Methodology for testing and development of parameter-free fault locators for transmission lines

Marjan Popov, Shreya Parmar, Gert Rietveld, Gary Preston and Vladimir Terzija

***Abstract*--This paper presents a comparison between two different approaches towards fault location detection with and without applying transmission line parameters. Firstly, an impedance based parameter dependent algorithm, derived by using the modal transformation theory and Fast Fourier Transform is presented. The methodology has the ability to locate the fault whether it is on the overhead line or on the underground power cable. The second algorithm is an improved parameter-free fault location method that uses time synchronization. The unknown fault location will be determined from voltage and current phasors, synchronously measured at both line terminals. This approach of fault detection renders the prior knowledge of line parameters as obsolete, since they are sometimes difficult to assess.**

The paper presents the results of the algorithms tested through the use of ATPDraw simulations and MATLAB. Some results are validated with laboratory experiments. The results of the line parameter-independent model will be compared by those provided by the parameter-dependent model. Both algorithms are tested for single line to ground faults.

***Keywords*: fault location, line parameters, two terminal, ATPDraw, parameter less, transmission line, protection.**

I. Introduction

Electrical transmission lines and facilities are a necessary part of every community's infrastructure. Power in today's world is provided by a diversity of sources, including coal, natural gas, oil, or renewable energy sources like hydropower, wind, or solar energy, where transmission lines are required to bring the generated power to remote loads. This also makes consumers more sensitive to power outages. Since electrical faults lead to mechanical damage, faults should be repaired before returning the lines in service and the restoration process can be quickened when the location of the fault is known [1]. Hence, designing line protection schemes that reliably detect and isolate faults compromising the security of the electric grid are essential.

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Paper submitted to the International Conference on Power Systems Transients (IPST2015) in Cavtat, Croatia June 15-18, 2015

A fault locator is a system designed to determine the position of a fault on a power transmission line with high accuracy. Fault locators augment protection equipment by applying fault-location algorithms to compute the distance to the fault from a reference point. In this way, the economic impact of the fault situations can be mitigated and their correction can be rendered in a simple and precise way. Electric utility services can be maintained when the fault location on a transmission line can be accurately determined, which saves time during the fault correction period, thus, making fault locators an important tool for power system protection [2], [3]. Quick and accurate fault location enables service crews to remove faults quicker, especially when generation happens in remote area, thereby improving the security and quality of the energy supply.

Though formulated to provide protection and detection of faults on transmission lines, there are some important differences between fault location algorithms (FLA) and conventional fault location techniques [4].

- Protective relays usually define a general protection area or zone while fault locators pinpoint these areas with a certain percentage of error, if any.
- Protective relays require high speed operations to alleviate fault current to other parts of the power network, which may compromise relay system security and selectivity sometimes. Fault locators on the other hand use algorithms that calculate fault locations in several seconds, if not in minutes.
- Relays employ a data window of several fundamental frequency cycles. Fault locators use the most compatible data windows to minimize the scope of errors in calculations.
- However, in a downside, determining and using the most suitable data window becomes of a considerable importance as it may affect the result of the algorithm.
- Fault locators do not possess any limitations of complexity. They can be relatively simple (based on impedance of line, or traveling wave methods) and may even increase in their complexity to incorporate a more versatile operation (use of neural networks, fuzzy logic, PMUs).

Existing methods for fault location [5] are classified in two main types:

- Methods based on traveling wave technology [6], [7], [8].
- Methods based on the transmission line parameters and voltage and current measurements [9], [10], [11], [12].

A basic fault locator can be designed by using different algorithms, which are applied in existing protection systems. Line parameters like resistance R, inductance L, and capacitance C per unit length are often used in algorithms [13]. These parameters are also dependent on the line loading, or weather conditions which may result in less accurate fault location detection. To tackle these problems, techniques were developed on the basis of the available voltage and current measurements at faulted line terminals to minimize the effects of parameters. Use of asynchronous data sampling [14] served as an iterative approach to these algorithms, yielding in limited fault detection based on the fault type. The parameter independent algorithms [15], [16], [17], then, provide a sharpened method to locate all fault types, without needing line parameters. Fast Fourier Transform is used in both algorithms to determine voltage and current samples needed by the fault locator. The simulation tests of the developed algorithm are then carried out prompting accurate results. The algorithm's sensitivity to fault resistance was also tested, which led to the conclusion of the algorithm being unaffected.

