ACCURATE LOCATION OF FAULTS IN PARRALLEL TRANSMISSION LINES UNDER AVAILIBILITY OF MEASUREMENTS FROM ONE CIRCUIT ONLY

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Abstract – This paper presents new one-end fault location algorithm for parallel transmission lines. Its distinctive feature relies in efficient adaptation to the case of complete lack of measurements from the healthy parallel line circuit. The unavailable zero sequence current from the healthy line is estimated and used for compensating the mutual coupling effect under phase-to-ground faults. The final formula for the sought distance to fault is of simpler form than in the earlier algorithms and requires less input data. The algorithm has been developed for the healthy line being operating as well as when it is switched off and earthed. Example of fault location with the developed fault location algorithm is presented. Results of ATP-EMTP testing and evaluation of fault location accuracy are reported.

Keywords: parallel transmission lines, mutual coupling, one-end fault location, limited measurements, adaptation

1 INTRODUCTION

This paper deals with one-end location of transmission line faults for inspection-repair purposes [1-9]. Accurate location of faults allows reducing the time required for repairing the damage caused by the fault and consequently improving reliability and continuity of energy supply. Different methods of fault location have been developed so far. In first approaches, i.e. in one-end fault location algorithms [4-9] the measurements acquired at only one side of the line have been utilised. Application of modern communication means allowed using much superior two-end techniques. However, due to technical and economical limitations the one-end algorithms are still used in many applications and are a subject of great interest.

The standard practice for one-end fault location algorithm [4] designed for application to parallel transmission lines relies on using the following input signals: – phase voltages of the faulted line, – phase currents from the faulted line, – zero sequence current from the healthy line. Providing the zero sequence current from the healthy line circuit enables to compensate for the mutual coupling between parallel lines, what is required for single phase-to-ground faults. The standard fault location algorithms with the input signals as listed above require knowing impedance data for equivalent sources behind the line terminals and using pre-fault measurements of currents from the faulted line. Certain improvements of the standard location algorithms have been presented in [7]. However, such modifications require increasing the number of the fault locator input signals, namely, instead of the zero sequence current from the healthy line the complete phase currents from this line have to be supplied to the locator. Such the possibility is available in some applications.

Yet another modification of the standard fault location algorithms has been presented in [8-9], where adaptation to the case of complete lack of measurements from the healthy line circuit has been introduced. This paper continues those efforts with the aim of achieving simpler form of the algorithm and use of less input data. Moreover, apart of considering the parallel line being in operation the case with this line switched off and earthed at both the ends is considered here.

Results of ATP-EMTP [10] testing and evaluation of accuracy of the developed fault location algorithm are reported. They illustrate effectiveness of the proposed algorithm.

2 FAULT LOCATION ALGORITHM

2.1 Basics

Fig. 1 presents configuration of the considered parallel transmission network. Parallel lines ($\underline{Z}_{LA}, \underline{Z}_{LB}$) are mutually coupled ($\underline{Z}_{0m}$ - mutual coupling impedance for the zero sequence). Systems behind the terminals of the lines are represented with the equivalents containing EMFs ($\underline{E}_{sA}$, $\underline{E}_{sB}$) and impedances ($\underline{Z}_{sA}$, $\underline{Z}_{sB}$).

The fault locator (FL) is considered as supplied with the following signals from the faulted circuit (line *LA*):

– post-fault phase voltages ($\underline{V}_{AA}$),
– post-fault and pre-fault phase currents ($\underline{I}_{AA}$).

Thus, the zero sequence current of the adjacent parallel line circuit (line *LB*) has to be estimated. For deriving the algorithm the flows of currents for particular sequences (Fig. 2) are considered. Moreover, the relations between the respective sequence components, relevant for the particular fault type, are utilised.

To develop the location algorithm conveniently, the shunt capacitances of the lines are not considered at this stage, however, they can be incorporated further.

