Locating Fault Using Voltage Sags Profile for Underground Distribution System

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***Abstract*—This paper presents an alternative fault location algorithm to estimate short-circuit faults location in electrical distribution networks using only voltage sags data. The proposed algorithm uses voltage sags profile as a means to locate fault. The possible fault locations is estimated by incorporating the measured voltage sags magnitude and its corresponding phase angle into an equation of voltage sag as a function of fault distance. A ranking procedure is also introduced to rank possible fault locations due the same electrical distance. The uncertainty of fault resistance is also considered in this algorithm. The performance of the technique is presented by testing it using an actual underground distribution network. The simulation results indicated a possibility of practical implementation.**

***Index Terms*— Fault location, distribution networks, voltage magnitude, phase shift.**

I. INTRODUCTION

Electric power distribution feeders are frequently subjected to short circuit fault caused by variety of conditions such as adverse weather conditions, animal contacts, equipment failure and accident. When fault occurs, it causes disturbance to the power supply and interruptions to the system. Such interruption often leads to losses to the utilities and customers. In order to minimize the losses and provides high quality of service, it is crucial for utilities to locate fault as quickly as possible.

The need of fast and accurate fault location leads to proposal of various automated fault location techniques and algorithms. Unfortunately most of the developed techniques and algorithms are for transmission system, which cannot be easily adopted for distribution network due to the limitation of monitoring in distribution system as well as complexity of the network. Distribution system often monitored only at the primary substation that caused limitation of data that can be used to assist in locating fault. Distribution network also complicated due to various factors such as non-homogeneity of line, uncertainty on fault resistance value, lateral branches, distributed loads and loading variation. All of these factors limited the used of some fault location techniques.

Due to the complexity of distribution network, automated fault locations utilizing data from real time measurement of the system have been proposed. These techniques are like Artificial Neural Network, Fuzzy Logic and Genetic Algorithms [1]-[3]. These techniques depend on external information such as from SCADA system, circuit breaker operation in substation, and feeder measurements. The accuracy of this technique is highly depending on the amount and accuracy of the data. These techniques may not be suitable for most distribution network that has limited monitoring equipments.

More suitable techniques for distribution network with limited data were proposed in [4]-[6]. The techniques are involving iterative calculation to locate fault. Due to single measurement, multiple possible fault locations are obtained using the proposed technique. The most likely fault location is found by identifying the operated protective device such as re-closer and fuses upon fault occurrence. The devices can be identified based on the waveform pattern of the measured current when fault occurs. By knowing the operated device and its location, the most likely fault location can be selected from the possible locations.

Fault location utilizing power quality data also has been proposed in literature [7]-[9]. The underlying principal of these methods is based on the fact that fault at different locations presents different voltage sag characteristic as seen at a measured location [10]. By identifying the patterns at different location, the location of fault can be determined. The earliest reported work on fault location using voltage sag data was in [7]. In this method, a fault in transmission line system is located based on voltage sag data from measurements at various locations. Similar approach also has been proposed, but applied for distribution network [8]. The algorithm is based on matching during-fault voltage sag magnitudes to find fault location. As in [7], the proposed algorithm requires multiple measurements of voltage sags. The most recent method of fault location using voltage sag data was proposed in [9]. Different from [8] and [7], the method requires single measurement of voltage sag at the primary substation. In this method, an algorithm was introduced to identify the possible faulted section by matching the measured one with the voltage sag

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patterns in the database. Since the method only identifies a faulted section, maintenance crew needs to patrol along the suspected faulted section to find the exact location of fault. The locating process may consume time if the section is long and may delay the restoration process.

This paper presents a fault location technique based on similar approach as in [7]-[9]. However, different from [9], the non-linearity of the voltage sag function is considered. The propose technique not only locate a faulted section, but at the same time estimate the distance of fault from sending end of the suspected faulted section. The voltage sags waveform captured by power quality monitoring equipment at the primary substation before and during the fault are used for this technique. Due to single measurement and uncertainty of fault resistance the proposed technique may produces multiple fault locations. This problem is addressed by a ranking procedure introduced in this research. The locations are ranked accordingly to provide the inspection sequence.