The paper uses synchronized data sampling at each line terminal and gives a detailed foundation to the algorithms' derivation. Additionally, simulation tests and their results are examined and their validity when tested with an impedance based fault location setup are also constituted.

The initial algorithm development and modeling was done in ATPDraw/EMTP environment for both fault locations methods [18]. Tests were run using MATLAB [19] as well, where simulated voltage and current signals were generated via ATPDraw model. The approach used in the algorithms is as explained below.

II. Fault Location Algorithms

A. Parameter Dependent Algorithm

Power transmission using a combination of overhead transmission lines and underground cables is commonly found in densely populated countries. The algorithm defined here uses an impedance based approach. Using Telegraphers' equations from a single line representation of a two terminal transmission line model as shown in Fig. 1, voltages and currents on an electrical transmission line can be defined with respect to distance and time. Clarke's transformation is applied to convert the original set of phase variables into a set of 0, α and β variables. This algorithm uses the work established in [20] and [21].

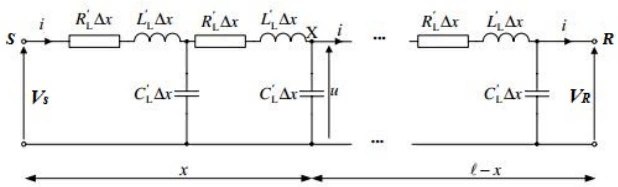


Fig. 1. Schematic representation of the elementary components of a transmission line.

Telegraphers' equations are given as:

$$\frac{\partial v}{\partial x} + L\frac{\partial i}{\partial t} = -Ri \qquad (1)$$

$$C\frac{\partial I}{\partial x} + \frac{\partial V}{\partial t} = -Gi \qquad (2)$$

where R, L, C and G are resistance, inductance, capacitance and conductance of the line/cable per unit length.

Fig. 2 shows a three phase network, where a fault F occurs from one of the line's phase to the ground. D is the total length of the transmission line whereas ℓ is the distance at which a fault F occurs from the sending end S terminal of the network. The same fault point can located at a distance $(D-\ell)$ when seen from the receiving end R terminal of the line.

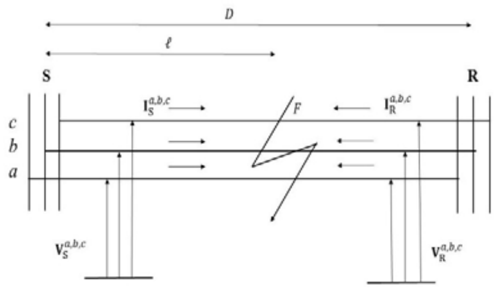


Fig. 2. Three phase representation of a faulted line.

The propagation constant γ and the characteristic impedance of the line Z_c are given as:

$$\gamma = \sqrt{(R+j\omega L)(G+j\omega C)}$$

$$Z_c = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$$

Telegraphers' equations (1) and (2) for a single phase line can be represented as:

$$\begin{bmatrix} \boldsymbol{V}_x \\ \boldsymbol{I}_x \end{bmatrix} = \begin{bmatrix} \cosh(\gamma x) & \boldsymbol{Z}_c \sinh(\gamma x) \\ \frac{\sinh(\gamma x)}{\boldsymbol{Z}_C} & \cosh(\gamma x) \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_{\mathrm{R}} \\ \boldsymbol{I}_{\mathrm{R}} \end{bmatrix} \qquad (3)$$

where $\boldsymbol{V_x}, \boldsymbol{I_x}$ are the voltage and current at any point x from the sending end of the line terminal and $\boldsymbol{V}_R, \boldsymbol{I}_R$ are the voltage and current at the sending end. Equation (3) can also be re-written in a way that $\boldsymbol{V_x}, \boldsymbol{I_x}$, expressed by the sending end voltages and currents $\boldsymbol{V}_{\mathrm{S}}$, $\boldsymbol{I}_{\mathrm{S}}$ for a single phase line as:

