A Synchrophasor Measurement-Based Fault Locator with Novel Fault Detection Technique

Exact fault location detection is vital for power system restoration and security purposes. The line parameters play a key role for accurately detecting fault location in a transmission line of a power network. In other fault location algorithms, line parameters used are approximately constant and they vary with weather and loading conditions also. So, an algorithm which is independent of the line parameters, is more accurate, flexible and robust. This paper presents a numerical algorithm for locating fault in a short transmission line with improved accuracy. This algorithm is independent of the line parameters for locating fault and accuracy of the algorithm is improved by using filtering algorithm. The performance of the algorithm is tested on several power networks by simulation carried out by PSCAD/EMTDC. It is found that the accuracy of the algorithm can be further improved by using a Butterworth 2nd order filter, which is used for the better refinement of collected current and voltage signals and to eliminate unwanted frequency components. A fault classification approach by use of zero sequence components of power and a faulty phase detection approach by the study of change of phase currents are also presented in the paper.

Keywords: Fault Location Algorithm; Butterworth Filter; Sampling; Symmetrical Fault; Asymmetrical Fault.

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1. Introduction

Fast and accurate fault detection and location is vital from the aspect of power system security and restoration. Algorithms which provide essential analysis for locating the fault of overhead transmission line is an important part of protection schemes. Fault locator, which helps to locate accurate fault location with appropriate fault location algorithm (FLA), is an important and essential component of such algorithms. It calculates the distance to the fault from a given reference point. Outage times can be reduced and service to consumers restored more quickly, if the location of the fault can be determined accurately [1].

Several fault location algorithm has been developed from the past. Some of them use data from single line terminal, some of them use data from multiple terminals, some of them use synchronized data sampling from terminals, and some of them use other techniques like travelling wave based methods or ANN, Fuzzy logic based methods etc. Single-end methods use local measurements of current and voltage at one terminal of the faulted line [2–3]. With the emergence of communication technologies, double end fault location method using synchronized or unsynchronized data samples from both terminals of a transmission line has been employed [4]. Single Terminal Fault location algorithms.
(STFLA) calculate impedance seen from the local terminals and then use line parameters to calculate the fault distance. The accuracy of the algorithm is largely affected by the zero sequence component of the line and fault resistance [5]. Two terminals FLA are relatively more accurate than STFLA as they are not affected by fault resistance but disadvantage of these methods is they need a mean to gather data from both terminals at one location prior to be analysed [1]. Speed of these algorithms are less than STFLA. Three-end and multi-end methods are extensions of double-end methods [6–7]. These methods identify the faulted sections by multi-end measurements first and then locate the fault along the identified section by the double-end methods. Fault location of a transmission line by travelling wave based methods and impedance based methods draws the attention of the researchers increasingly [8-9]. The measurement may also not available at faulted line terminal rather it may be available in buses distant from the faulted line [8]. In [10] a method is described which requires data from both ends of the line requires synchronized sampling. In [11] a technique is presented for estimating fault location which requires unsynchronized data sampling at both ends of the transmission line. [12] presents a fault location technique which incorporates analysis of data during circuit breaker operation. [13] investigates the malfunctioning of the circuit breaker and their impact on hidden failure. During a 3-phase circuit breaker operation all the three phases may not open simultaneously. The individual zero crossing of each phase may be displaced by certain degree, accordingly several discrete states known as inter-pole states may arise due to this phenomena which may affect the desired result or accurate fault location. Selection of window size for extracting fundamental frequency may also affect the accuracy of the algorithm. e.g- The use of full cycle, fractional cycle or multiple cycle of waveform for extracting fundamental components may affect the results also. In [14] a PMU based fault location method is discussed for series compensated line which uses sequence components of voltages and currents and Islanding technique of power network to detect fault in a series compensated transmission line inside a power network. In [15] a fault location technique is presented which uses voltage and current phasors computed from two or three line terminals.

