Development of Automated Fault Location Software for Distribution Network

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Abstract **- This paper presents on an ongoing development of automated fault location software for distribution network. The proposed method of the software is able to identify the most possible faulty section based on voltage sags feature i.e. magnitude and phase shift. The actual voltage sags caused by fault is compares with simulated voltage sags stored in a database. The matching will give all possible faulty sections that have been stored in the database. The software is developed by integrating various software modules. The module will be developed into a component type using Component Based Development (CBD) approach. By developing the software from component, replacement or modification can be done to any of the module without affecting the whole software. The test results of the proposed method show satisfactory. Future works in order to improve the software and method are also discussed in this paper.**

Keyword - *Voltage sag, Database, Component, Fault Section Identification, Distribution Networks.*

I. Introduction

Outages and interruptions in distribution system often causing enormous losses to utility and customer. Such disturbance is mainly caused by fault, which is inevitable. It could be caused by many factors such as adverse weather condition, equipment failure, ageing factors and instruction of animal. This problem unacceptable in an electricity supply industry that is privately owned and operates in a competitive environment. Distribution companies in the UK are under considerable pressure by the regulator and customer to improve the reliability of their network and the quality of the service they provide. These objectives can be achieved if the location of fault can be detected as quickly as possible before appropriate action can be taken.

At present, identification of fault location in some distribution system (particularly in 11 kV systems) is using trial and error method. This technique is time consuming, costly, tedious and exposed additional stress to equipment. With the recent technology in distribution automation system (DAS), fault location can be detected automatically. This technology help to reduce the outage times and therefore improve the reliability and quality of service at a relatively low cost. Various automated fault location methods have been proposed for automatic fault location system. In general, fault location methods in literature can be divided into four main categorizes. The first category is involving mathematical analysis. This method often uses analogue feeder information such as fault current waveforms, circuit breaker status, fault indicator status in addition to conventional control centre information to identify fault types and calculate fault location [1-4]. However, a limited status information available on distribution networks, in particular on 11kV networks, makes this approach very difficult, if not impossible, to establish reliable statistical estimates. The accuracy of fault location based on this method also depends much on the accuracy of the network model. To obtain an accurate network model is not easy since distribution network is a complex system consists of variety of conductors, structures and lateral branches. It also subjects to constant modification on the network topology and load, which made the technique in some cases not applicable. Some of this method also time consuming due to iterative process [2, 3].

The second category is knowledge-based method, for examples neural network, fuzzy logic, expert system and genetic algorithm [4, 5, 6]. The accuracy of the result using this method is highly depends on the given set of information such as short-circuit current and information from fault detection devices at the main feeders. Unfortunately, some of the information is not available in many distribution systems since measurement is usually located at the main substation. This method also requires training process that consumes time and need to be repeated whenever there are changes in the system.

The third category is based on traveling wave technique [7, 8]. Although this technique can locate fault with a high accuracy, the implementation is complex and expensive. More over, it may not work with network having many branches and laterals. The last category is based on comparison of historical fault data [9]. Whenever fault occurs in the distribution network, the waveform of voltage sags measured at the substation is recorded into the database together with the known fault type and location. This database is updated whenever fault occurs in the system. When actual fault occurs, the measured voltage sags waveforms at the substation are compared to all the voltage sags waveforms in the database. The most similar waveform in the database will give the type

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of fault and estimated location. The drawback of this method is that it will not work if the actual fault never happens before, or never recorded in the database.

Different from other methods, this study use database approach in estimating fault location. The fault location in this study is considered between two nodes, which is the section. The database is prepared first from simulation of fault analysis. The magnitude and phase shift of voltage sags at the monitored node and the faulted node are stored into the database. When actual fault occurs, the voltage sags is compares with the voltage sags in the database. The matching will give the corresponding faulted sections.

The main advantage of this method is that it is not costly for implementation since it requires only one measurement at the substation. For practical usage, automated fault location software is currently under development using C++ Borland Builder version 6.0.