$$\begin{bmatrix} \boldsymbol{V}_x \\ \boldsymbol{I}_x \end{bmatrix} = \begin{bmatrix} \cosh(\gamma(D-x)) & -\boldsymbol{Z}_c \sinh(\gamma(D-x)) \\ -\frac{\sinh(\gamma(D-x))}{\boldsymbol{Z}_C} & \cosh(\gamma(D-x)) \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_{\mathrm{S}} \\ \boldsymbol{I}_{\mathrm{S}} \end{bmatrix} \qquad (4)$$

where D is the total line length and x is any point on the line, can also be represented as the fault point F.

When a fault occurs ℓ km away from the sending end, by making use of above equations, the distance to the fault can be determined by:

$$\ell = \frac{1}{\gamma} tanh^{-1}\left(\frac{A}{B}\right)$$

Here, the constants A and B are given as:

$$A = \boldsymbol{V}_{\mathrm{S}} \cosh(\gamma D) - \boldsymbol{Z}_C \boldsymbol{I}_{\mathrm{S}} \sinh(\gamma D) - \boldsymbol{V}_{\mathrm{R}}$$
$$B = \boldsymbol{I}_{\mathrm{R}} \boldsymbol{Z}_C + \boldsymbol{V}_{\mathrm{S}} \sinh(\gamma D) - \boldsymbol{Z}_C \boldsymbol{I}_{\mathrm{S}} \cosh(\gamma D)$$

By making use of the Clarke's transformation, the single-phase solution can be extended to a three-phase solution:

$$\begin{bmatrix} \boldsymbol{V}_0 \\ \boldsymbol{V}_\alpha \\ \boldsymbol{V}_\beta \end{bmatrix} = T \begin{bmatrix} \boldsymbol{V}_a \\ \boldsymbol{V}_b \\ \boldsymbol{V}_c \end{bmatrix}$$
$$\begin{bmatrix} \boldsymbol{I}_0 \\ \boldsymbol{I}_\alpha \\ \boldsymbol{I}_\beta \end{bmatrix} = T \begin{bmatrix} \boldsymbol{I}_a \\ \boldsymbol{I}_b \\ \boldsymbol{I}_c \end{bmatrix} \tag{5}$$

where $T = \begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix}$ is the Clarke's Transformation.

Hence, the distance to fault in a three phase system can be shown as:

$$\ell_{0,\alpha,\beta} = \frac{1}{\gamma_i} \tanh^{-1}\left(\frac{A_i}{B_i}\right) \tag{6}$$

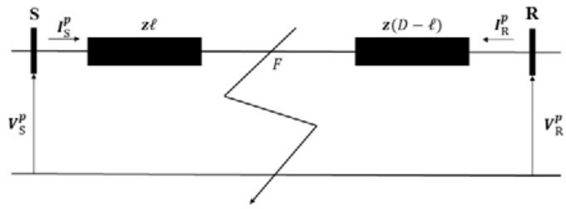
where ℓ_0 is the ground mode, ℓ_α and ℓ_β are the two areal modes,

$\gamma_i = \sqrt{Z_i Y_i}$, $\boldsymbol{Z}_{C,i} = \sqrt{Z_i / Y_i}$,
$A = \boldsymbol{V}_{\mathrm{S},i} \cosh(\gamma_i D) - \boldsymbol{Z}_{C,i} \boldsymbol{I}_{\mathrm{S},i} \sinh(\gamma_i D) - \boldsymbol{V}_{\mathrm{R},i}$ and
$B = \boldsymbol{I}_{\mathrm{R},i} \boldsymbol{Z}_{C,i} + \boldsymbol{V}_{\mathrm{S},i} \sinh(\gamma_i D) - \boldsymbol{Z}_{C,i} \boldsymbol{I}_{\mathrm{S},i} \cosh(\gamma_i D)$