A common feature or essence of these various FLA are, they requires the knowledge about the system parameters like – line length, line parameters (R, L etc) and appropriate equation for computation of fault distance. But the line parameters may vary depending upon different loading, weather conditions, aging etc which may of course affect the accuracy of the algorithm. So, an algorithm is needed which is independent of line parameters and thus which will be more accurate, robust and flexible. In [16], [17], [18] proposed fault location algorithms do not require line parameters to locate fault. [16] & [17] Algorithms uses voltage and current data and avoided the necessity of data sampling synchronization. However those parameters having limitations to locate symmetrical fault.

There are two FLAs are presented in [18]. First one uses both pre-fault and fault data and then uses iterative technique to locate fault. The second one uses fault data to locate asymmetrical faults only. In [1] an FLA is derived which uses data from both ends of the line with assuming synchronized data sampling for all kinds of the fault. However, the algorithm does not need synchronized data sampling to locate symmetrical three-phase faults. Further, since it is developed in the phasor-domain, it does not require a very high sampling frequency. In this paper we worked further on this algorithm and proposed a measure to improved the accuracy of the above algorithm. The objective of the paper is to enhance the accuracy of the above algorithm with appropriate data extraction procedure. A fault classification approach by use of zero sequence components of power and a faulty
phase detection approach by the study of change of phase currents are also presented in the paper.

2. Synchronized measurement system

A synchrophasor system composed of Phasor measurement unit (PMU), phasor data concentrator (PDC), GPS satellite system, super PDC as shown in Fig1. The PMU collects the real time data from the various remote areas and send over it to local data concentrator called phasor data concentrator via communication system. This system serves as the backup protection system for Wide area protection systems (WAPS) and it is capable of acting as the substitution of conventional backup protection in power system[19]. The relay takes the decision is based on collected data through communication network. The suggested technique increases the reliability, security and stability of the system. PMU measures positive sequence voltage magnitude and current phase angle of a power system in real time with synchronised time stamped data[19]. The synchronization is done by sampling of voltage and current waveforms using timing signals from different common time reference frame, such as the Global Positioning System (GPS) Satellite or any other reference timing signal generator [20-26].

![Fig1: Wide Area Measurement Protection](image)

Depending on the system requirements and size, number of data concentrators can vary. Phasor information is collected by data concentrators and information collected by two or more data concentrators is forwarded to Super PDC. Selected Wide area monitoring, protection and control (WAMPAC) applications can be run directly at this level, along with the data archiving [1]. In the improved algorithm two PMUs are expected to be in two terminals of the transmission line studied, which will capture the both ends data required for fault location calculation in case of asymmetrical fault and also the fault voltage data in case of a symmetrical fault. The captured signal should pass through a second order Butterworth filter before calculation of fault location of the transmission line.
3. Proposed fault location algorithm

3.1 Asymmetrical Fault:

LG, LLG, LL are asymmetrical faults. During asymmetrical fault, the fault location algorithm (FLA) is derived here. Assume an asymmetrical fault is taken place in the transmission line at L km length from the sending end of the transmission line, and total line length is considered as D Km.