II. VOLTAGE SAGS CALCULATION

For a radial system, sag magnitude (V_{sag}) and phase shift, ϕ due to three phase fault are calculated using the following equation;

$$V_{sag} = \frac{Z_{fault}}{Z_{fault} + Z_{source}} V^{pre-fault} \quad (1)$$

$$\phi = \tan^{-}\left(\frac{X_{fault}}{R_{fault}}\right) - \tan^{-}\left(\frac{X_{fault} + X_{source}}{R_{fault} + R_{source}}\right) \quad (2)$$

Equation 1 and 2 show the close relationship between the fault impedance and the source impedance for calculation of voltage sags and phase shift in the system. The nearer the fault to the source (i.e. $Z_{fault} <<< Z_{source}$), the deeper the voltage sags and the phase shift becoming larger as well.

For a large-scale network, bus impedance matrix is used to calculate voltage sags. Magnitude of the voltage sags at node *i* which caused by fault at node *j* in the network is calculated using equation below:

$$V_i = V_i^{pre-fault} + \Delta V_{i,j} \quad (3)$$

Where $V_i^{pre-fault}$ is the pre-fault voltage at node *i*, and ΔV_i is the voltage change on node *i* due to fault at node *j* which can be expressed as $\Delta V_{i,j} = Z_{ij} I_j$. Where $Z_{i,j}$ is the transfer impedance between node *i* and *j*, and $I_j = -\frac{V_j^{pre-fault}}{Z_{jj}}$, thus, in general $V_i = V_i^{pre-fault} - \frac{Z_{ij}}{Z_{jj}} \times V_j^{pre-fault}$

(4)

By using equation (4), voltage sag at node *i* due to fault at any node in the system can be calculated. For phase shift at node *i* the general equation is as follows;

$$\phi_i = \left|\theta_i^{pre-fault} - \theta_i^{during-fault}\right| \quad (5)$$

The pre-fault phase angle and during-fault phase angle can be obtained from analysis of three phase load flow and fault analysis respectively.

III. FAULT SECTION ESTIMATION

The whole process of fault location estimation is presented in the flow chart shows in Figure 1. The process can be divided into two sections; A) Database development and B) Fault section estimation. The database contains magnitude and phase shift of voltage sags together with the corresponding fault node.

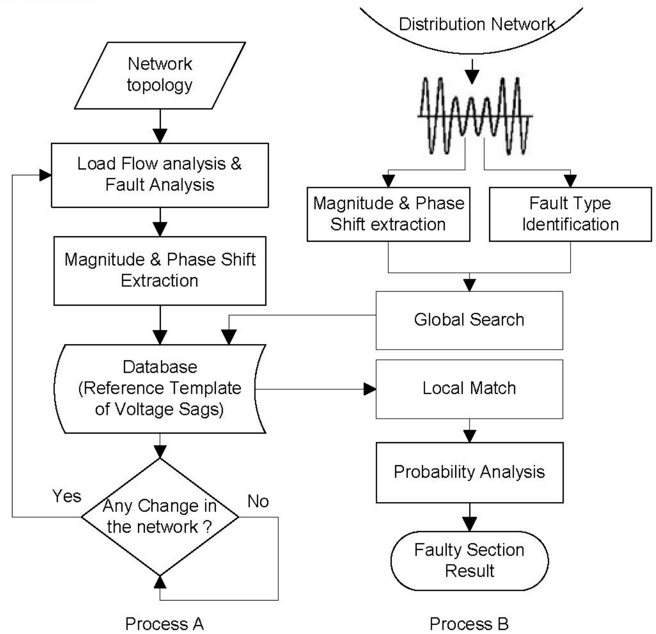

Fig. 1: Flow chart of overall process in fault section identification

The waveform is monitored continuously using data acquisition device. The RMS value of the voltage magnitude is calculated once every cycle for every phase. When the magnitude detected to be lower than 0.9 pu of the nominal voltage, the sags waveform is captured and stored into the PC until the magnitude recovers back to a minimum of 0.9 pu. The maximum cycle is set to 8 cycles. This setting can be changed accordingly depends on the circuit breaker operation time. Fast Fourier Transform (FFT) is used to extract the fundamental voltage sag from the sags waveform. The lowest magnitude together with the corresponding phase shift is used to find the possible fault section.