II. Basic Principle of the Technique

The basic principle of voltage sag characteristic used in this proposed technique is based on the relationship between fault location and voltage sags, measured at the primary substation. This is possible since voltage sag changes as fault occur at different location as seen at the monitored location [10].

A. Fault Location in Distribution System

Most of underground distribution networks consist of different type of cables and size. As a result, the impedance is not distributed equally through-out the network. Due to this, the process of locating fault using the voltage sag concept needs to consider each cable as a separate function of fault distance between two adjacent nodes (section). Each section has its own voltage sag as a function of fault distance.

To illustrate the fault location approach for a distribution system, a network with one main line and 2 lateral branches is considered, as shown in Fig. 1. Each section, which represented by *a-b*, *b-c* and so on is assumed has it owns impedance value. A power quality device is placed at the primary substation network of node *a* to monitor and record voltage sags activities during fault.

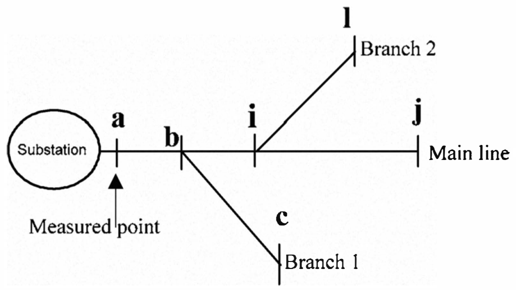

Fig. 1. Typical distribution network

When fault occurs for example on section *i-j*, a voltage sags is detected at node *a*. The fault location can be estimated by matching this voltage sags with previous voltage sags due to actual fault at that section. However, if the actual fault never occurs at this location, the location cannot be determined using this approach. Instead of using actual fault data, this work used fault analysis to generate voltage sag and its corresponding fault location. This data are stored in database. The actual voltage sag due to fault can be compared with the generated ones in database. By using simulation, fault can be simulated at any location and therefore any voltage sags value can be compared.

Since fault could occur at any locations, the problem is to decide how many fault locations need to be simulated and stored the voltage sags into the database. If the simulated locations are too many, the database can be too huge that can lead to a high processing time of finding the possible location. On the other hand, if the simulated faults not cover the entire system, there is a possibility of getting incorrect location. In order to resolve this problem, a function representing the changes of voltage sags over a distance as monitored at the primary substation between two adjacent nodes of a section is used as the basis of this work.

In order to derive the equation of voltage sags as a function of fault distance, a few locations between two adjacent nodes are simulated with fault. The lowest magnitude and its corresponding phase angle of the three phases are taken. Using the obtained voltage magnitudes and its corresponding fault locations measured from node *i*, curve fitting method is used to estimate the equation of the voltage sags as a function of fault distance measured at node *a*. This equation derivation is illustrated in Fig. 2. In the figure, voltage magnitude as a function of distance between node *i-j* is obtained by simulating fault at 0.0, 0.25, 0.5, 0.75, and 1.0 per-unit of distance from node *i*. From initial study, it was found out that the curve can be a non-linear as in Fig. 2, or almost linear or constant changes, which depends on the impedance of the line of the section.

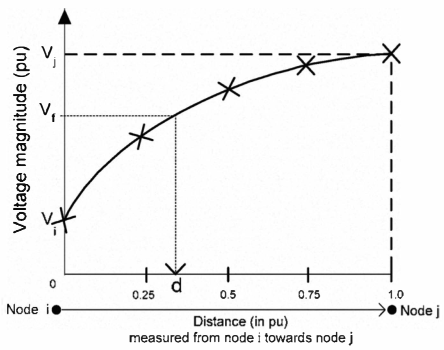

Fig. 2. Estimated voltage sag profile curve for section *i-j*

By having the general equation of voltage magnitude between two adjacent node nodes, the distance of fault from node *i* is can be estimated by incorporating the measured voltage at node *a* into the equation. This is illustrated in Fig. 1, where voltage magnitude of V_f (the lowest voltage magnitude) at node a produces the distance of fault measured from node i. The equation of phase angle can also be created in the same way as the voltage magnitude equation and use to estimate fault location. The reason of using both types of equations is to compare the distances in order to identify the most likely fault location.

