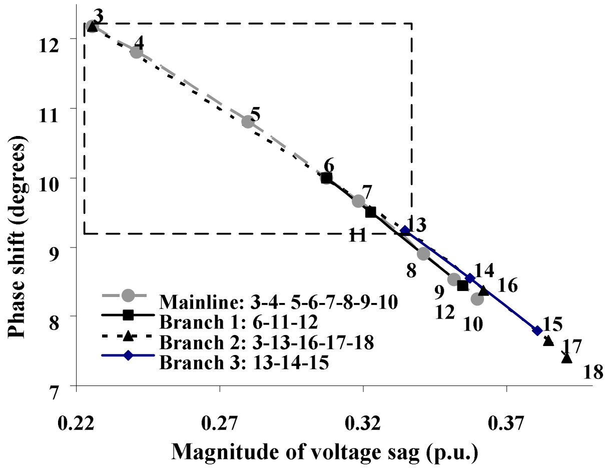

Fig. 5. Analytical voltage sag phase shift versus magnitude for SLGF

Fig.5 shows that the phase shift decreases as voltage sag magnitude increases when a SLGF moves away from the primary substation of node 1. Similarly, as a fault closer to the primary substation, voltage sag magnitude becomes deeper. Fig.5 also shows that mainline, branch 1, branch 2, and branch 3 have different sag pattern paths. They are divided into three major categories: (i) Non-overlapping, (ii) Overlapping and (iii) Crossover between lines.

The line between nodes 17-18 in branch 2 is non-overlapping line. The lines of nodes 6-11-12 along branch 1 overlap with the lines of node 6-7-8-9-10 along mainline. Similarly the lines of node 13-14-15 along branch 3 overlap with the lines of node 13-16-17-18 along branch 2. The overlapping is caused by same value of electrical impedance distance seen at node 1 to the fault. Finally, the mainline of nodes 3-4-5-6-7-8 (dot-line) crossover at near node 6 with branch 3 of nodes 3-13 (dash line). Crossover line between branches is due to same electrical impedance distance at that particular point in the network. This phenomenal often occurs at node 3, 6 and 13 where a lateral branch occurs. These characteristic can be seen more clearly in Fig.6. Crossover occurs at node 3 between the mainline (dash line) and branch 2 (dot line), at node 6 between mainline (dash line) and branch 1 (solid line), and at node 13 between branch 3 (solid line with diamond symbol) and branch 2 (dot line).

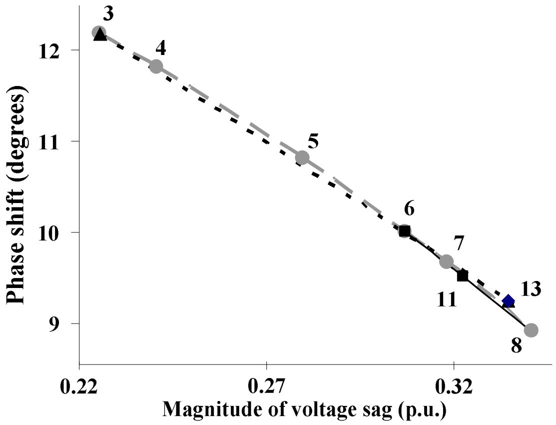

Fig. 6. Close up look diagram of the dash line box area in Fig. 5

2) Different Types of Faults: Further examination of analytical voltage sags patterns were extended to other types of faults, i.e. Three Phase to ground fault (LLLGF), Double phase to ground fault (LLGF) and also Double Phase fault (LLF). The analytical voltage sag phase shifts versus magnitudes for all types of fault is shown in Fig.7.

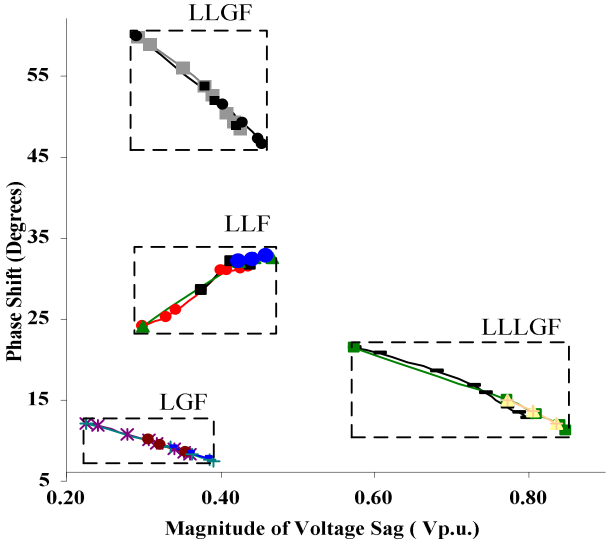

Fig. 7 Overall patterns of voltage sags for all type of faults

Each type of fault locates in its own boundary that significantly distinctive in term of its sag pattern and position from each other. Fig.7 also shows that SLGF produces the most severe of voltage sag magnitude. However LLLGF produces the least severe voltage sag magnitude. In term of phase shift, LLGF produces the largest phase shift when comparing it with others.