In the fault type identification, discrete wavelet transform is applied. The method is based on the work conducted in [11]. Multi Resolution Analysis (MRA) is performed to decompose the signal to several levels. For every resolution level, the standard deviation is calculated for the wavelet coefficients. By calculating the standard deviation, the energy level for each resolution level of MRA can be observed. Standard deviation can be determined by the following equation:

$$\sigma = \left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2\right)^{\frac{1}{2}} \quad (6)$$

where x_i is the sampling value at point *i*, *n* is the number of elements in the sample and $\bar{x}$ is the mean expressed by;

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (7)$$

It was found out that for each type of fault, different standard deviation values for different resolution level was produced. Based on these characteristics, the type of fault and the faulted phases can be known. Level 8 is chosen due to operating frequency of the test system is 60 Hz which fall in level 8.

The 'global search' and 'local match' are the pattern recognition algorithms to find the most similar features in the database with the actual voltage sags. The most similar one will give the corresponding faulty section. Finally, probability approach ranks the possible faulty sections. In case of any changes such as loading or network parameters, the database can be updated.

A. Voltage sag database development - Process A

The procedures to develop database are as follows:

i) Three phase unbalanced load flow analysis program is used to obtain pre-fault voltage and phase angle on all nodes.
ii) All type of faults is simulated using fault analysis program at one node to obtain voltage sag and phase angle at the monitored node. The lowest magnitude between the three phases is chosen together with the corresponding phase shift.
iii) The chosen voltage magnitude, phase shift and the corresponding faulted node are stored into the database. This same procedure is repeated for the other nodes in the system.

B. Fault section estimation – Process B

Pattern Recognition technique for this study is divided into two parts i.e. global search and local match. Similar technique has been applied in other fields such as image processing, medical and security system [12,13].

(i) Global Search

The objective of global search is to find all possible sections that fulfill the following conditions.

$$V_p^{sag} \le V_{input}^{sag} \le V_q^{sag} \quad \text{and} \quad \phi_p^{sag} \le \phi_{input}^{sag} \le \phi_q^{sag} \tag{8}$$

Where p and q is two adjacent nodes with their respective voltage magnitude and phase shift. This condition can be explained based on Fig. 2 below.

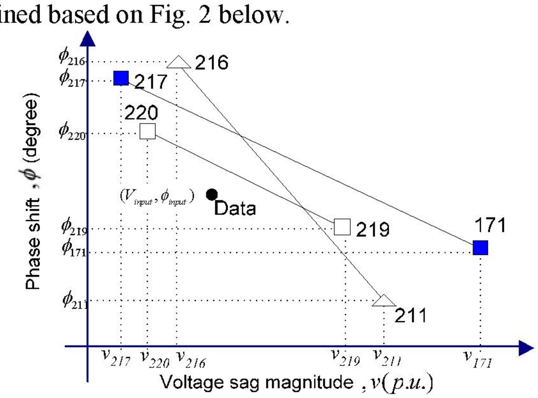

Fig 2: Sections selection in Global search

In the above graph, the points are referring to the node in the network. These points are determined by the phase shift and voltage magnitude at the monitored node when fault occurred at that respective node. The '*Data*' is the actual phase shift and magnitude due to fault. The nodes of 216-211, 217-171 and 220-219 are representing a section in the network. The magnitude and phase shift between two adjacent nodes are assumed to be directly propositional to the distance from the monitored node.

(ii) Local Match

Local match will calculate the closest distance between the actual data with the selected candidates from global search. This distance is a perpendicular to the line of section p and q as shown in Fig. 3.