Since this technique considers single measurement at the primary substation, multiple possible faulty sections could be produced. This occurs for networks that have parallel branches likes the network shown in Fig. 2. If fault occur at one of the parallel branches, the electrical impedance as viewed from the monitored node to the location of fault are the same, which produce the same voltage. For example, if fault occurs at the main line of section *i-j*, there is possibility of getting the same voltage as if fault occurs at branch 1 or branch 2. Considering this problem, the possible faulty sections are ranked according to a sequence of inspection.

III. Description of The technique

The equation of voltage sag as a function of fault distance is assumed to be a second order of a polynomial equation. Although there is a linear type changes, this second degree equation still valid. However, for a constant type changes, different approach is taken. The general equations of voltage sags as a function fault distance are as follows:

$$V = a_{V,0}d_V^2 + a_{V,1}d_V + a_{V,2} \quad (1)$$

$$\phi = a_{\phi,0}d_\phi^2 + a_{\phi,1}d_\phi + a_{\phi,2} \quad (2)$$

where,

V voltage magnitude
ϕ phase angle
d_V , d_ϕ fault distance (in per unit) for voltage magnitude and phase angle equation respectively
$a_{0,V}, a_{1,V}, a_{2,V}$ coefficients of the voltage magnitude equation
$a_{0,\phi}, a_{1,\phi}, a_{2,\phi}$ coefficients of the phase angle equation

For non-linear changes, the fault distance can be calculated by solving the quadratic equation (1) and (2). Since there will be two possible answers for each equation, the selected solution of distance should fulfil the following condition:

$$0.0 \le d_V \le 1.0 \text{ and } 0.0 \le d_\phi \le 1.0 \quad (3)$$

For constant changes, the distance of the fault from particular node cannot be calculated since at any fault location in the section the voltage or phase angle is remains the same. However, if one of the equations is not a constant type, the distance can be estimated either using solution of (1) or (2). On the other hand, if both types of equations are a constant type, only the section where fault occur is possible to be estimated.

The type of voltage sag changes can be identified by checking the coefficients in (1) and (2). If the following conditions occur, fault is assumed occur at node or close to a node.

$$\left|V_f - V_k\right| < \alpha \qquad \left|\phi_f - \phi_k\right| < \alpha \quad (4)$$

where V_k and ϕ_k are represent voltage magnitude and phase angle of node *k* respectively. These data are simulated ones and stored in the database. α is the specified threshold value to determine the matching between the actual value from the simulated one. The threshold is required because it is not possible to obtain exactly the same value of both the simulation and actual measurement.

A. Algorithm of the Proposed Technique

The fault location estimation process is illustrated in the flow chart of Fig. 3. It starts with the extraction of voltage sags waveform into fundamental components using Fast Fourier Transform (FFT). The RMS value of the voltage magnitude is calculated once every cycle for each phase. When the magnitude detected to be 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 minimum of threshold value.

The obtained fundamental voltage components are then used to estimate the type of fault. The main reason of fault type identification is to narrow down the search area. Only the respective database of the fault type needs to be checked rather than checking the entire databases.

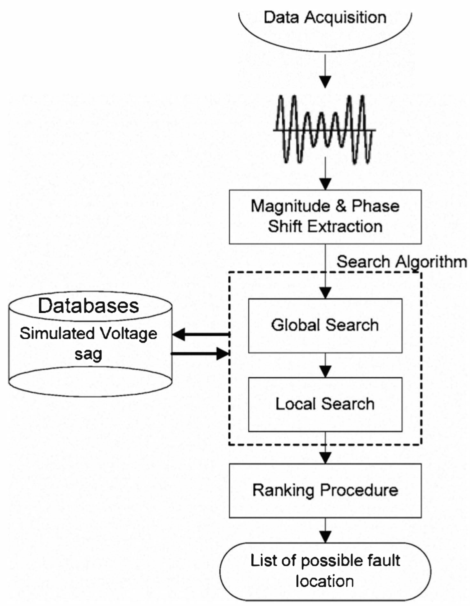

Fig. 3. Flow chart of the fault section estimation

After the fault has been identified, the lowest voltage magnitude and its corresponding phase angle are selected for the input to the algorithm. The search algorithm consists of global search and local search. In the global search, faulted sections and the possible fault resistance are estimated based on the simulated voltage sags in the database. The measured voltage sag magnitude is compared with the simulated data of voltage sag magnitude in the database to find all the possible fault location candidates. In the local search, the obtained candidates from the global search are evaluated further to find the final possible fault location/locations by considering the phase angle equation as well.