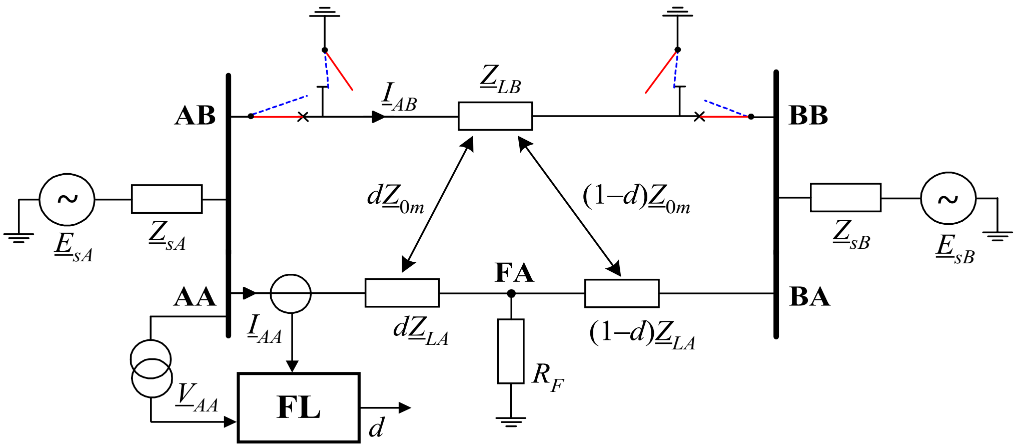

Figure 1: Arrangement of the studied transmission network with parallel lines.