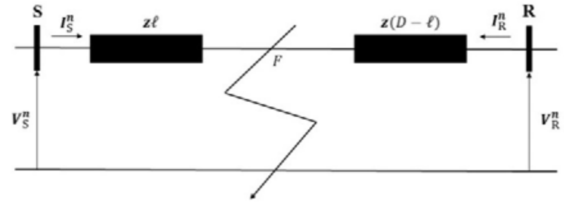
Accurate fault location can be selected by the appropriate mode and the fault type. ℓ_α mode is valid for all types of faults except line-line faults for which the ℓ_β mode is selected.

B. Parameter- independent Algorithm

Understanding the ambiguous nature of line parameters, an algorithm, which is capable of accurately determining the fault location on the transmission line without needing these parameters, becomes more flexible, reliable and user friendly. The parameter-independent algorithm [22] uses only the fundamental phasors of line voltages and currents sampled at each end of the transmission line. It is not affected by varying line parameters or by load, fault impedances or arc resistances. It can locate all fault types - including balanced three-phase faults - through the use of positive and negative-sequence current and voltage components. The Fast Fourier Transform is applied to extract the fundamental phasors from the voltage and current samples. Synchronized Measurement Technology (SMT) [23], [24] is used here, which can be implemented most easily using Phasor Measurement Units (PMUs) [25] in an actual grid system to receive voltage and current samples from instrument transformers at each end of the line. An asymmetric or unbalanced fault does not affect each of the three phases of a line equally and the easiest method to analyze this is with the use of *symmetrical components*, where decomposition of the unbalanced system into three sequence of balanced networks is done. The networks are then coupled only at the point of the unbalance, that is, at the fault location.



(a). Equivalent positive sequence circuit of the faulted line.



(b). Equivalent negative sequence circuit of the faulted line.

Fig. 3. Symmetrical components circuit of the faulted line.

In Fig. 2, by using the symmetrical components method, the positive, negative; as seen in Fig. 3(a) and Fig. 3(b) and zero sequence symmetrical components from of the voltages and currents at the sending and receiving ends can be formulated. The faulted three phase circuit from Fig. 2 is asymmetrical, because the fault at the point F can be represented by three single - phase equivalent circuits, which are representative of its positive (p), negative (n) and zero (0) sequence components respectively. Thus, the network equations can be shown as:

$$\boldsymbol{V}_{\mathrm{S}}^p - \boldsymbol{z}\ell \boldsymbol{I}_{\mathrm{S}}^p = \boldsymbol{V}_{\mathrm{R}}^p - \boldsymbol{z}(D-\ell)\boldsymbol{I}_{\mathrm{R}}^p \tag{7}$$

$$\boldsymbol{V}_{\mathrm{S}}^n - \boldsymbol{z}\ell \boldsymbol{I}_{\mathrm{S}}^n = \boldsymbol{V}_{\mathrm{R}}^n - \boldsymbol{z}(D-\ell)\boldsymbol{I}_{\mathrm{R}}^n \tag{8}$$

where $\boldsymbol{V}_{\mathrm{S}}^{p,n}$, $\boldsymbol{V}_{\mathrm{R}}^{p,n}$, $\boldsymbol{I}_{\mathrm{S}}^{p,n}$ and $\boldsymbol{I}_{\mathrm{R}}^{p,n}$ are positive and negative sequence voltages and currents for sending and receiving ends respectively and $\mathbf{z}$ is the positive (and negative) sequence line impedance.