In summary, by examining the analytical voltage sags patterns for all fault types, it shows that the proposed method can easily distinguish the different fault types, hence searching and matching voltage sags from different types of fault databases can easily leads to the fault section identification.

C. Case Studies

1) SLGF at Mid Point of Line: When a fault occurs at mid point of line, the method firstly selects all possible faulted sections. The number of possible faulted sections due to SLGF at mid point of each line is shown in Table I

TABLE I
POSSIBLE FAULTED SECTIONS DATABASE SEARCH ALGORITHM

Fault between two nodes (mid point)	Possible Fault sections	Number of sections
1-2 in ML	1-2	1
2-3 in ML	2-3	1
3-4 in ML	3-4, 3-13	2
4-5 in ML	4-5, 3-13	2
5-6 in ML	5-6, 3-13	2
6-7 in ML	6-7, 6-11, 3-13	3
7-8 in ML	7-8, 11-12	2
8-9 in ML	8-9, 11-12	2
9-10 in ML	9-10	1
6-11 in B1	6-11, 6-7, 3-13	3
11-12in B1	11-12, 8-9	2
3-13 in B2	3-13, 5-6	2
13-16 in B2	13-16, 13-14	2
16-17 in B2	14-15, 16-17	2
17-18 in B2	17-18	1
13-14 in B3	13-14, 13-16	2
14-15 in B3	14-15, 16-17	2

ML, B1, B2 and B3 denote Mainline, Branch 1, Branch 2 and Branch 3, respectively.

Table I shows the method finds one possible faulted section for the fault at mid point of line 1-2 or 2-3 or 9-10 or 17-18. By examining the network in Fig.4, any fault in line 1-2 or 2-3, the voltage sag patterns are unique. Hence, the method selects only one possible faulted section for the line 1-2 and 2-3. By examining voltage sag pattern in Fig.5, it is clearly seen that that the voltage sag patterns to the fault at mid point of lines 9-10 and 17-18 are also unique. Hence, the method also finds one possible faulted section. However, as the voltage sag patterns in other lines are more complicated, multiple possible faulted sections would be found. Results shown in Table I show that the method finds two possible faulted sections for the fault at mid point of lines 3-4, 4-5, 5-6, 7-8, 8-9, 11-12, 3-13, 13-16, 16-17, 13-14 and 14-15, and three possible faulted sections for the fault at mid point of lines 6-7 and 6-11.

After finding all possible faulted sections, the method uses the rank reasoning algorithm. Results obtained from the rank reasoning analysis for SLGF tests is listed in Table II. Table II shows that the distance between the measured voltage sag pattern and the selected possible analytical voltage sag determine the ranking. Table II also shows that most fault sections in the tested distributed network feeder can be located by the first attempt. All remaining fault sections can be found by the 2nd attempt.

Results in Table II may be analyzed by using The Matching Performance (MP) in (9):

$$MP = \frac{TCM}{TTS} \times 100\% \tag{9}$$

Where TCM is the Total Correct Matching section at the 1st attempt and TTS is the Total Tested Section.

TABLE II
RANKING ANALYSIS RESULTS

Fault No	Fault	Candidates	d_k	Ranking	1st Attempt	2nd Attempt
Mainline						
1	1-2	1-2	0.00012	1	Correct	-
2	2-3	2-3	0.000112	1	Correct	-
3	3-4	3-4	0.002456	1	Correct	-
		3-13	0.012023	2		-
4	4-5	4-5	0.006053	1	Correct	-
		3-13	0.032561	2		-
5	5-6	5-6	0.037453	1	Correct	-
		3-13	0.061866	2		-
6	6-7	6-11	0.002083	1	Wrong	-
		6-7	0.003006	2		Correct
		3-13	0.00543	3		-
7	7-8	7-8	0.001625	1	Correct	
		11-12	0.003852	2		-
8	8-9	8-9	0.0001	1	Correct	-
		11-12	0.002329	2		-
9	9-10	9-10	0.003162	1	Correct	-
Branch 1						
10	6-11	6-11	0.000751	1	Correct	
		6-7	0.001664	2		-
		3-13	0.004734	3		-
11	11-12	11-12	0.05787	1	Correct	-
		8-9	0.092767	2		-
Branch 2						
12	3-13	5-6	0.016386	1	Wrong	-
		3-13	0.032458	2		Correct
13	13-16	13-16	0.016908	1	Correct	-
		13-14	0.025811	2		-
14	16-17	16-17	0.001443	1	Correct	-
		14-15	0.007719	2		-
15	17-18	17-18	0.001926	1	Correct	-
Branch 3						
16	13-14	13-14	0.005659	1	Correct	-
		13-16	0.011199	2		-
17	14-15	14-15	0.005229	1	Correct	-
		16-17	0.005379	2		-