Finally, the selected locations are ranked accordingly. The final result is all the possible faulty sections ranked according to inspection priority. This ranking is important to assist the technical crew to start at particular location for visual inspection. In the case the first choice is not the actual faulty location, the other locations need to be checked until the correct fault location is found.

IV. Search Algorithm

A. Global Search - Selection of Possible Faulted Section

The global search finds section where its curve of voltage magnitude intersects with the measured magnitude (V_f). In order to explain this, consider Fig. 4. There are three curves representing an equation of voltage magnitude as a function of fault distance for three different fault resistance values.

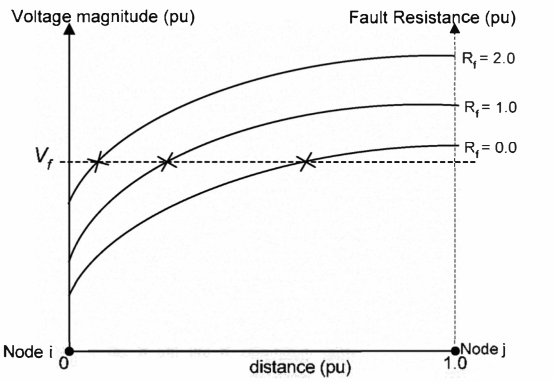

Fig. 4. General pattern of voltage magnitude with different fault resistance values

The intersections of V_f with all the curves mean that there are possibility that fault could occur on section *i-j* with the fault resistance ranging from 0.0 pu to 2.0 pu. Hence, the section *i-j* is taken as the candidate with the fault resistance between 0.0 pu to 1.0 pu and 1.0 pu to 2.0 pu as the possible fault resistance.

B. Local Search - Selection of Faulted Section and Fault Resistance

The obtained faulted section candidate with it's correspond fault resistance range are further evaluated to determine the final possible faulted sections with the possible fault resistance. This is done by solving (1) and (2) iteratively with different fault resistance values. The one that fulfill (3) will be considered as the most possible faulted section together with the fault resistance.

C. Ranking Procedure

The ranking process is based on the degree of matching between the simulated data with the actual measurement. The matching is measured by calculating the mismatch between the distance obtained from (1) and (2):

$$\sigma = \left| d_V - d_\phi \right| \tag{5}$$

The matching is considered 100% accurate if $\sigma \approx 0.0$. The lower the value of σ, the higher the matching will be. The candidate with to lowest value of σ is considered as the most matching pair and assigned as the first rank.

All the obtained locations are considered for inspection due to various uncertainty factors in the process of fault location. These including uncertainty in the fault resistance value, error in measurement, different between actual measurement data and simulated ones.

V. Simulation Tests and Results

The proposed method was evaluated using an underground rural distribution network. The one-line diagram of the tested network is shown in Fig. 5. The network consists of a 132 kV source, one units of step down 132/11kV transformer and one main feeder with 3 branches. All cables in the network are three-phase balanced underground system. The network is divided into 4 branches with total 17 line sections and 17 nodes.

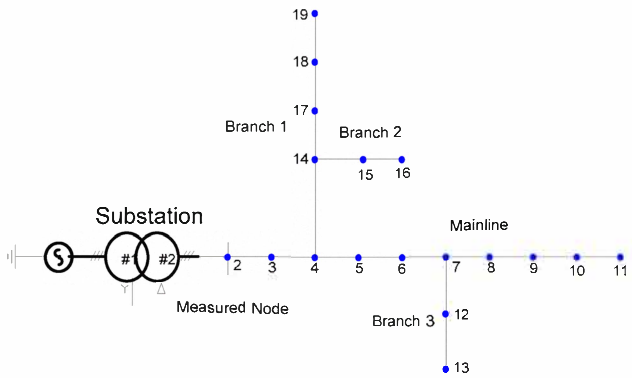

Fig. 5. Subsystem of 11 kV distribution networks

The system is modelled and simulated using PSCAD/EMTDC software. Loads were modelled as constant impedance. At the measured node 2, the obtained voltage waveform is process using Fast Fourier Transform (FFT) to calculate the voltage sag magnitude and phase angle during the fault. The lowest value voltage magnitude is taken as an input to the algorithm together with its corresponding phase angle.