Assuming line length less than equals to 100 Km (short transmission line), the shunt conductance and shunt capacitance of a transmission line can be neglected. A faulted line is shown in Fig 2. Fault location is denoted by F in Fig 3 & Fig 4. D is the total line length and L is the faulted length from reference point i.e. sending end. S denotes sending end and R denotes receiving end. s subscript denotes a sending end variable and R subscript denotes a receiving end variable. p superscript denotes positive sequence variable and n superscript denotes a negative sequence variable. Voltage and current samples are synchronously sampled here in both the line terminals. Corresponding Phasors are calculated by using standard signal processing techniques with the help of voltage and current samples after passing them consecutively through a Second order Butterworth filter and FFT block. From Fig 3 & Fig 4 it can be written-
\[ V_S^p - ZL I_S^p = V_R^p - Z(D - L)I_R^p \]  
\[ (1) \]
\[ V_S^n - ZL I_S^n = V_R^n - Z(D - L)I_R^n \]  
\[ (2) \]
By solving equation (1) & (2) we get
\[ ZL = \frac{(V_S^p - V_R^p)I_R^n - (V_S^n - V_R^n)I_R^p}{(I_S^p I_R^n - I_S^n I_R^p)} \]  
\[ (3) \]
\[ Z(D - L) = \frac{(V_S^p - V_R^p)I_R^n - (V_S^n - V_R^n)I_R^p}{(I_S^p I_R^n - I_S^n I_R^p)} \]  
\[ (4) \]
Fault distance is \( L \) & total line length is \( D \). Fault distance can be expressed as a percentage of total length-
\[ \% L = 100 \times \left( \frac{L}{D} \right) \]  
\[ (5) \]
Equation (5) can be rewritten as-
\[ \% L = 100 \times \left( \frac{ZL}{ZL + Z(D - L)} \right) \]  
\[ (6) \]
From equation (3), (4) and (6), it can be written as
\[ \% L = 100 \times \frac{(V_S^p - V_R^p)I_R^n - (V_S^n - V_R^n)I_R^p}{(V_S^p - V_R^p)(I_S^p + I_R^n) - (V_S^n - V_R^n)(I_S^p + I_R^p)} \]  
\[ (7) \]
3.2 Symmetrical Fault:

![Symmetrical Fault Diagram](image)

\[ \text{Fig 5: Equivalent positive sequence circuit for Symmetrical Fault} \]
In case of symmetrical faults, only positive sequence network is present, no negative or zero sequence network. \( R_f \) denotes fault resistance and \( V_f^P \) is fault voltage. From Fig 5 we are getting the following equations:

\[
V_S^P - ZL I_S^P - V_F^P = 0 \quad (8)
\]
\[
V_R^P - Z(D - L) I_R^P - V_F^P = 0 \quad (9)
\]

From Equation (8), (9) & (5), (6) we get-

\[
\% L = 100 \times \frac{\left( V_S^P - V_F^P \right) I_R^P}{\left( V_S^P - V_F^P \right) I_R^P + \left( V_R^P - V_F^P \right) I_S^P} \quad (10)
\]

The proposed algorithm does not need to know any fault type or line parameters. The presence of negative sequence current determines difference between symmetrical and asymmetrical fault. The flow chart of the proposed algorithm is shown in Fig 6.

![Flow Chart of the Proposed Algorithm](image)

**Fig 6**: Flow Chart of the Proposed Algorithm

4. Results and Discussions:

Test results of the algorithm is carried out on a 400 KV, 100 Km long overhead transmission line using PSCAD / EMTDC software. Multiple cases of symmetrical and asymmetrical faults were carried out. All the parameters used here are same as reference [1]. The FLA results for both kinds of fault are listed in Table-1 and Table-2.
4.1 Asymmetrical Faults: Asymmetrical faults (LG, LLG, LL etc) faults were simulated at the various points of the line. Fault initiation time \( t = 0.2 \) sec. Sampling frequency \( f_s = 4 \) KHz. It is assumed all the phasors are ideally synchronized \( (\phi = 0^\circ) \). Using the voltage current samples unknown fault locations has been calculated. The results related to asymmetrical faults are listed in Table 1.