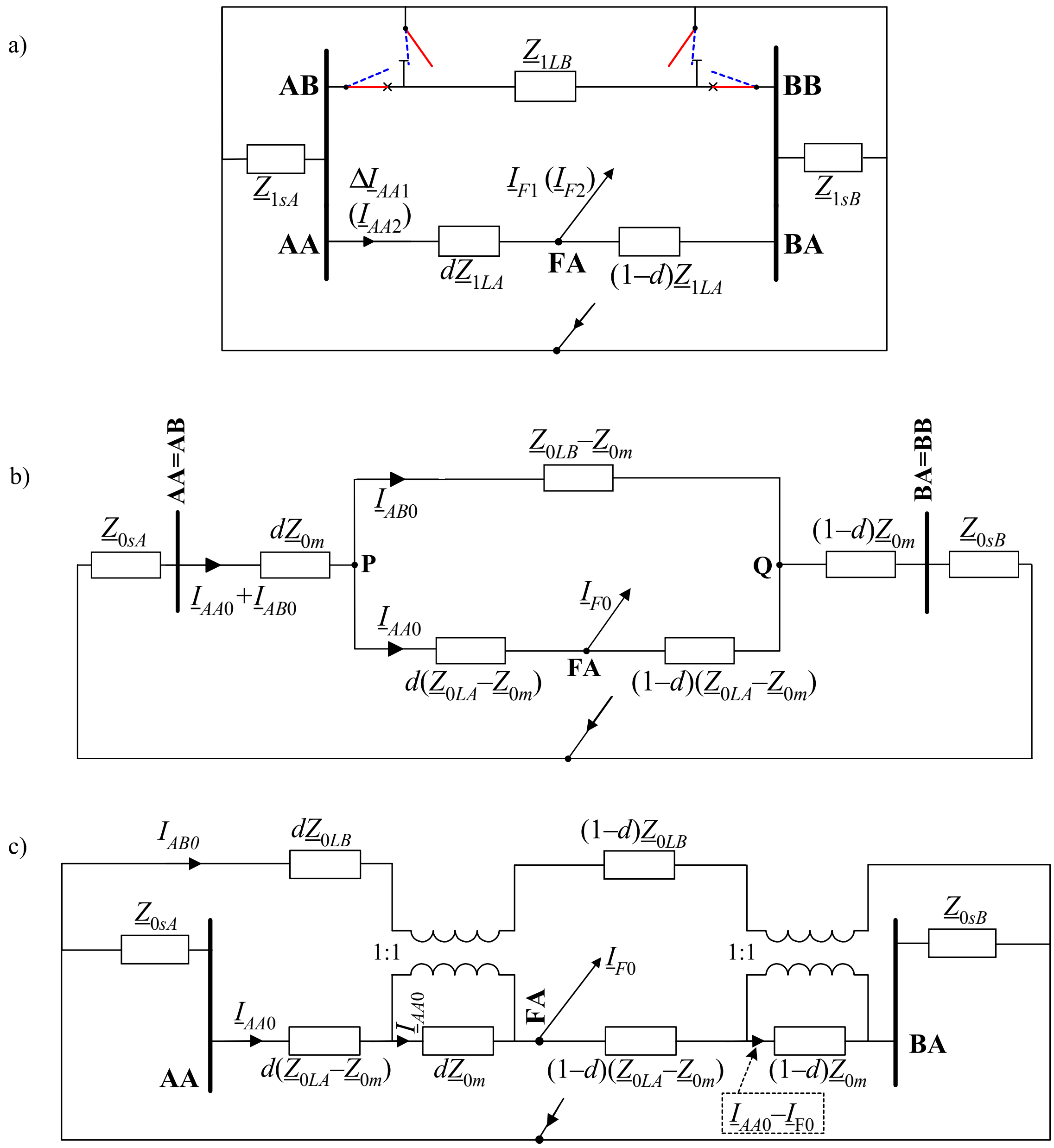

Figure 2: Equivalent circuit diagrams for: a) incremental positive or negative sequence, b) zero sequence under both lines in operation, c) zero sequence under the parallel line being switched off and earthed – for considering the healthy line path.

2.2 Derivation of the fault location algorithm

The algorithm estimates distance to fault (d) by considering the Kirchhoff's voltage law for the fault loop as seen from the locator installation point:

$$\underline{V}_{AA\_p} - d\underline{Z}_{1LA}\underline{I}_{AA\_p} + - R_F\left(\frac{\underline{a}_{F1}\Delta\underline{I}_{AA1}}{\underline{k}_{F1}} + \frac{\underline{a}_{F2}\underline{I}_{AA2}}{\underline{k}_{F2}} + \frac{\underline{a}_{F0}\underline{I}_{AA0}}{\underline{k}_{F0}}\right) = 0 \quad (1)$$

Fault loop voltage ($\underline{V}_{AA\_p}$) and current ($\underline{I}_{AA\_p}$) can be expressed in terms of the symmetrical quantities:

$$\underline{V}_{AA\_p} = \underline{a}_1\underline{V}_{AA1} + \underline{a}_2\underline{V}_{AA2} + \underline{a}_0\underline{V}_{AA0} \quad (2)$$

$$\underline{I}_{AA\_p} = \underline{I}^{SL}_{AA\_p} + \frac{\underline{Z}_{0m}}{\underline{Z}_{1LA}}\underline{I}_{AB0} \quad (3)$$

where:

$\underline{I}^{SL}_{AA\_p} = \underline{a}_1\underline{I}_{AA1} + \underline{a}_2\underline{I}_{AA2} + \underline{a}_0\frac{\underline{Z}_{0LA}}{\underline{Z}_{1LA}}\underline{I}_{AA0}$ – fault loop current without compensating for the mutual coupling effect (as for the single line),

$\underline{a}_1$, $\underline{a}_2$, $\underline{a}_0$ – complex coefficients gathered in Table 1,

$\underline{V}_{AA1}$, $\underline{V}_{AA2}$, $\underline{V}_{AA0}$ – positive, negative and zero sequence of measured voltages,

$\underline{I}_{AA1}$, $\underline{I}_{AA2}$, $\underline{I}_{AA0}$ – positive, negative and zero sequence current from the line LA,

$\underline{I}_{AB0}$ – unavailable zero sequence current from the healthy parallel line LB,

$\underline{Z}_{1LA}$, $\underline{Z}_{0LA}$ – positive and zero sequence impedance of the whole line LA,

$\underline{Z}_{0m}$ – zero sequence impedance for mutual coupling between the lines LA and LB,

R_F – unknown fault resistance.

FAULT	$\underline{a}_1$	$\underline{a}_2$	$\underline{a}_0$
a-g	1	1	1
b-g	$\underline{a}^2$	$\underline{a}$	1
c-g	$\underline{a}$	$\underline{a}^2$	1
	$\underline{a} = \exp(j2\pi/3)$		

Table 1: Coefficients for composing fault loop signals.