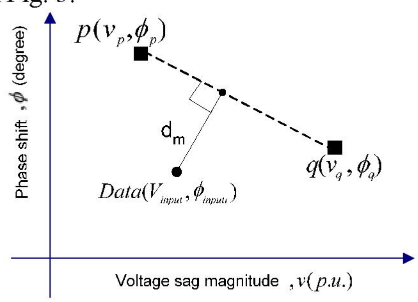

Fig 3: Shortest Distance d_m between the actual data with the section

The result of the local matching ($d_1, d_2, d_3, \ldots d_m$) will be evaluated to determine the best candidate which also known as most probable faulty section using probability approach as explained in the following section.

(iii) Probability analysis

Since the primary distribution feeders have several lateral branches, there is possibility of getting multiple sections that produce similar voltage sags features at the monitored bus. This might occur when multiple fault locations have the same electrical impedance as seen from the measured point. Thus, a probability analysis is used to rank the possible faulty section locations. The equation is follows:

$$P(i) = \frac{BMi}{\sum_{i=1}^{m} BMi} \times 100\ \% \tag{9}$$

where

$i = 1 \ldots m$ = number of possible candidates and

$BM_i = 1/d_m$

The outcome calculation of the above equation is the probability value in percentage. The section with the highest percentage will be chosen first for visual inspection. Incase incorrect, the second or third highest can be checked.

IV. Validation of the Method

The developed automated fault section algorithms are tested using Real Time Digital Simulator (RTDS). Figure 4 shows the experimental setup.

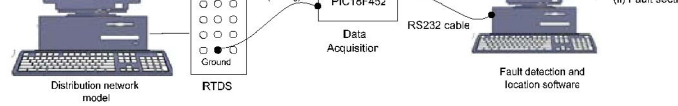

Fig. 4: Experimental setup for real time test

The test is conducted to simulate real time application of the algorithms. The data acquisition device in this study is developed using PIC18F452 microcontroller. The role of this microcontroller is to digitize the analog measurement before sending the data serially to the PC through RS232 cable.

A distribution networks in Fig. 5 is modeled using PSCAD before it programmed into RTDS. The distribution network consists of 33kV equivalent network source, a 33/11kV transformer and an 11kV feeder with 21 nodes i.e. 19 sections and 2 branches. The nodes on the RTDS that represents the monitored bus bar is identified and then connected to the data acquisition device.

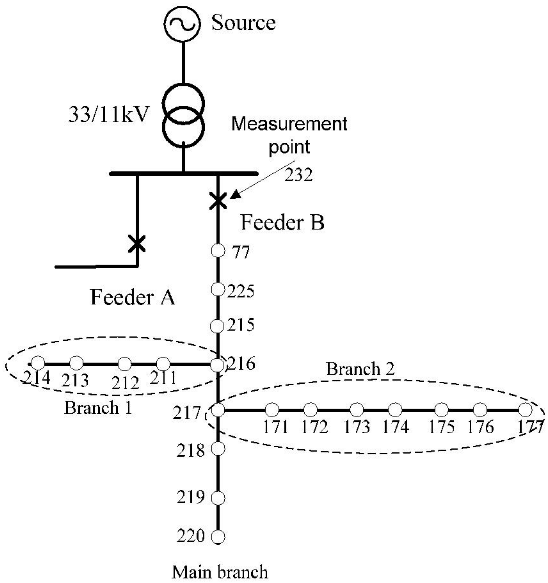

Fig. 5: Typical arrangement of 11kV distribution networks

A. *Development of voltage sags database*

Development of the voltage sags database is very crucial task to ensure accurate information or ‘reliable template’ stored in the database. At present, there are three methods to establish the database; power quality recorder, SCADA system and simulated data using power system software. The first two methods require a long period of time and costly to implement. In this study, the database is established from the simulation study as discussed in section III.A.