Table 1: %Errors in Asymmetrical Fault Distance Calculation

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault Resistance ( (\Omega) )</th>
<th>Fault Distance ( (\text{Km}) )</th>
<th>% error before using Butterworth filter</th>
<th>% error after using Butterworth 2\textsuperscript{nd} order filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>0.01</td>
<td>40</td>
<td>0.10925</td>
<td>0.02125</td>
</tr>
<tr>
<td>ABG</td>
<td>0.01</td>
<td>65</td>
<td>0.0471</td>
<td>0.0424</td>
</tr>
<tr>
<td>BCG</td>
<td>100</td>
<td>60</td>
<td>0.0471</td>
<td>0.01406</td>
</tr>
<tr>
<td>ABG</td>
<td>0.01</td>
<td>30</td>
<td>0.1136</td>
<td>0.068</td>
</tr>
<tr>
<td>ABG</td>
<td>2</td>
<td>30</td>
<td>0.2063</td>
<td>0.1165</td>
</tr>
<tr>
<td>ABG</td>
<td>0.1</td>
<td>20</td>
<td>0.1453</td>
<td>0.075</td>
</tr>
<tr>
<td>AB</td>
<td>100</td>
<td>75</td>
<td>0.4221</td>
<td>0.3893</td>
</tr>
<tr>
<td>ABG</td>
<td>0.01</td>
<td>75</td>
<td>0.3875</td>
<td>0.333</td>
</tr>
</tbody>
</table>

Different results are generated with varying faults and varying fault resistance \( R_f \). Fault location percentage error is calculated as a percentage of full line length.

\[
\% Error = \left( \frac{I_{\text{calculated}} - I_{\text{exact}}}{I_{\text{exact}}} \right) \times 100 \tag{11}
\]

4.2 Symmetrical Faults: Symmetrical faults (LLL and LLLG) are simulated and calculated fault distance by using the FLA. Fault Location errors are listed in Table 2. Other parameters remain same as asymmetrical fault.

Table 2: %Errors in Symmetrical Fault Distance Calculation

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault Resistance ( (\Omega) )</th>
<th>Fault Distance ( (\text{Km}) )</th>
<th>% error before using Butterworth filter</th>
<th>% error after using Butterworth 2\textsuperscript{nd} order filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLLG</td>
<td>0.01</td>
<td>80</td>
<td>0.0496</td>
<td>0.0011</td>
</tr>
<tr>
<td>LLL</td>
<td>0.25</td>
<td>35</td>
<td>0.1679</td>
<td>0.0033</td>
</tr>
<tr>
<td>LLL</td>
<td>2</td>
<td>60</td>
<td>2.008</td>
<td>0.02496</td>
</tr>
<tr>
<td>LLLG</td>
<td>100</td>
<td>30</td>
<td>0.2063</td>
<td>0.1165</td>
</tr>
<tr>
<td>LLLG</td>
<td>100</td>
<td>50</td>
<td>1.4914</td>
<td>0.7539</td>
</tr>
<tr>
<td>LLL</td>
<td>1</td>
<td>75</td>
<td>1.324</td>
<td>0.1382</td>
</tr>
<tr>
<td>LLL</td>
<td>1</td>
<td>10</td>
<td>0.9390</td>
<td>0.4104</td>
</tr>
</tbody>
</table>

4.3 Improved accuracy using higher order filter:

With the use of higher order filter, better refinement in voltage and current signals can be achieved and unwanted frequency components can be eliminated with better accuracy. As a result better accuracy in the above fault location algorithm can be achieved. The only disadvantage of using higher order filter is, with the increase of order of the filter
the size and cost of the filter will also increase and that will affect the economy of the process. So, it is suggested to optimize the accuracy with economy of the process. In Table 3 the comparison of percentage error with Butterworth 2\textsuperscript{nd} and Butterworth 4\textsuperscript{th} Order filter is shown in context to proposed methodology. It is suggested that for all calculations the first half cycle samples of voltage and currents of the faulted duration can be ignored as they are contaminated by dc off-set signals which can affect the accuracy of the algorithm.