By solving equations (7) and (8), we get:

$$\boldsymbol{z}\ell = \frac{(\boldsymbol{V}_{\mathrm{S}}^p - \boldsymbol{V}_{\mathrm{R}}^p)\boldsymbol{I}_{\mathrm{R}}^n - (\boldsymbol{V}_{\mathrm{S}}^n - \boldsymbol{V}_{\mathrm{R}}^n)\boldsymbol{I}_{\mathrm{R}}^p}{\boldsymbol{I}_{\mathrm{S}}^p \boldsymbol{I}_{\mathrm{R}}^n - \boldsymbol{I}_{\mathrm{S}}^n \boldsymbol{I}_{\mathrm{R}}^p} \tag{9}$$

$$\boldsymbol{z}(D-\ell) = \frac{(\boldsymbol{V}_{\mathrm{S}}^p - \boldsymbol{V}_{\mathrm{R}}^p)\boldsymbol{I}_{\mathrm{S}}^n - (\boldsymbol{V}_{\mathrm{S}}^n - \boldsymbol{V}_{\mathrm{R}}^n)\boldsymbol{I}_{\mathrm{S}}^p}{\boldsymbol{I}_{\mathrm{S}}^p \boldsymbol{I}_{\mathrm{R}}^n - \boldsymbol{I}_{\mathrm{S}}^n \boldsymbol{I}_{\mathrm{R}}^p} \tag{10}$$

The distance to the fault, ℓ can be expressed as a percentage of the line length D as:

$$\ell\% = \frac{\boldsymbol{z}\ell}{\boldsymbol{z}\ell + \boldsymbol{z}(D-\ell)} 100 \tag{11}$$

By rearranging the above equation, we get the final solution as:

$$\ell\% = \frac{(V_S^p - V_R^p) I_R^n - (V_S^n - V_R^n) I_R^p}{(V_S^p - V_R^p)\,(I_S^n + I_R^n) - (V_S^n - V_R^n)(I_S^p + I_R^p)} 100 \quad (12)$$

As it can be seen from the equation, the fault location uses only the symmetrical components of the measured current and voltage phasors from the sending and receiving end of the transmission network. Thus, a parameter independent fault location algorithm was developed.

The given equation to locate fault on a transmission line can be readily implemented with an SMT, with or without PMUs. In summary, the fault location algorithms discussed here can be described as given in Fig. 4.

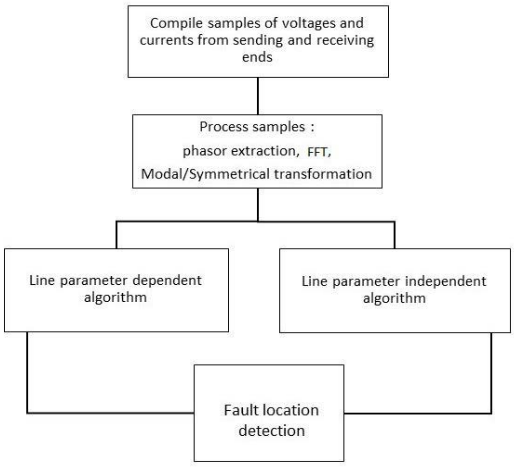


Fig. 4. Flowchart depicting approach used in fault location algorithms.

The fault locator is based on the assumption that the sending and receiving voltages and currents are perfectly synchronized.

III. Simulation Results

In this section, the simulations for the two fault location algorithms explained in the previous sections are performed. The algorithm testing was carried out by simulation analysis performed in ATPDraw environment for a total line length of 60 km. A schematic of the transmission line is shown in Fig. 5.

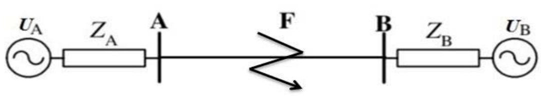


Fig. 5. Single line diagram depicting the fault line simulations.

The network parameters used for the simulation tests are as shown in Table I and the applied line constants are shown in Table II. The impedance and capacitance parameters of the line, which were used for the parameter dependent fault location algorithm are as shown in Table III.

