New Approach for Fault Location on Transmission Lines Not Requiring Line Parameters

Z. M. Radojević, C. H. Kim, M. Popov, G. Preston, V. Terzija

***Abstract*—This paper presents a new numerical algorithm for fault location on transmission lines. It does not require line parameters, which is a radical step forward compared to the existing approaches, which require this information, so the algorithm can be considered as a settings-free algorithm. Line parameters are only approximately constant; they differ with the loading and weather conditions. Thus, an approach which does not require them would be more robust, accurate and flexible, than those approaches that do require line parameter information to determine the location to the fault. This is essential for the fast and secure elimination of faults on transmission lines, and, consequently, the solution leading to a significant improvement of the quality of the energy supply. The new algorithm uses synchronised data sampling at both line terminals, which is a prerequisite for the successful algorithm application. The paper presents the results of the initial algorithm testing through the use of ATP-EMTP simulations.**

***Keywords*: Fault location, transmission lines, GPS synchronization, settings-free algorithm.**

I. INTRODUCTION

Reliable algorithms for the analysis of faults on overhead transmission lines have become an essential part of modern transmission line protection schemes. An integral part of such algorithms is the fault locator, which determines the distance to the fault from the local line terminal(s). Various methods of fault location have been developed in the past, some of which use data from one line terminal and some of which use data from two or more line terminals [1]-[10]. Further publications on this important subject can be found in [11]. One common factor between all of the various methods is the requirement of the line parameters and the line length to determine the fault distance. However, the parameters of lines are not always available and they can vary with differing loading and weather conditions. In [12], Liao and Elangovan proposed an algorithm for locating faults on transmission lines which does not require the parameters of the line in question. Because the algorithm assumes asynchronous data sampling, it requires the use of iterative techniques to locate line-line faults and it cannot be used to locate balanced three-phase faults. Also, it does not consider zero-sequence coupling.

In contrast, the algorithm proposed in this paper can be used to locate all fault types – including balanced three-phase faults – without recourse to supplementary techniques, and, because it uses positive and negative-sequence components, it is not susceptible to zero-sequence coupling.

The aim of this paper is to develop a new numerical algorithm that can determine the distance to the fault on a transmission line without any knowledge of the line parameters. It was assumed that the unknown fault location will be determined from voltage and current phasors, synchronously measured at both line terminals. In a number of approaches, the fault location is calculated by using information about the line parameters (e.g. resistance and inductance per unit length, which are known in advance) and the measured voltage and current phasors. Here the 'fault location calculation' is deterministic and based on a suitable formula for calculating the fault location. In reality, a number of stochastic factors generate a high level of uncertainty in determining the fault location. For example, the fault resistance, or fault arc, other non-linear effects on instrument transformers, as well as the random errors introduced during A/D conversion, can adversely affect the accuracy of fault location. This makes the problem even more challenging and requires very careful algorithm design.

The paper discusses synchronised data sampling at each line terminal and gives a detailed algorithm derivation. Furthermore, it includes a Section in which the new algorithm was tested and validated through computer simulated tests. Since the new method is based on the use of the emerging Synchronised Measurement Technology (SMT), a brief description of this is given in the next Section.

The new algorithm is developed for the most frequent fault type: the single line to ground fault. From the methodology presented in this paper, a more general solution could be also derived. The authors' intention was to propose the new approach for fault location, to test it and to assess the limitation of the new approach.

II. SYNCHRONIZED MEASUREMENT TECHNOLOGY

Synchronized Measurement Technology (SMT) is a new concept, based on the use of the Global Positioning System (GPS), synchronising different intelligent Electronic Devices

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Z. M. Radojević is with The University of Belgrade, Faculty of Electrical Engineering, Serbia, (e-mail: radojevic@ieee.org).
C. H. Kim is Director of Center for Power IT, Sungkyunkwan University, Suwon, Korea (e-mail: chkimskku@yahoo.com).
M. Popov is with the Delft University of Technology, The Netherlands, e-mail: (m.popov@tudelft.nl).
G. Preston and V. Terzija are with The University of Manchester, UK, (e-mail: g.preston@student.manchester.ac.uk, terzija@ieee.org).

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(IEDs) in a large network. The new concept includes the following main building blocks:

a) synchronized measurement units (SMUs, also commonly known as phasor measurement units - PMUs),
b) data concentrators,
c) communication network and
d) applications.