In this paper, the performance of the algorithm is measured by testing fault at the middle of each line for all section in the system. In this test, SLGF is simulated at all section on the middle of the line. SLGF is applied for the test since it is most frequent type of fault happen in distribution system. A fault resistance of 0 Ω, 5 Ω, 10 Ω, 20 Ω and 25 Ω are applied for the simulated fault. .

A. Overall Ranking

The overall ranking of the correct selected faulted section is presented in the form of bar graph in Fig. 6 and Fig. 7. The x-axis presenting the section and the y-axis is for the rank number of the correct fault section. The first, second, third, forth and fifth bar for each section is representing the fault resistance of 0, 5, 10, 20 and 25 ohm respectively.

From the graphs, it can be seen that there is no direct relationship between the ranking numbers of the correct location with the value of fault resistance. The high value of fault resistance does not necessary increase the ranking number. This occurs on sections 12-13, 14-17 and 15-16 where the 20 Ω fault resistance produced higher ranking as compared to the 25 Ω fault resistance. On the other hand, other sections like 5-6, 8-9, 10-11 and 14-15 show the higher fault resistance increases the number of ranking. The higher ranking of the correct fault section for this test case is four, which is for sections 8-9 and 12-13. Although the rank is quite high, it is much better than guessing the location of the faulted line. After the fourth attempt of visual inspection the fault can be located correctly and appropriate action can be taken.

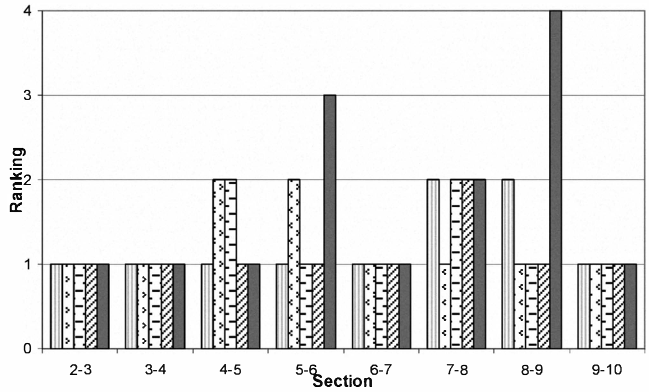

Fig. 6. Ranking of the actual faulty section with different fault resistance from section 2-3 to section 9-10.

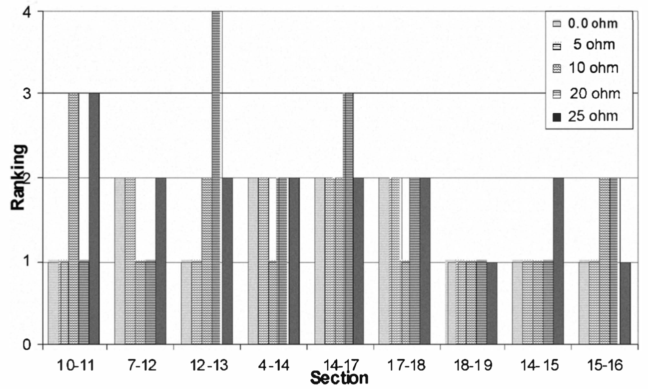

Fig. 7. Ranking of the actual faulty section with different fault resistance from section 10-11 to section 15-16

There are also sections where their ranking number does not change with different fault resistance. This can be seen on sections 2-3, 3-4, 6-7, 9-10 and 18-19. There are two possible reasons. The first one is because the involve sections not in parallel with any other line section. The second possible reason is that the section is selected as the first rank due to the distances obtained from voltage magnitude and phase angle are nearly the same.

In order to understand why certain sections are selected correctly in the first rank, the overall pattern of the voltage magnitude or phase angle as a function of fault distance is plotted. The graph is shown in Fig. 8, where the points in the graphs are representing the voltage magnitude and phase angle (measured at the primary substation) due to fault at the specific location between the two adjacent nodes.