**Table 3**  Comparison of % error of fault distance with Butterworth 2\textsuperscript{nd} and Butterworth 4\textsuperscript{th} Order filter

<table>
<thead>
<tr>
<th>Fault type</th>
<th>Fault Resistance (Ω)</th>
<th>Fault Distance (Km)</th>
<th>% error before using Butterworth 2\textsuperscript{nd} order filter</th>
<th>% error after using Butterworth 4\textsuperscript{th} order filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABG</td>
<td>0.1</td>
<td>15</td>
<td>0.6113</td>
<td>0.4548</td>
</tr>
<tr>
<td>ABG</td>
<td>0.01</td>
<td>75</td>
<td>0.3333</td>
<td>0.07989</td>
</tr>
<tr>
<td>LLLG</td>
<td>0.01</td>
<td>80</td>
<td>0.0011</td>
<td>0.000705</td>
</tr>
<tr>
<td>LLL</td>
<td>0.01</td>
<td>40</td>
<td>0.03125</td>
<td>0.0049</td>
</tr>
<tr>
<td>BCG</td>
<td>0.1</td>
<td>15</td>
<td>0.6007</td>
<td>0.3011</td>
</tr>
<tr>
<td>AG</td>
<td>1</td>
<td>40</td>
<td>0.26</td>
<td>0.234</td>
</tr>
<tr>
<td>LLL</td>
<td>2</td>
<td>75</td>
<td>0.2204</td>
<td>0.1108</td>
</tr>
<tr>
<td>AB</td>
<td>100</td>
<td>75</td>
<td>0.3893</td>
<td>0.1455</td>
</tr>
</tbody>
</table>

4.4 Application of the Methodology in case of a series compensated transmission line:

![Fig 7: Equivalent Positive Sequence Network in case of series-compensation involved](image)

![Fig 8: Equivalent Negative Sequence Network in case of series-compensation involved](image)
Here we are considering the line having series capacitor $c$ per unit length. In that case the equivalent networks needed for derivation of the FLA will be as above Fig 7, 8 & 9. In that case we can derive the above FLA by substituting $Z'$ instead of $Z$ in the equations (1) to (10). Where $Z' = (Z - j\omega c)$. Rest of the calculations are same as above. Assumption to use this FLA in case of series compensation involved in transmission line is the capacitor is assumed to be distributed throughout the line. Hence we can derive two lumped capacitors in the model for calculation. One capacitor is up to faulted point from sending end side and another from faulted point up to receiving end side of the transmission line.

5.Classification of fault:

Fault can be classified as Symmetrical and asymmetrical w.r.t presence of negative and zero sequence current or voltage. Presence of positive sequence current or voltage only (no negative/zero sequence) indicates that the fault is a symmetrical fault i.e LLL or LLLG fault. LLL or LLLG fault is almost identical. Due to balanced nature of fault there will be no current flowing through neutral wire. But in practical case there might be existence of a small current flow in the neutral wire which can distinguish LLLG and LLL type fault. Asymmetrical faults can be distinguished through study of its active and reactive power profile due to zero sequence fault voltage and current. From the theory Zero Sequence component of Power during fault

$$\mathbf{S_{f0} = V_{f0}I_{f0}^*}$$

Zero Sequence Active Power during fault can be written as

$$\mathbf{P_{f0} = \text{Real} \left(V_{f0}I_{f0}^*\right)}$$

Zero Sequence Reactive power during fault can be written as

$$\mathbf{Q_{f0} = \text{Imaginary} \left(V_{f0}I_{f0}^*\right)}$$

In the below Fig 10 (a,b) , Fig 11(a,b) , Fig 12(a,b) , Zero sequence active and reactive power profile are Studied during different Kinds of asymmetrical faults like – LL ,LLG and LG faults. From the study of the below figures it is clear that the Zero Sequence Power components in case of a LL fault is almost negligible (almost in the order of $10^{-29}$ p.u). So, from the study of Zero Sequence components of power during fault we can easily distinguish a LL fault from LLG and LG fault.
Fig 10 (a,b): Profile of Active and reactive power during LL fault

(a) Zero Sequence Active Power vs time during LL fault

(b) Zero Sequence Reactive Power vs time during LL fault

(a) Zero Sequence Active Power vs time during LLG fault
(b) Zero Sequence Reactive Power vs time during LLG fault