TABLE 1 MAGNITUDE AND PHASE SHIFT STORED AS A TEMPLATE IN THE DATABASE

	Single Line to Ground Fault		**Three Phase Fault**	
Fault Node	Magnitude	Phase Shift	Magnitude	Phase shift
	Main Line		**Main Line**	
77	0.016	37.801	0.082	35.935
225	0.036	50.497	0.174	20.851
⋮	⋮	⋮	⋮	⋮
220	0.296	14.157	0.787	16.028
	Branch 1		**Branch 1**	
211	0.181	21.095	0.62	22.789
⋮	⋮	⋮	⋮	⋮
214	0.291	14.893	0.78	16.085
	Branch 2		**Branch 2**	
171	0.218	20.429	0.677	19.601
⋮	⋮	⋮	⋮	⋮
177	0.324	13.087	0.813	14.615

Table 1 shows some values of the database for Single Line to Ground Fault (SLGF) and Three Phase faults (LLLGF). The graphs on Fig. 6 and Fig. 7 show the pattern characteristics of voltage sag magnitude and phase shift for both faults type. However, only the SLGF test result will be discussed thoroughly as example to show the capability of the algorithms. The pattern for three phase fault (LLLF) in Fig. 7 will be discussed in general.

B. *Test results*

The criterion for evaluating the overall performance of the method is defined as; *performance matching*, which is the percentage of correct match over the total section tested. Table 2 shows the test result for SLGF.

TABLE 2 RESULT ‘SEARCH AND MATCH’ ALGORITHM FOR SLGF

No	Simulated fault between nodes	Selected section	Distance-d	Confidence level--%	Final Decisions	Result
1	232-77	232-77	0.0023	100.00	232-77	✓
2	77-225	77-225	0.013	100.00	77-225	✓
3	225-215	225-215	0.011	100.00	225-215	✓
4	215-216	215-216	0.003	100.00	215-216	✓
5	216-211	216-211	0.0144	100.00	216-211	✓
6	211-212	211-212	0.0035	49.28		
		212-213	0.0034	50.72	212-213	×
7	212-213	212-213	0.54	55.17	212-213	✓
			0.6645	44.83		
8	213-214	213-214	0.0033	69.44	213-214	✓
			0.0075	30.56		
9	216-217	216-217	0.0166	51.03	216-217	✓
		216-211	0.0173	48.97		
10	217-171	217-171	0.0124	100	217-171	✓
11	171-172	171-172	0.0083	36.15		
		172-173	0.0047	63.85	172-173	×
12	172-173	172-173	0.0017	100.00	172-173	✓
13	173-174	173-174	0.0014	100.00	173-174	✓
		218-219				
14	217-218	217-218	0.0034	48.48		
		211-212	0.0032	51.52	211-212	×
15	218-219	218-219	0.0036	9.71		
		213-214	0.000387	90.29	213-214	×
16	219-220	219-220	0.000547	100.00	219-220	✓

Total sections tested = 16, Correct Matching =12,
Overall Performance Matching = (12/16) x 100% = 75%

The method has accurately identified faulty section for nodes 232, 77, 225, 215 and 216. For line 2, any fault between the two sections, algorithm has no difficulty to give an accurate result. However, due to overlapping of pattern characteristic between main line and line 1, any fault between these two lines, algorithm presents two possibilities of faulty section. It was found out that the similarity pattern occurred because of main line and line 1 have similar type and size of underground cable i.e. similar value for R and X per unit. On the other hand, line 2 has different type and size of underground cable than main line and line 1.

Point P, Q, R and S in Fig. 6(a) indicate the test points. At point P, algorithm has difficulties to select faulty section. There are two possibilities faulty section i.e. 217-218 or 211-212 with confidence level of 48.8% and 51.52 % respectively. The algorithm has selected wrong section i.e. 211-212. Alternatively, the operators still have the chance to select second option at a latter stage. At point Q, algorithm managed to get the correct answer since the fault occurred between sections in line 2. At some points, such as R and S, algorithm able to identify faulty section correctly. Overall, pattern 'search and match' algorithm achieved 75 % accuracy for identifying faulty section in the network.