The weighting coefficients ($\underline{a}_{F1}$, $\underline{a}_{F2}$, $\underline{a}_{F0}$), used for determining the voltage drop at fault, can be calculated from the boundary conditions relevant for the considered particular fault type. Processing the boundary conditions one determines the weighting coefficients required in (1). However, there is some freedom for that. Therefore, it has been proposed to utilise firstly this freedom for avoiding zero sequence quantities. This is well known fact that the zero sequence impedance of the line is considered as unreliable parameter. This is so due to dependence of this impedance upon the resistivity of the soil, which is changeable and influenced by weather conditions.

Moreover, as a result of influence of overhead ground wires the zero sequence impedance is not constant along the line length. Thus, it is highly desirable to avoid completely of using the zero sequence quantities when determining the voltage drop across the fault path. This can be accomplished by setting $\underline{a}_{F0} = 0$ – see Table 2.

SET	FAULT	$\underline{a}_{F1}$	$\underline{a}_{F2}$	$\underline{a}_{F0}$
1st	*a-g*	0	3	0
	b-g	0	$3\underline{a}$	0
	c-g	0	$3\underline{a}^2$	0
2nd	*a-g*	3	0	0
	b-g	$3\underline{a}^2$	0	0
	c-g	$3\underline{a}$	0	0
3rd	*a-g*	1.5	1.5	0
	b-g	$1.5\underline{a}^2$	$1.5\underline{a}$	0
	c-g	$1.5\underline{a}$	$1.5\underline{a}^2$	0
		$\underline{a} = \exp(j2\pi/3)$		

Table 2: Weighting coefficients for determining the voltage drop across a fault path.

The sets from Table 2 provide flexibility in using particular quantities. The negative sequence currents alone (the 1st set), the incremental positive currents alone (the 2nd set) or both types of the quantities together (the 3rd set) can be applied for determining the voltage drop across a fault path.

Fault current distribution factors ($\underline{k}_{F1}, \underline{k}_{F2}, \underline{k}_{F0}$) are utilised in (1) for determining the voltage drop across a fault resistance. Since it is adjusted $\underline{a}_{F0} = 0$ (as in Table 2) the positive and negative sequence distribution factors are of our interest only:

$$\underline{k}_{F1} = \frac{\Delta\underline{I}_{AA1}}{\underline{I}_{F1}} \quad (4)$$

$$\underline{k}_{F2} = \frac{\underline{I}_{AA2}}{\underline{I}_{F2}} \quad (5)$$

Impedances for the positive and negative sequences are basically identical and thus fault current distribution factors for these sequences are also identical. Considering the flow of currents in the equivalent circuit of Fig. 2a yields:

$$\underline{k}_{F1} = \underline{k}_{F2} = \frac{\underline{K}_1 d + \underline{L}_1}{\underline{M}_1} \quad (6)$$

If the parallel line (LB) is in operation then:

$$\underline{K}_1 = -\underline{Z}_{1LA}(\underline{Z}_{1sA} + \underline{Z}_{1sB} + \underline{Z}_{1LB})$$
$$\underline{L}_1 = -\underline{K}_1 + \underline{Z}_{1LB}\underline{Z}_{1sB} \quad (7)$$
$$\underline{M}_1 = \underline{Z}_{1LA}\underline{Z}_{1LB} + \underline{Z}_{1LA}(\underline{Z}_{1sA} + \underline{Z}_{1sB}) + \underline{Z}_{1LB}(\underline{Z}_{1sA} + \underline{Z}_{1sB})$$

Subscript "1" in impedances denotes positive sequence.

For the case with the parallel line (LB) switched off and earthed one obtains the following set:

$$\underline{K}_1 = -\underline{Z}_{1LA}$$
$$\underline{L}_1 = \underline{Z}_{1LA} + \underline{Z}_{1sB} \quad (8)$$
$$\underline{M}_1 = \underline{Z}_{1sA} + \underline{Z}_{1sB} + \underline{Z}_{1LB}$$

Since the zero sequence current from the healthy line ($\underline{I}_{AB0}$) is considered here as unavailable it has to be estimated.

In case when the parallel line (*LB*) is in operation the equivalent circuit diagram for the zero sequence is as depicted in Fig. 2b. In [8-9] the flow of currents has been considered for the whole circuit of Fig. 2b. However, for the purpose of the presented method the flow of currents only in the closed mesh between points: (P, Q, FA, P) has been considered. It will be shown that this provides simpler form of the fault location algorithm than the earlier algorithms [8-9].