Fig 11 (a,b): Profile of Active and reactive power during LLG fault

(a) Zero Sequence Active Power vs time during LG fault

Fig 12 (a, b): Profile of Active and reactive power during LG fault

Now to distinguish between a LLG and a LG fault we will again study their Zero Sequence component power profiles during fault. It is seen from the study that Zero sequence components of power that during an LLG fault the values are more compare to an LG fault. Thus we can distinguish between a LLG and a LG fault.

\[
P_{f0LG} < P_{f0LLG} \quad \&\& \quad Q_{f0LG} < Q_{f0LLG}
\]

6. Detection of Phases of fault:

Faulty phases can be identified by the study of the change in phase current characteristics. To study the said behaviour, different types of faults are created with fault duration 0.02 sec with initiation of fault at 0.2 sec. Change in phase current is captured from 0.19 sec-0.22 sec.
From the Fig 13(a,b,c), it is clear that in case of faulty phases (Ph-A & Ph-B), there is a sharp change in change of phase current waveform at the time of fault inception (absolute value around 0.2 unit at 0.2 sec). Whereas the change is almost negligible (in the order of $10^{-5}$ unit) at the same time in case of healthy phase (Ph-C). Similar Characteristics can be generated in case of a LL fault to detect the faulty phase.
From Fig 14( a,b,c) it is clear that there is a sharp change in phase current in case of faulty phase (Ph-A, at 0.2 sec, $\Delta I_a$ value is around 0.15 unit), whereas for healthy phases (Ph-B & Ph-C) this change is almost negligible (order of $10^{-5}$ unit) at the same time. So, to detect faulty phases and healthy phases the following condition can be imposed:

$$\text{ABS}(\Delta I) > \text{ABS}(\Delta I_{\text{threshold}}),$$

$\Delta I_{\text{threshold}}$ should be properly chosen to solve the problems. In this work its value was chosen $\pm 0.1$ unit. In case of symmetrical faults all the three phases are faulty.

7. Advantages of the proposed algorithm:

The work done prior to this work on the same problem (i.e designing transmission line parameter independent fault locator) are very little. This work have several strong features that leads the proposed approach to supersede other techniques developed prior to
this work. First of all, almost all the techniques developed prior to this work addressing the same problem have certain limitations in locating symmetrical or asymmetrical faults but the proposed technique is capable of detecting and locating both symmetrical and asymmetrical faults. Second of all, some of the techniques developed prior to the proposed technique use iterations to get the desired solution which is lengthy and time consuming. But the proposed technique does not use iterations. It uses direct expressions. The proposed technique is advanced over [1], as it uses appropriate filtering technique for signals to improve accuracy of the algorithm. It also shows with the use of higher order filters the accuracy of the algorithm can be improved further. Third important point in this respect is the proposed algorithm can further classify faults which all the previous algorithms cannot do. Even the proposed technique can predict the faulty phase also. Proposed fault classification and faulty phase detection methods are very simple, accurate and fast. The proposed technique does not affect the system stability or fault level and it works fine in case of transient network conditions also. So, this technique is better than other developed techniques prior to it addressing the same problem.

8. Conclusions

In this paper a flexible, robust improved FLA is presented, which can work in the absence of any information of system parameters. Proposed algorithm can be applied in case of both symmetrical and asymmetrical faults and the use of filtering technique with FFT will increase the performance of the proposed algorithm. This algorithm can be applied during the presence of capacitor (series compensation) and contingency conditions of the network also. It does not require any pre-fault data and remains unaffected by fault and arc resistances. The work is extended by improving accuracy of the algorithm further by using 4th Order Butterworth filter, application in series compensated transmission line, classification of faults by using active and reactive power components of zero sequence power during fault and faulty phase detection by study of change in phase current profiles. All the studies are carried out in the paper by PSCAD simulation model of the test system and found to be accurate and fast.

References