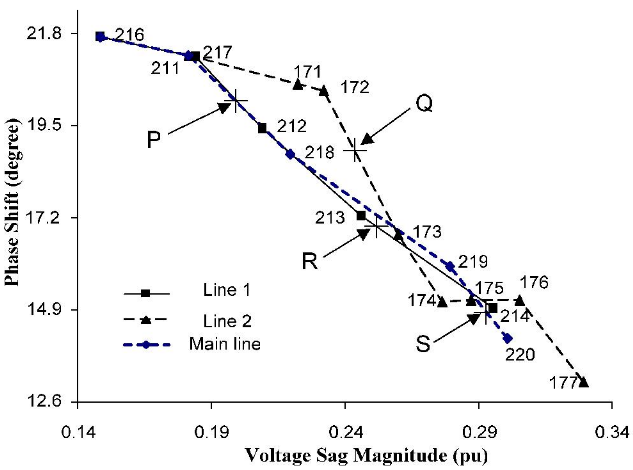

Fig. 6: Characteristic for SLGF and test points (P, Q, R and S)

Fig. 7 shows pattern of voltage sags as observed at the monitored node when three phase fault occurred. It can be seen clearly that similar characteristic occurred as in SLGF where line 1 nearly overlaps with the main line. This is due to similar value of impedance as seen from the monitored node. This also suggests that there is possibility to get more than one possible fault section if the actual fault data situated near to both lines.

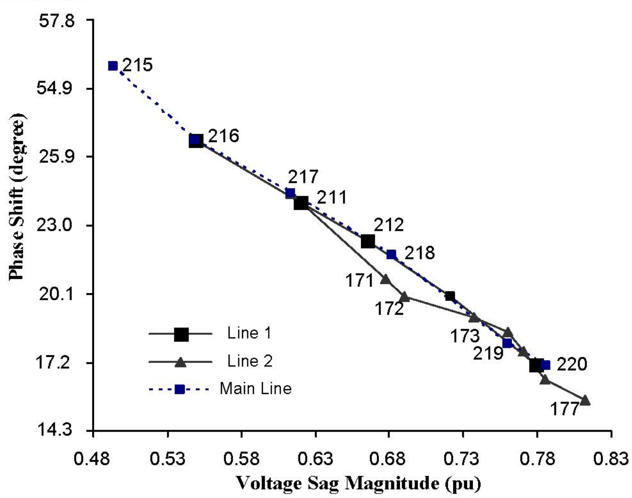

Fig. 7: Characteristic for Three Phase fault

The test also have been conducted for other type of faults and showed excellent result. Overall performance matching of each type of fault is around 70 %. Even though at some points, the algorithm failed to identify faulty section correctly especially when fault occurs between sections in line 1 or main line, the operator still able to make a right decision for the second or third attempts based on the probability value.

V. Future works

The development of the software is in the early stage. Thus, further study is required to improve the fault location estimation method and the software. The following are future works for this study.

A. Software development

Presently, the process of identification faulty section is not in continues flow since the algorithms were written in different programming language i.e. Visual C++ and MATLAB. Due to this, it is difficult to integrate all the algorithms to be comprehensive software. Due to this, the present work now is to modify the existing programs to be a 'component' type using C++ Builder. A component is a piece of pre-built software with well-defined interfaces and behaviors, accessible only via its interface [10]. A component is a part of a larger structure, an element contributing to the composition of the whole, with stable, defined interfaces. CBD technology enables software to be developed by integrating various components, which are independent between each other. Any of the components can be modified or replaced without affecting the whole software. The flexibility of the software for future upgrading is obtained from these components.

The plan is develop the automated fault location software by integrating seven power system analysis modules, which will be a component type as shown in Fig. These modules are independent between each other. The proposed software consists of two parts; the analyses to estimate fault location and the database development, which both have been discussed in section III.