For the case with the parallel line (*LB*) switched off and earthed one obtains the simpler algorithm if the path of the healthy line (thus with excluding impedances of the equivalent sources) is considered.

Proceeding in such the way one obtains for both the cases (healthy line is in operation and it is switched off and earthed) very compact formula for the zero sequence component of the total fault current:

$$\underline{I}_{F0} = \frac{\underline{I}_{AA0} - \underline{P}_0 \underline{I}_{AB0}}{1-d} \quad (9)$$

where:

– <u>line *LB* operating:</u> $\underline{P}_0 = \frac{\underline{Z}_{0LB} - \underline{Z}_{0m}}{\underline{Z}_{0LA} - \underline{Z}_{0m}}$ (10)

– <u>line *LB* switched off and earthed:</u> $\underline{P}_0 = -\frac{\underline{Z}_{0LB}}{\underline{Z}_{0m}}$ (11)

In order to estimate the unknown quantity (zero sequence current from the healthy line circuit: $\underline{I}_{AB0}$) it is proposed to utilise information contained in the fault type [9]. For the considered here single phase-to-ground faults one has the following relation between the zero sequence current at fault and the sequence currents:

$$\underline{I}_{F0} = \underline{b}_{F1} \frac{\Delta \underline{I}_{AA1}}{\underline{k}_{F1}} + \underline{b}_{F2} \frac{\underline{I}_{AA2}}{\underline{k}_{F2}} \quad (12)$$

where:

$\Delta\underline{I}_{AA1}$, $\underline{I}_{AA2}$ – incremental positive and negative sequence currents at the fault locator installation point,

$\underline{k}_{F1}$, $\underline{k}_{F2}$ – fault current distribution factors for the respective sequence quantities,

$\underline{b}_{F1}, \underline{b}_{F2}$ – weighting coefficients dependent on the fault type as gathered in Table 3.

Comparing (9) with (12) and taking into account (6) one obtains the following formula for estimation of the unavailable zero sequence current from the healthy line circuit:

$$\underline{I}_{AB0} = \frac{1}{\underline{P}_0}\left(\underline{I}_{AA0} - \frac{(1-d)\underline{Q}_0}{\underline{K}_1 d + \underline{L}_1}\right) \quad (13)$$

where:

$$\underline{Q}_0 = \underline{M}_1\left(\underline{b}_{F1}\Delta\underline{I}_{AA1} + \underline{b}_{F2}\underline{I}_{AA2}\right)$$

FAULT	$\underline{I}_{F0} = \underline{b}_{F1}\underline{I}_{F1} + \underline{b}_{F2}\underline{I}_{F2}$					
	I set		II set		III set	
	$\underline{b}_{F1}$	$\underline{b}_{F2}$	$\underline{b}_{F1}$	$\underline{b}_{F2}$	$\underline{b}_{F1}$	$\underline{b}_{F2}$
a-g	0	1	1	0	0.5	0.5
b-g	0	$\underline{a}^2$	$\underline{a}$	0	$0.5\underline{a}$	$0.5\underline{a}^2$
c-g	0	$\underline{a}$	$\underline{a}^2$	0	$0.5\underline{a}^2$	$0.5\underline{a}$
	$\underline{a} = \exp(j2\pi/3)$					

Table 3: Weighting coefficients in the formulae (12)-(13).

Substituting (13) into the formula for the fault loop current (3) and then into the fault loop model (1) one obtains the following quadratic complex formula:

$$\underline{A}_2 d^2 + \underline{A}_1 d + \underline{A}_0 + \underline{A}_{00} R_F = 0 \quad (14)$$

where:

$$\underline{A}_2 = -\underline{Z}_{1LA}\underline{K}_1\underline{I}^{SL}_{AA\_p} - \frac{\underline{Z}_{0m}}{\underline{P}_0}\underline{K}_1\underline{I}_{AA0} - \frac{\underline{Z}_{0m}}{\underline{P}_0}\underline{Q}_0$$