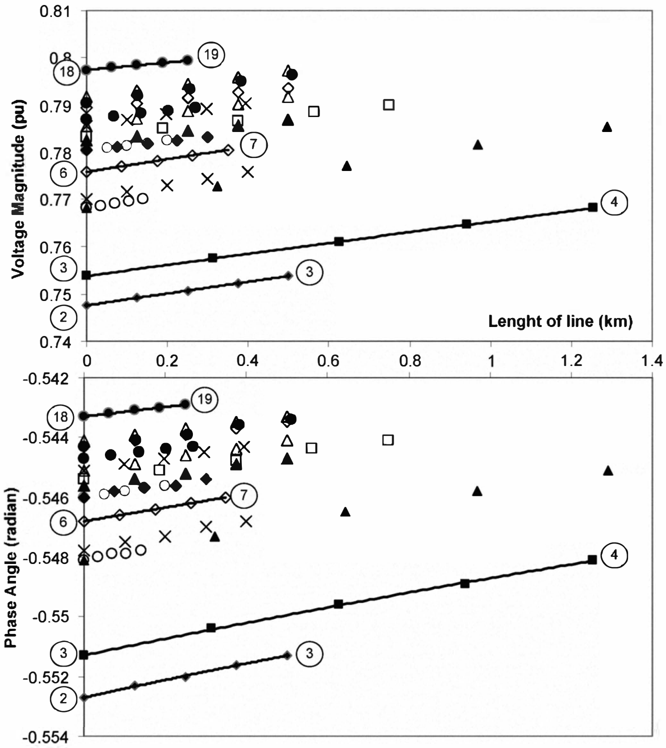

Fig. 8. Overall pattern of voltage sag magnitude and phase angle as a function of fault location between two adjacent nodes (fault resistance 10 ohm)

It can be seen clearly that the value of voltage magnitude or phase angle for sections 2-3, 3-4, 6-7 and 18-19 (shown by a straight line) do not overlap with other section values. Any fault on these sections will produce a voltage sag in the range of that section only. Thus, a single section where fault most likely occur can be identified. The fault in this section can be estimated accurately without getting other possible faulted section. On the other hand, if fault occurs at other than these sections, multiple possible sections will be selected.

The graph in Fig. 9 is an example of other section in a close-up look. There are three important observations can be seen in the pattern shown in Fig. 8 and 9, which are as follows:

i) Non-overlapping range of voltage magnitude or phase angle with other section, for example section 2-3, 3-4, 6-7 and 18-19. As a result only one possible faulty section will be selected.
ii) Overlapping range voltage magnitude or phase angle with other section, for example section 4-14 with 5-6 and 6-7. This condition will produce multiple possible fault location.
iii) Overlapping values, for example section 4-5 with section 4-14 and section 7-12 with section 7-8. The reason behind this is because the overlap section has the same value of sequence impedance per unit length. The different is on the length. Any fault on the overlap characteristic will produce at least 2 possible faulted sections.

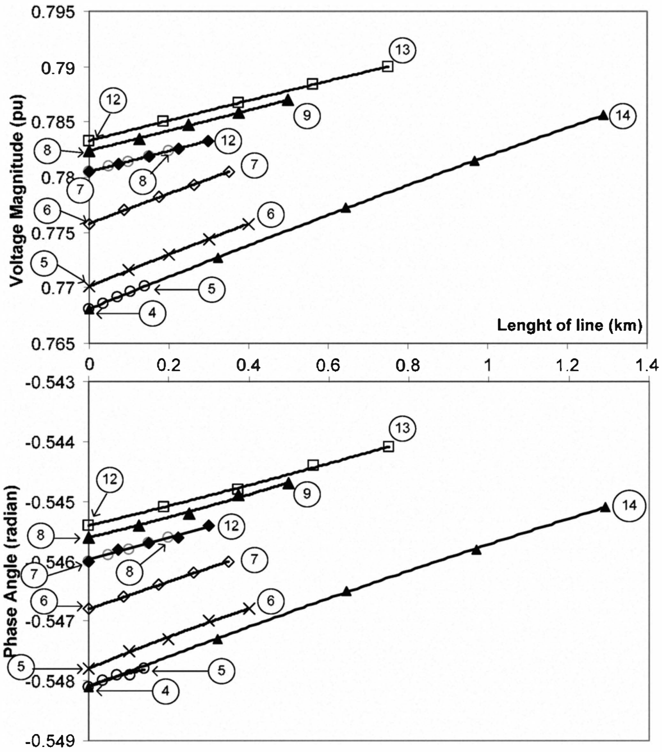

Fig. 9. Close-up looks of voltage magnitude and phase angle function for other sections in the system