Each of the modules in the software has its own task. The 'Main/GUI' module is responsible of coordinating all process in the software. A part from that, the module also deal with graphical user interface (GUI) so as user will be able to supply data or to update the databases as well as to view results.

The main module stores data receive from data acquisition device and then prepared data according to the required format for each module. In order to obtain the fault type, the voltage sags waveform data from the main component will be sent to the fault type identification. This component will identify the type of fault. The same waveform will also be used in the 'magnitude and phase extraction' module to get the lowest fundamental RMS magnitude of voltage sags and phase shift.

At present, a probability analysis based on equation 7 is employed. This probability analysis is based on the distance measurement between actual data with the simulated data. In the future, a historical data of fault location will be used to enhance the probability analysis. This data is a frequent number of faults occurrence at particular location. Thus, by combining this data with the probability analysis, more realistic probability indication of the possible fault location can be produced.

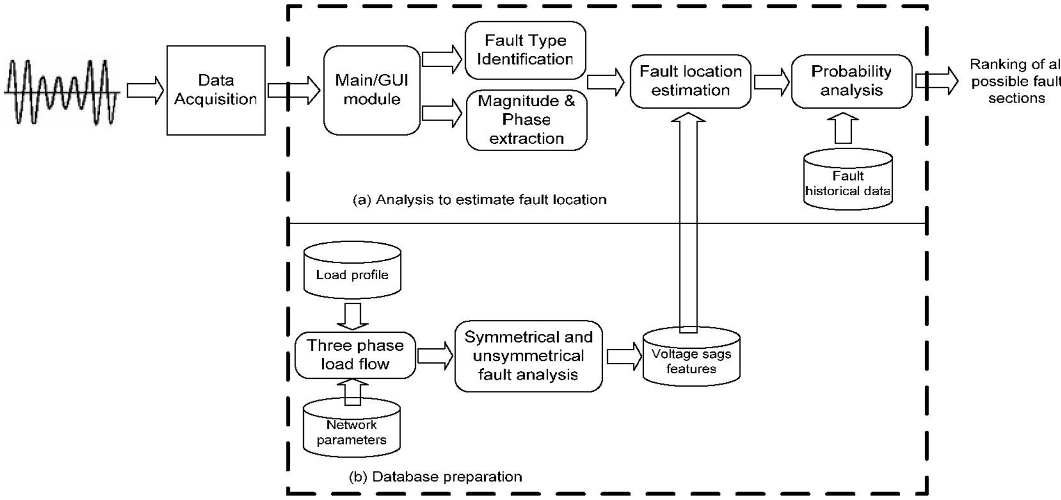

Fig. 8: Proposed automated fault location software using component based integration approach

B. Method improvement

i) The effect of load modeling, line modeling and fault impedance to the performance of the proposed algorithm will be studied and improvement will be conducted if necessary.
ii) In order to have more realistic probability value for multiple fault sections, a statistical data of fault from the historical fault events will be considered in the probability module.
iii) To study other pattern recognition method to improve the 'search and match' algorithms for the database in terms of search time and the accuracy of the result.
iv) Since the present method only considers a faulty section, a method to estimate the exact location of fault will be studied.
v) The software will be tested using a practical distribution network from utility. This will give more clear indication of the method performance.

VI. Conclusion

In this paper, a new method to estimate fault location in term of section in the distribution networks has been presented. Result indicates that the proposed method has a very significant improvement by at least 70% over the conventional methods trial and error for identifying faulty section in the networks. The method is not time consuming since not involving any iterative process. Any changes such as load variations or network reconfiguration will not affecting the performance of the algorithm since the database can be updated. The proposed method requires measurement of voltage sags magnitude and phase shift at the substation. Thus, the method is inexpensive and possible to be implemented in any distribution network to locate faulty section.

This paper also has outlined future works for the development of automated fault location software and improvement of the existing method. The software will be developed using CBD technology. Using this technology, the proposed software will have the flexibility for future upgrading. Modification or upgrading can be done without affecting the whole software.

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