The new algorithm for the ‘settings-free fault location’, which will be presented in this paper, presents a new SMT application, where it is assumed that the other required building blocks are available and technically ready to fulfil the algorithm’s requirements. Such practical implementation issues will not be discussed in this paper. It is assumed that the SMT infrastructure is capable of fulfilling the algorithm’s requirements (e.g. reliable and fast communication links between remote line terminals).

The Global Positioning System (GPS) is a space-based positioning, navigation, and timing system, consisting of 24 satellites that constantly revolve around the earth. Since a GPS receiver provides time synchronization with an accuracy of ±1 μs, PMUs using GPS-synchronization in power systems can be successfully applied to fault location/analysis and the protection of overhead transmission lines. The GPS is used to synchronize the clocks of the measuring devices which sample voltages and currents at the line terminals. For the purpose of the new settings-free fault location algorithm it is assumed that the synchronisation is achieved at the sample/sampling level.

In Fig. 1 two Synchronized Measuring Units (SMUs) at each line terminal are presented. This would be the architecture necessary for the successful implementation of the new algorithm. In Fig. 1 two SMUs constantly acquire voltage and current samples from voltage and current instrument transformers installed at each end of the line. The voltage and current samples collected from the SMUs are forwarded to a central Data Concentrator (DC), in which the processing of simultaneously sampled voltages and currents is carried out. This processing is actually the new numerical algorithm for fault location. If faulty conditions are detected, the numerical algorithm for fault location is instantly started and within 20-40 ms the fault location is determined. How fast the unknown fault location will be determined depends on the method for extracting the voltage and current phasors. In this paper this issue will not be separately considered. Simply, the commonly used Fast Fourier Transform will be implemented for this task.

In the next paper Section, the new *settings-free numerical algorithm for fault location*, based on synchronised data acquisition from both line terminals, will be presented.

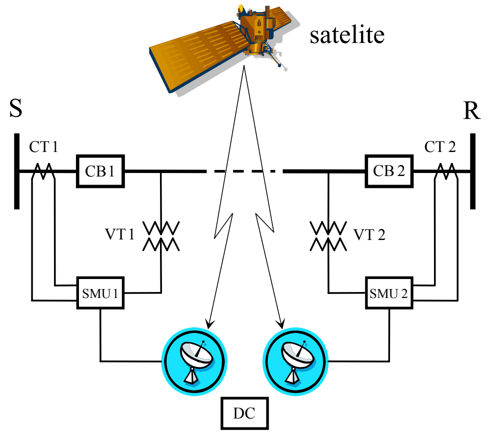

Fig. 1. Synchronized sampling arrangement (CT – current transformer, VT – voltage transformer, CB - circuit breaker, SMU – synchronised measurement unit, DC – data concentrator).

III. DERIVATION OF THE NEW FAULT LOCATION ALGORITHM

In this Section, a new, settings-free numerical algorithm for fault location will be presented. It will give solutions for single line to ground faults, which are the most common type of fault on overhead transmission lines.

Let us assume an *a*-phase single line to ground fault on a transmission line at distance ℓ from the left line terminal, as presented in Fig. 2. Assuming that the line is less than 100 km long (such lines can be considered as *short lines*), the shunt capacitance and the shunt conductance of the transmission line can be neglected. In Fig. 2 the fault location is denoted by **F**, the fault distance by ℓ, D is the line length, and subscripts S and R denote the sending- and receiving end of the line, respectively. Voltages and currents are synchronously sampled at both line terminals.

Using standard signal processing techniques, the corresponding phasors can be calculated from the voltage and current samples. In this paper the Fast Fourier Transform (FFT) was used to filter the voltage and current phasors from their samples. A traditional approach, in which voltages and currents were sampled with the sampling frequency f_s=3.2kHz (64 samples per 20ms) was used, setting the data window size, T_{dw}, to correspond to the fundamental period, T_0=20ms. As with any method, the efficiency of the new method depends upon the fast and reliable determination of the voltage and current phasors. This paper will not consider the sensitivity of the new algorithm to the quality of the phasors’ determination. It is known, that the FFT approach is sensitive to the existence of the decaying DC component in the fault current. For this challenge, a separate solution can be derived. Other solutions – such as optimal estimation theory [13] – can also be used for phasor extraction.