TABLE I
NETWORK PARAMETERS

Parameters	Network A	Network B
$U_{LL,rms}$ (KV)	416	400
ϕ (°)	0	-20
R (Ω)	1.0185892	0.6366183
L (H)	0.0509295	0.0318309
R_0(Ω)	2.0371785	1.2732366
L_0(H)	0.1018589	0.0636618

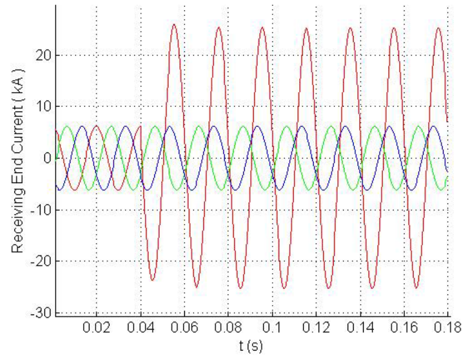
TABLE II
LINE PARAMETERS

Parameters	p-n sequence	zero sequence
R (Ω/km)	0.065	0.195
L (mH/km)	0.95493	2.86479

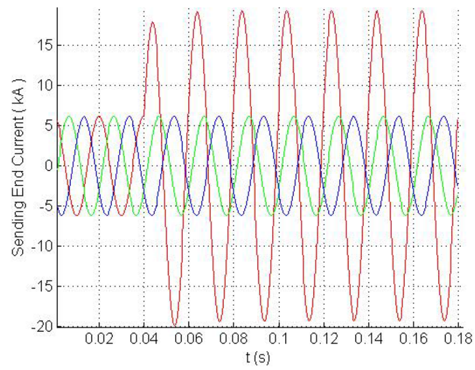
TABLE III
LINE IMPEDANCE AND CAPACITANCE PARAMETERS

Parameters	Values
Z_1 (Ω/km)	0.3317+j0.41634
Z_0 (Ω/km)	0.1972+j0.3699
C_1 (μF/km)	0.008688
C_0 (μF/km)	0.004762

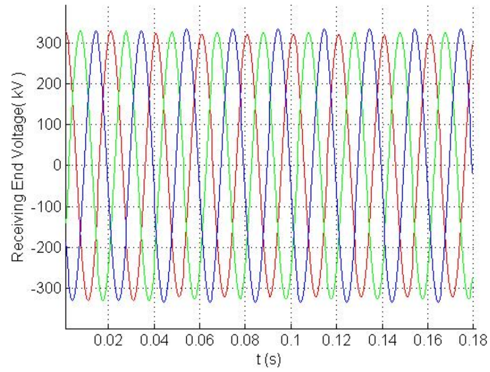
Single line-to-ground (SLG) faults were simulated in ATPDraw at different locations along the line with the use of a 3 phase controlled switch. The fault was set to occur at 40 ms. It was assumed that the line was loaded before the fault inception. The sampling frequency was f_S = 25 kHz. The data window size was 20 ms. This corresponds to N = 50 samples per data window. It is assumed that the synchronization error is equal to 0 degrees. The simulated faulted phase voltages and currents at both sending and receiving end terminals, shown in Fig. 6, were used as an input to both algorithms after proper variable assignment.



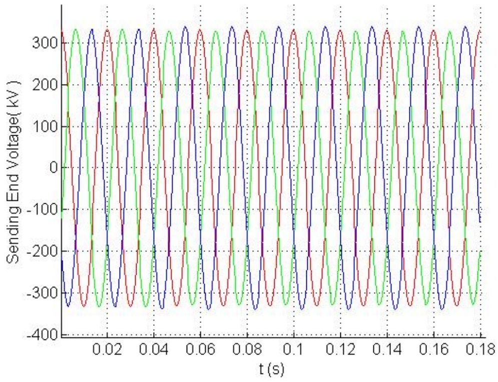
(a). Receiving end line terminal current waveform



(b). Sending end line terminal current waveform.



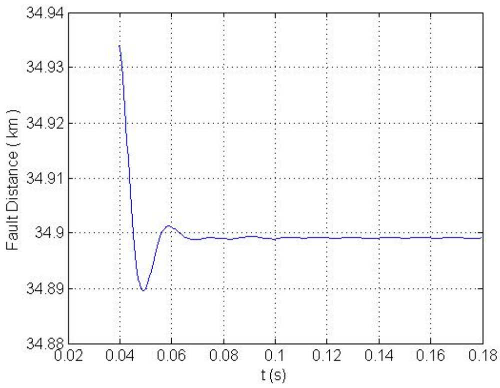
(c). Receiving end line terminal voltage waveform.