The MP indicates the percentage of the correct faulted section that found at the 1st attempt for a specific fault type and test location. The matching performance for the SLGF testing results in Table II is calculated using (9). In this case, the correct matching at the 1st attempt is 15 sections out of 17 tested sections. Thus, the calculated MP in the 1st attempt is 88.24 %. The tests confirm that the proposed method can find faulted sections with good fault section finding rate of 88.24% in the 1st attempt.

2) SLGF, LLLGF, LLGF, LLF at Mid Point of Line: Similar test as in SLGF were also conducted for other type of fault. Based on (9), the matching performance for each fault types are calculated and presented in Table III.

TABLE III
MATCHING PERFORMANCES FOR FAULT AT MID-POINTS

Fault types	MP of the 1st attempt for faulted section finding (%)
Single Line to Ground Fault	88.24
Three Phase to Ground Fault	82.35
Double line to Ground Fault	94.12
Line to Line Fault	88.24

Table III shows that the performance of the proposed method is quite good in locating the faulted section by the 1st attempt. The lowest performance was occurred in Three Phase to Ground Fault test case, where, 82.35% tested sections were found by the 1st attempt. The highest performance occurred in Double Line to Ground Fault test case, where 94.12% tested sections was found by the 1st attempt.

3) Faults Near to a Node: In this test, fault is simulated near to a node of the test network. Since there can be any possible locations near to a node, the test is repeated 2%, 5%, 7% and 10% away from a node for each fault type. The MP for each fault type and location is calculated using Eq. (9). However, to see overall matching performance for each fault type test with different locations, the average of matching performance (AMP) is considered as in Eq. (10).

$$AMP = \frac{1}{N}\sum_{i=1}^{N} MP_i \qquad (10)$$

Where i is the number of test location and N is the total test locations for a specific fault type. The results for each type of fault test case for the average of 2%, 5%, 7% and 10% away from a node is listed in Table IV.

TABLE IV
AVERAGE MATCHING PERFORMANCES FOR FAULT NEAR NODES

Type of fault	MP of the 1st attempt for faulted section finding (%)
Single Line to Ground Fault	57.82
Three Phase to Ground Fault	69.59
Double line to Ground Fault	70.59
Line to Line Fault	73.53

Table IV shows that the highest performance of the method is the LLF test case. By comparing the voltage sag line pattern of LLF in Fig.9 with others in Fig.5, 7 and 8, it can be seen that sags patterns in Fig.9 are more distinctive (i.e. non-overlapping and crossover lines are less closer to each other) than the other types of fault. In contrast, the voltage sag pattern of SLGF in Fig.5 shows the non-overlap and crossover lines are closer than that in Fig.9.

Comparing results between Table III and Table IV, it can be seen that the performance of the method for faults near to node is worse than that for faults at mid-point. Because voltage sag pattern crossover occurs at node, the voltage sag pattern for the fault near node is closer to the health section. This makes the method more difficulty to find the right faulted section by the 1st attempt. In contrast the voltage sag pattern due to the fault at mid point of line has less chance to overlap with healthy section that can be observed in Fig.5, 6, 7 and 8. Hence, the method has performed better for the fault at mid point of line than the fault near node.

VI. CONCLUSION

This paper has presented a method to locate a faulted section in a distribution network using voltage sag pattern characteristic. For multiple possible faulted sections, a ranking reasoning is proposed to provide a list of inspection priorities. The ability of the method to locate faulted section has been validated by using an actual 11kV subsystem. The overall results show that the most fault sections in the tested distributed network feeder can be located by the 1st attempt. All remaining fault sections can be found by the 2nd attempt. The pattern analysis also reveals that the analytical voltage sag patterns for different fault types on the feeder are distinctive from each other. Hence the proposed method has no problem to find different types of faults.

The method can be considered inexpensive for implementation since it requires single measurement. Further work will be conducted to include the effect of fault resistance into the proposed method.

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