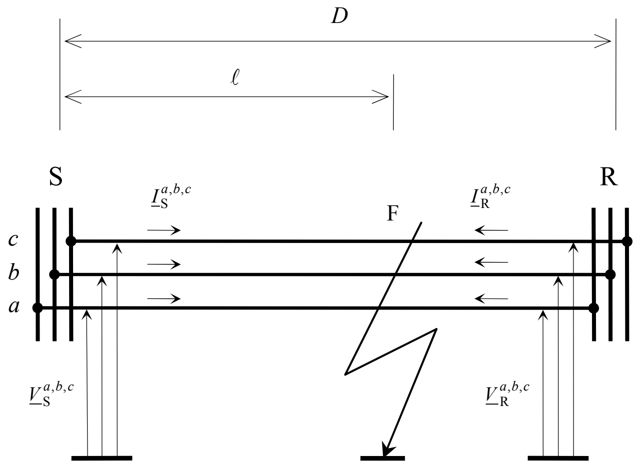

Fig. 2. Three-phase representation of the faulted line.

Based on the voltage and current phasors, by using the symmetrical components method, the positive, negative and zero sequence symmetrical components of the voltages and currents can be determined. The new method requires just the positive and negative sequence components, i.e. their equivalent circuits. So, the unsymmetrical three phase circuit from Fig. 2 (it is unsymmetrical, because the fault at the point F is a line to ground fault) can be represented by three single-phase equivalent circuits – positive (*p*), negative (*n*), and zero (*0*) sequence circuits, respectively. As stated, only the positive and negative sequence components/circuits will be used. These are presented in Figs. 3a and 3b.

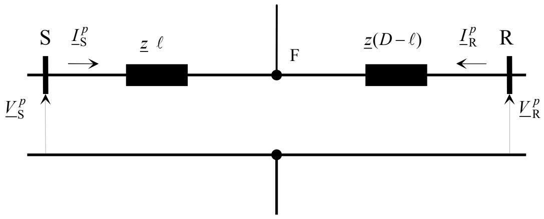

Fig. 3a. Equivalent positive sequence circuit of the faulted line from Fig. 2.

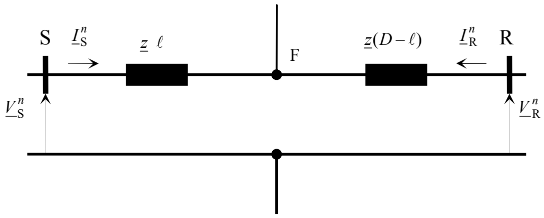

Fig. 3b. Equivalent negative sequence circuit of the faulted line from Fig. 2.

In both of the equivalent circuits in Figs. 3a and 3b, the line positive and negative impedances are equal. For the circuits depicted in Figs. 3a and 3b the following equations hold:

$$\underline{V}_{\mathrm{S}}^{p} - \underline{z}\ell\underline{I}_{\mathrm{S}}^{p} = \underline{V}_{\mathrm{R}}^{p} - \underline{z}(D-\ell)\underline{I}_{\mathrm{R}}^{p} \tag{1}$$

$$\underline{V}_{\mathrm{S}}^{n} - \underline{z}\ell\underline{I}_{\mathrm{S}}^{n} = \underline{V}_{\mathrm{R}}^{n} - \underline{z}(D-\ell)\underline{I}_{\mathrm{R}}^{n} \tag{2}$$

where:

$\underline{V}_{\mathrm{S}}^{p,n}$, $\underline{V}_{\mathrm{R}}^{p,n}$ are the positive- and negative sequence phase voltages at both line terminals;

$\underline{I}_{\mathrm{S}}^{p,n}$, $\underline{I}_{\mathrm{R}}^{p,n}$ are the positive- and negative sequence phase currents at both line terminals;

$\underline{z}$ are positive- or negative sequence line impedance, which are equal.

It is obvious, that in equations (1) and (2) just two terms ($\underline{z}\ell$ and $\underline{z}(D-\ell)$) are unknown. They can easily be determined by solving equations (1) and (2). The two solutions are given in following two formulas:

$$\underline{z}\ell = \frac{(\underline{V}_{\mathrm{S}}^{p} - \underline{V}_{\mathrm{R}}^{p})\underline{I}_{\mathrm{R}}^{n} - (\underline{V}_{\mathrm{S}}^{n} - \underline{V}_{\mathrm{R}}^{n})\underline{I}_{\mathrm{R}}^{p}}{\underline{I}_{\mathrm{S}}^{p}\underline{I}_{\mathrm{R}}^{n} - \underline{I}_{\mathrm{S}}^{n}\underline{I}_{\mathrm{R}}^{p}} \tag{3}$$

$$\underline{z}(D-\ell) = \frac{(\underline{V}_{\mathrm{S}}^{p} - \underline{V}_{\mathrm{R}}^{p})\underline{I}_{\mathrm{S}}^{n} - (\underline{V}_{\mathrm{S}}^{n} - \underline{V}_{\mathrm{R}}^{n})\underline{I}_{\mathrm{S}}^{p}}{\underline{I}_{\mathrm{S}}^{p}\underline{I}_{\mathrm{R}}^{n} - \underline{I}_{\mathrm{S}}^{n}\underline{I}_{\mathrm{R}}^{p}} \tag{4}$$