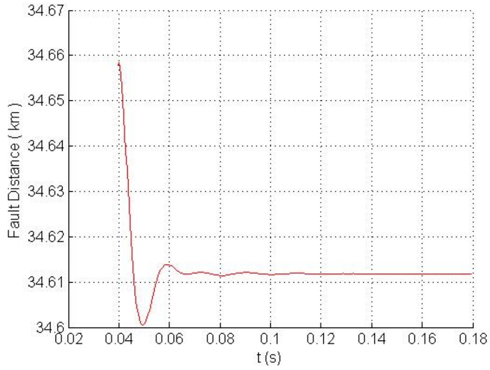
(d). Sending end line terminal voltage waveform.

Fig. 6. An example of sending and receiving end current and voltage waveforms for a SLG fault at 35 km in the transmission line network used in simulations.

Then, the fault location was computed with respect to the sending end side. For example, Fig. 7 shows the simulation result for fault location algorithms for a SLG fault at 35 km from the sending end terminal.



(a). Fault location by the parameter-dependent algorithm.



(b). Fault location by the parameter-independent algorithm.

Fig. 7. Estimated fault location by the fault location algorithms for a fault simulated to be at 35 km from sending end.

The results for both algorithms were then compared as shown in the Table IV.

TABLE IV
SIMULATION RESULT COMPARISON

Actual Fault (km)	Parameter Dependent FLA (km)	Parameter-independent FLA (km)
15	13.897	15.21
20	19.132	20.025
25	24.382	24.873
30	29.638	29.737
35	34.899	34.611
40	40.158	39.487
45	45.426	44.377
50	50.691	49.265
55	55.957	54.154

The error percentage comparison is as shown in the Table V, where the error percentage is given as:

$$error = \frac{actual\ value - calculated\ value}{actual\ value} 100\%$$

TABLE V
ERROR PERCENTAGE COMPARISON FOR THE FLAS

Actual Fault (km)	Parameter Dependent FLA error (%)	Parameter-independent FLA error (%)
15	7.353	-1.40
20	4.34	-0.125
25	2.427	0.508
30	1.206	0.875
35	0.288	1.109
40	-0.932	1.384
45	-0.946	1.384
50	-1.382	1.47
55	-1.74	1.538

As it can be seen from the results, the error margin in the algorithms, is shown to increase as the fault is closer to the ends of the line terminal.

IV. MEASUREMENTS AND LABORATORY MODEL OF TRANSMISSION LINE

A single phase high-voltage line was realized by an experimental setup at VSL Laboratory [26] by placing 6 air inductors in series as shown in Fig. 8.

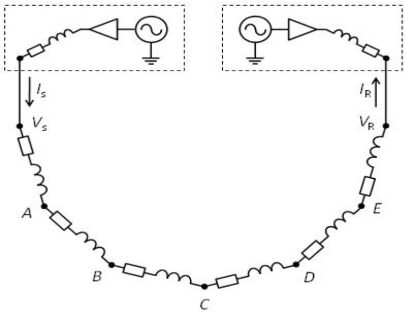


Fig. 8. Schematics of the experimental setup.

Bolted faults are performed at the interconnections of the inductors (points A to E) representing a transmission line by connecting these points to ground during measurements. The current and voltage were measured at the points using a current probe and a voltage divider.

A. RL Measurements

Measurements were taken to find the *R* and *L* of the air cored inductors used in the setup for the transmission lines. These measurements were then used to find the positions of faults made at certain points in the setup, replicating an SLG fault. The *R* and *L* measurements were taken with the help of an HP 3458A multimeter. Measurements were taken using the 4 wire (compensates load resistance) and converter on/off (compensates thermal voltages) methods. Care was taken to ensure that the measurements and calibrations were carried out at a fixed temperature.