B. Error Estimation

An estimation of error fault location between two adjacent nodes is calculated using (6). The fault location is based on the calculation of (1), which based on the voltage magnitude as a function of fault distance.

$$\%error = \left| \frac{d^{estimated} - d^{calculated}}{Total\ Lenght\ of\ Section} \right| \times 100 \qquad (6)$$

The graphs in Fig. 10 and Fig. 11 show the obtained error estimation of fault on the middle of the section for the network.

It can be observed that at fault resistance zero, the estimation error is very low and at some section it can't be seen at all in the graph. In general, the increment of the fault resistance increases the estimation error. However, the increment of fault resistance value does not necessary increase the error estimation. This can been seen for example on section 5-6, where the 20 ohm fault resistance produced higher error estimation as compared to 25 ohm fault resistance.

The highest error estimation calculated occurs for section 7-8 with the highest fault resistance, which is around 4.4 %. This error is quite low and therefore the fault distance can be estimated within a high accuracy. The accuracy of the estimated distance is highly depending to the length of the line. It can be seen a long line for example sections 2-3, 3-4 and 4-14 have a low estimation error, which is less than 1% for all fault resistance values. This is because these sections have a long line compared to the others. On the other hand, section 4-5 and 7-8 have a short line. Despite the accuracy of the estimated fault distance, at less a faulted section can be determined correctly.

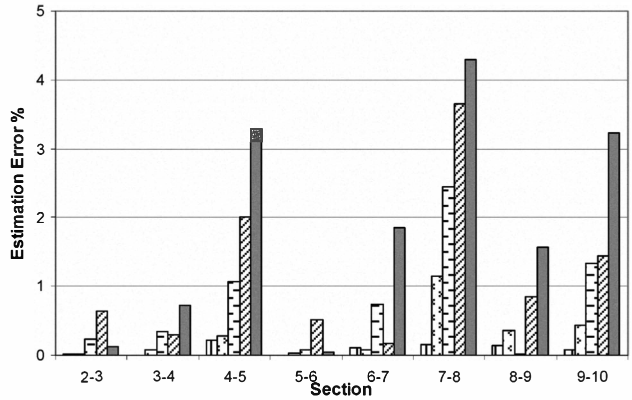

Fig. 10. Error estimation for fault on the middle of the line for section 2-3 to section 8-9

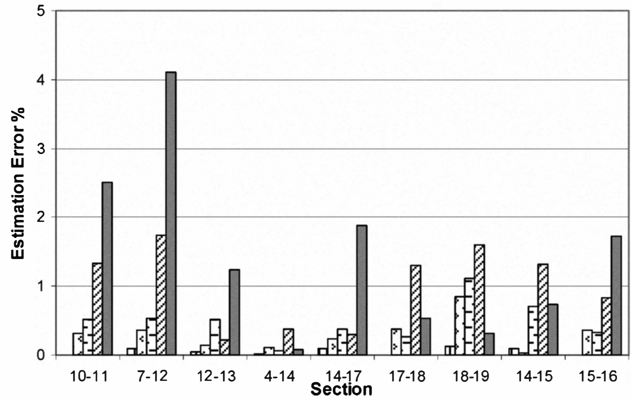

Fig. 11. Error estimation for fault on the middle of the line for section 10-11 to section 15-16

VI. CONCLUSION

In this paper, a new technique based on voltage sags characteristic has been presented to estimate fault location for distribution system. The technique produces a ranked of multiple possible faulty sections. At the same time, the location of fault measured from particular node is also calculated. The effect of fault resistance is also being considered. The test showed promising results with a low error estimation and low ranking number.

The technique is economical since it uses a single measurement at the primary substation. More over, an existing voltage sags monitoring equipment at the primary substation can be utilised to obtain the voltage sags. Since the technique depends on the pre-developed database, any changes such as load variations or network reconfiguration can be adapted by this technique by updating the database.

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