Conventional fault location methods based on one or two terminal data, would be solved using the above equations and information about the line parameters R (Ω/km) and X (Ω/km). As discussed above, a more flexible solution can be achieved if the fault location algorithm is independent of line parameters. This was achieved and demonstrated in the following text.

Let us express the distance to the fault, ℓ, as a percentage of the line length, D, through the following formula:

$$\ell\% = \frac{\ell}{D}100 \tag{5}$$

The above formula can be presented in the following form:

$$\ell\% = \frac{\underline{z}\ell}{\underline{z}\ell + \underline{z}(D-\ell)}100 \tag{6}$$

After including the expressions for $\underline{z}\ell$ and $\underline{z}(D-\ell)$ in equation (6), the following formula for the distance to the fault can be obtained:

$$\ell\% = 100\frac{(\underline{V}_{\mathrm{S}}^{p} - \underline{V}_{\mathrm{R}}^{p})\underline{I}_{\mathrm{R}}^{n} - (\underline{V}_{\mathrm{S}}^{n} - \underline{V}_{\mathrm{R}}^{n})\underline{I}_{\mathrm{R}}^{p}}{(\underline{V}_{\mathrm{S}}^{p} - \underline{V}_{\mathrm{R}}^{p})(\underline{I}_{\mathrm{S}}^{n} + \underline{I}_{\mathrm{R}}^{n}) - (\underline{V}_{\mathrm{S}}^{n} - \underline{V}_{\mathrm{R}}^{n})(\underline{I}_{\mathrm{S}}^{p} + \underline{I}_{\mathrm{R}}^{p})} \tag{7}$$

where n and p denote negative and positive sequence variables, and S and R denote the sending- and receiving end variables. *Obviously, the algorithm does not require the line parameters or information about the line length.* It is just based on the processing of synchronously recorded voltage and current samples, determining their 50 Hz phasors, and calculation of the positive and negative sequence voltage and current components. Equation (7) provides the explicit expression for fault location in the case of single line to ground faults on overhead transmission lines.

The new settings-free numerical algorithm was thoroughly tested using a number of computer simulated cases, as presented in the next paper Section.

IV. COMPUTER SIMULATED TESTS

The algorithm testing was carried out through dynamic simulation analysis using the ATP-EMTP software [14]. In Fig. 4, the schematic diagram of a 400 kV, 100 km long, overhead transmission line is presented. In Tables I and II, the parameters of active networks A and B and the line parameters are listed, respectively.

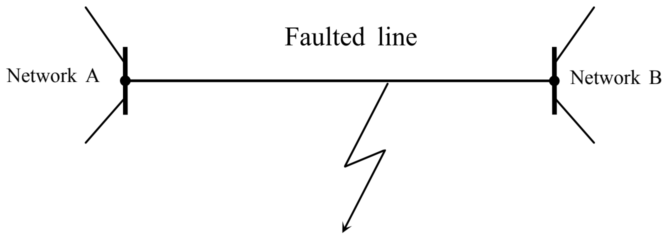

Fig. 4. Single line diagram of the simulated faulted line.

TABLE I
PARAMETERS OF NETWORKS A AND B.

Parameters	Networks	
	A	**B**
$U_{LL,RMS}$ [kV]	416	400
φ_1 [^{0}]	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.

Parameter	p- and n-sequence	0-sequence
resistance, Ω/km	0.065	0.195
inductance mH/km	0.95493	2.86479

Single line-to-ground bolted (metallic) faults were simulated at different locations along the line. In each case the fault inception time was set at t = 23 ms. It was assumed that the line was loaded before the fault inception. The sampling frequency was $f_s = 3.2$ kHz. The data window size was $T_{dw} = 20$ ms (N = 64 samples per data window). It is assumed that all phasors are perfectly synchronized (the synchronization error is equal to 0 degrees).

Figs. 5-8 show the simulated faulted phase voltages and currents at both line terminals, which were used as an input to the new algorithm. It is obvious that all curves correspond to the single line to ground fault. The fault was simulated at the 35*th* km, observed from the left line terminal (terminal S).