B. Fault Location on Setup

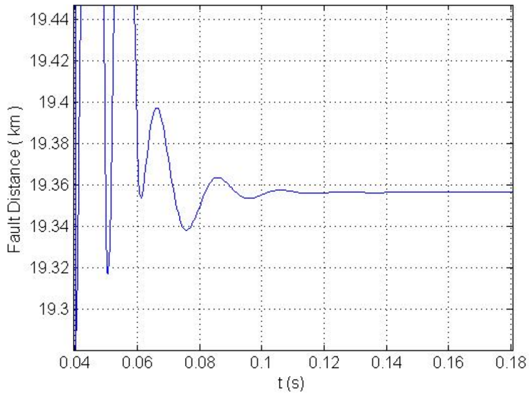
The fault location on the setup was determined on the basis of the short circuit faults made at the points A - E. Assuming a total line length of 60 km, per unit *R, L* and impedances for the elements were found, separately and collectively. Then, five measurements were performed with the fault made at the 5 interconnections between the inductors. The fault location in these five measurements were based on the total impedances up to the point representing the sending and the receiving end. Fault locations on the setup were calculated by dividing the total line length into segments and finding the respective impedances.

C. Fault Locations as per the Algorithms

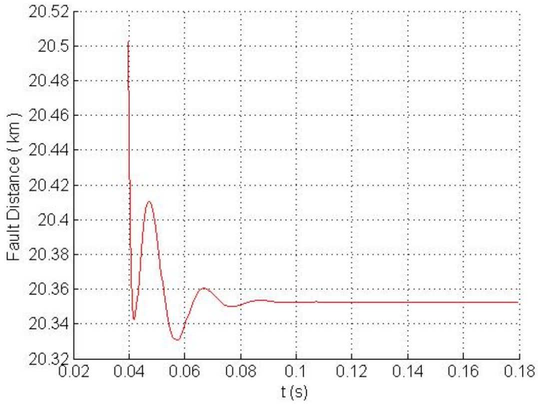
The results of the Fault Location Algorithms discussed so far and a comparison between them is given in the following Table VI. An example of the FLAs results can be seen in Fig. 9 below.

TABLE VI
FAULT LOCATION ALGORITHMS' RESULT COMPARISON

Point on setup	Calculated Fault (km)	Parameter Dependent FLA (km)	Parameter-independent FLA (km)
A	10.04	12.350	10.51
B	19.99	19.354	20.348
C	29.98	27.055	29.732
D	40.02	35.450	39.500
E	50.00	48.850	49.262



(a). Fault location by the parameter dependent algorithm.



(b). Fault location by the parameter independent algorithm.

Fig. 9. Computed fault location by the fault location algorithms for a fault simulated at point B on the setup.

V. CONCLUSION

Because of continuous exposure to atmospheric conditions, the occurrence of faults on transmission lines is a common practice. Fault location algorithms are important tools for expediting repairs after the occurrence of a fault on a transmission line.

This paper compares two fault location schemes for transmission line networks. The first algorithm uses line parameters to locate faults. The second algorithm is independent of the line parameters. Both schemes use synchronized voltage and current signals. Extensive simulations were carried out using ATPDraw and MATLAB to evaluate the performance of both algorithms under SLG faults which are the most common types of faults on transmission lines. From the errors observed in both FLAs, we see that the parameter-independent fault location algorithm gives sometimes a better accuracy over the parameter dependent algorithm. The ease of fault location detection is also complimented by its capability of being easily practiced with existing power system protection schemes.

Equations (9) and (10) are valid for shorter transmission lines where line capacitances are small. For longer transmission lines the effects of shunt capacitance should be taken into account. ATPDraw provides users with a wide range of options for using short and long transmission lines via distributed and pi modelling, taking care of the travelling wave time and time steps. Harmonics in transmission line voltage and currents are most closely associated to electric arcs which occur during faults. These tend to distort the line waveforms and might affect the sampling of the algorithm. In an untransposed line, the effects of mutual coupling between line phases are severe, making the voltage drops along them not equal. This can disturb the balance between the line ends, but it can be rectified by the use of symmetrical transformation. The analysis of long lines by taking into account fault arcing will be a matter of investigation in the future. In order to study the effect of the arc, primary and secondary arc should be included my making use of an appropriate arc model.

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