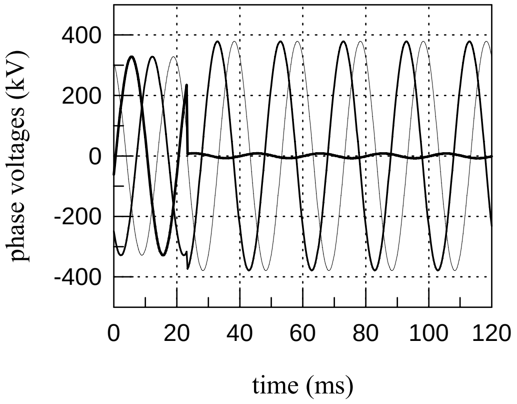

Fig. 5. Faulted phase voltages at the line sending end (S).

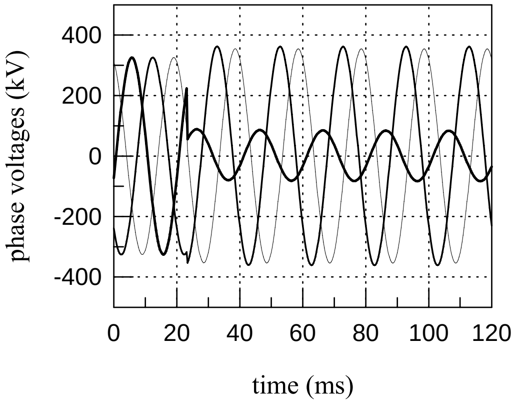

Fig. 6. Faulted phase voltages at the line receiving end (R).

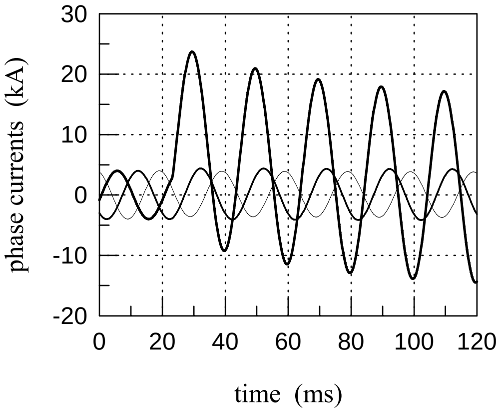

Fig. 7. Faulted phase currents at the line sending end (S).

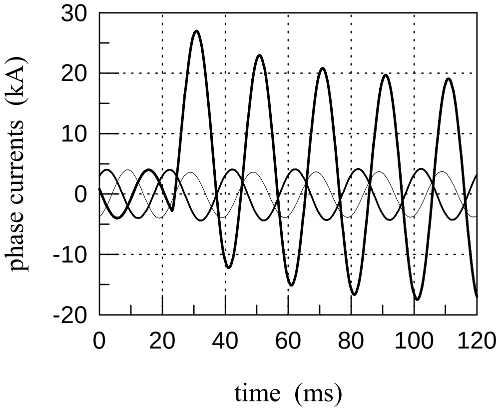

Fig. 8. Faulted phase currents at the line receiving end (R).

Based on the voltages and currents shown in Figs. 5-8, the unknown fault location was calculated using equation (7), as presented in Fig. 9.

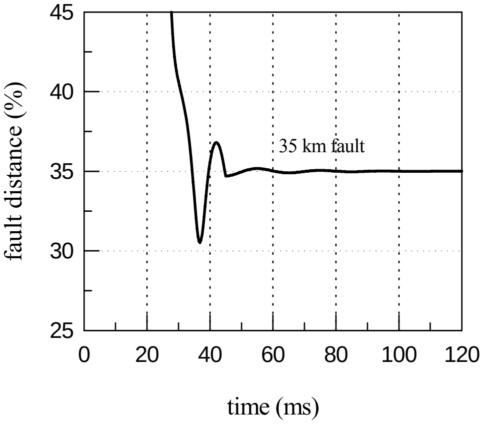

Fig. 9. Estimated fault location (the exact value used by EMTP was 35 km).

From Fig. 9 it is obvious that accurate values were obtained after a short convergence process. The algorithm convergence properties are determined by the quality of the method for phasors extraction. As mentioned above, the FFT algorithm was used for this purpose, and it is known to be sensitive to the decaying DC component existing in the fault current(s). In this paper, methods of improving the quality of extraction of voltage and current phasors are not considered. In [13] some alternative solutions for this problem, which are not sensitive even to changes of the system frequency, are proposed. It is obvious that accurate values are obtained.

In order to further demonstrate the algorithm efficiency, faults were simulated over a range of distances. The results (in %) for the different fault locations are presented in Fig. 10. Since the line length was 100km, based on the results obtained, it can be concluded, that the accurate results were obtained for the full range of fault locations.

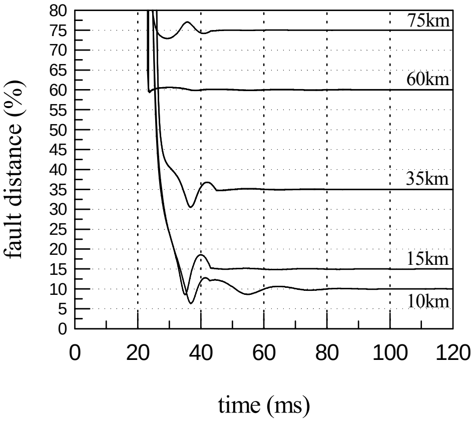

Fig. 10. Calculated fault locations (in %) for different fault locations.

In the next test example, the algorithm sensitivity to the fault resistance and fault arc was investigated. An arcing fault over fault resistance (R_F=10Ω) at 60km was simulated. The length of the arc was around 3 m. The fault arc was simulated as a current and arc length dependent voltage source [15]. In Fig. 11 the sending line terminal voltages for this case are presented. From the waveform of the faulted phase voltage, it can be noted that it is slightly distorted, a typical consequence of the fault arcs. The equivalent distortions are obvious in the faulted phase voltage signal from the receiving line end, as well. In spite of such fault conditions, the algorithm delivered the correct result (see Fig. 12, in which the calculated fault distance, 60km, is presented), proving that it is not sensitive to fault and arc resistances.

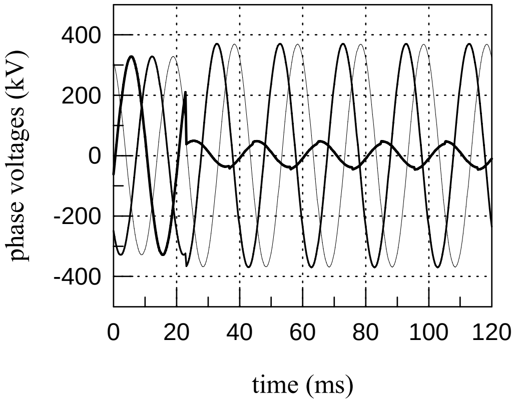

Fig. 11. Faulted phase voltages at the line sending end (S)

As stated above, the algorithm presented requires ideal synchronization, which might be a challenge in real-time applications. Based on the computer simulation testing, it was concluded that an inaccurate synchronization introduces errors in the application. For example, for a synchronization error of t = 1ms, the error in fault distance is round 3%. The authors are currently deriving new solutions, which will not be sensitive to synchronization errors.

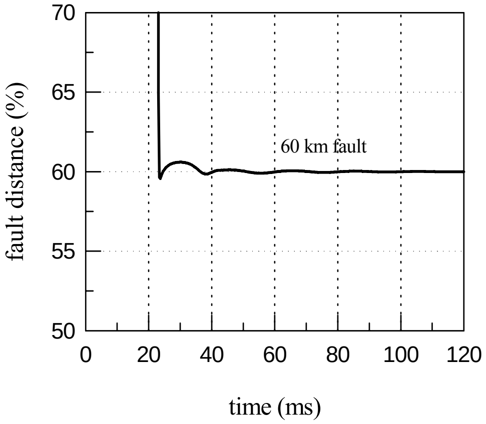

Fig. 12. Estimated fault location (60 km arcing fault over fault resistance).

V. CONCLUSION

In this paper a new efficient settings-free numerical algorithm for fault location on overhead transmission lines is presented. The algorithm is based on synchronized measured voltages and currents, sampled at both line terminals, and the use of fast communication channels between two synchronized measurement units (SMUs) installed at the line terminals. It does not require line parameters to determine the fault location. In the paper, the solution for the most common fault type, the single line to ground fault, is presented and thoroughly tested. The algorithm is derived in the spectral domain and based on the processing of voltage and current phasors. For this purpose it applies the Fast Fourier Transform approach. Through algorithm testing it was proved that the algorithm efficiently and accurately determines fault locations and that is unaffected by fault and arc resistances. The authors are currently deriving a solution that does not require synchronized sampling.

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