$$\underline{A}_1 = \underline{K}_1\underline{V}_{AA\_p} - \underline{Z}_{1LA}\underline{L}_1\underline{I}^{SL}_{AA\_p} - \frac{\underline{Z}_{0m}}{\underline{P}_0}\underline{L}_1\underline{I}_{AA0}$$

$$\underline{A}_0 = \underline{L}_1\underline{V}_{AA\_p}$$

$$\underline{A}_{00} = -\underline{M}_1\left(\underline{a}_{F1}\Delta\underline{I}_{AA1} + \underline{a}_{F2}\underline{I}_{AA2}\right)$$

$$\underline{Q}_0 = \underline{M}_1\left(\underline{b}_{F1}\Delta\underline{I}_{AA1} + \underline{b}_{F2}\underline{I}_{AA2}\right)$$

– <u>line *LB* is in operation:</u>

$\underline{P}_0$ – as in (10)

$\underline{K}_1$, $\underline{L}_1$, $\underline{M}_1$ – as in (7)

– <u>line *LB* is switched off and earthed:</u>

$\underline{P}_0$ – as in (11)

$\underline{K}_1$, $\underline{L}_1$, $\underline{M}_1$ – as in (8)

The complex coefficients from (14) are duly expressed with the measured symmetrical components of currents / voltages and the coefficients dependent on the fault type (Tables 1–3).

Resolving (14) into the real and imaginary parts one obtains two equations, which after eliminating a fault resistance lead to the final formula:

$$B_2 d^2 + B_1 d + B_0 = 0 \quad (15)$$

where:

$$B_2 = \text{real}(\underline{A}_2)\,\text{imag}(\underline{A}_{00}) - \text{real}(\underline{A}_{00})\,\text{imag}(\underline{A}_2)$$

$$B_1 = \text{real}(\underline{A}_1)\,\text{imag}(\underline{A}_{00}) - \text{real}(\underline{A}_{00})\,\text{imag}(\underline{A}_1)$$

$$B_0 = \text{real}(\underline{A}_0)\,\text{imag}(\underline{A}_{00}) - \text{real}(\underline{A}_{00})\,\text{imag}(\underline{A}_0)$$

The obtained quadratic formula is much simpler than for the earlier algorithms [8-9], where forth order formula was derived. Moreover, the developed fault location algorithm (15) requires less input data since the zero sequence impedance of the remote source impedance $\underline{Z}_{0sB}$, used in the algorithms from [8-9], is not needed here. Thus, uncertainty with respect to the impedance $\underline{Z}_{0sB}$, which is not measurable by the locator installed at the local end, has no influence on fault location accuracy.

3 TESTING AND EVALUATION

To illustrate the actual benefits of the proposed algorithm the ATP-EMTP software package [10] has been used to simulate faults in the considered transmission network (Fig. 1). Parallel transmission lines of 400 kV and 120 km or 300 km length have been taken into account. Variety of fault cases has been simulated for generating fault data used for reliable evaluation of the developed fault location algorithm. The results are shown in Fig. 3–5.

Data for the parallel lines (impedances and capacitances) and impedances of the equivalent systems:

$\underline{Z}_{1LA} = \underline{Z}_{1LB} = (0.0275 + 0.31513\,\mathrm{j})\ \Omega/\mathrm{km}$

$\underline{Z}_{0LA} = \underline{Z}_{0LB} = (0.275 + 1.0265\,\mathrm{j})\ \Omega/\mathrm{km}$

$\underline{Z}_{0m} = (0.2 + 0.6283\,\mathrm{j})\ \Omega/\mathrm{km}$

$C_{1LA} = C_{1LB} = 13.0\ \mathrm{nF/km}$

$C_{0LA} = C_{0LB} = 8.5\ \mathrm{nF/km}$

$C_{0m} = 5.0\ \mathrm{nF/km}$

$\underline{Z}_{1sA} = (1.312 + 15\,\mathrm{j})\ \Omega$

$\underline{Z}_{0sA} = (2.334 + 26.6\,\mathrm{j})\ \Omega$

$\underline{Z}_{1sB} = 2\underline{Z}_{1sA},\ \underline{Z}_{0sB} = 2\underline{Z}_{0sA}$

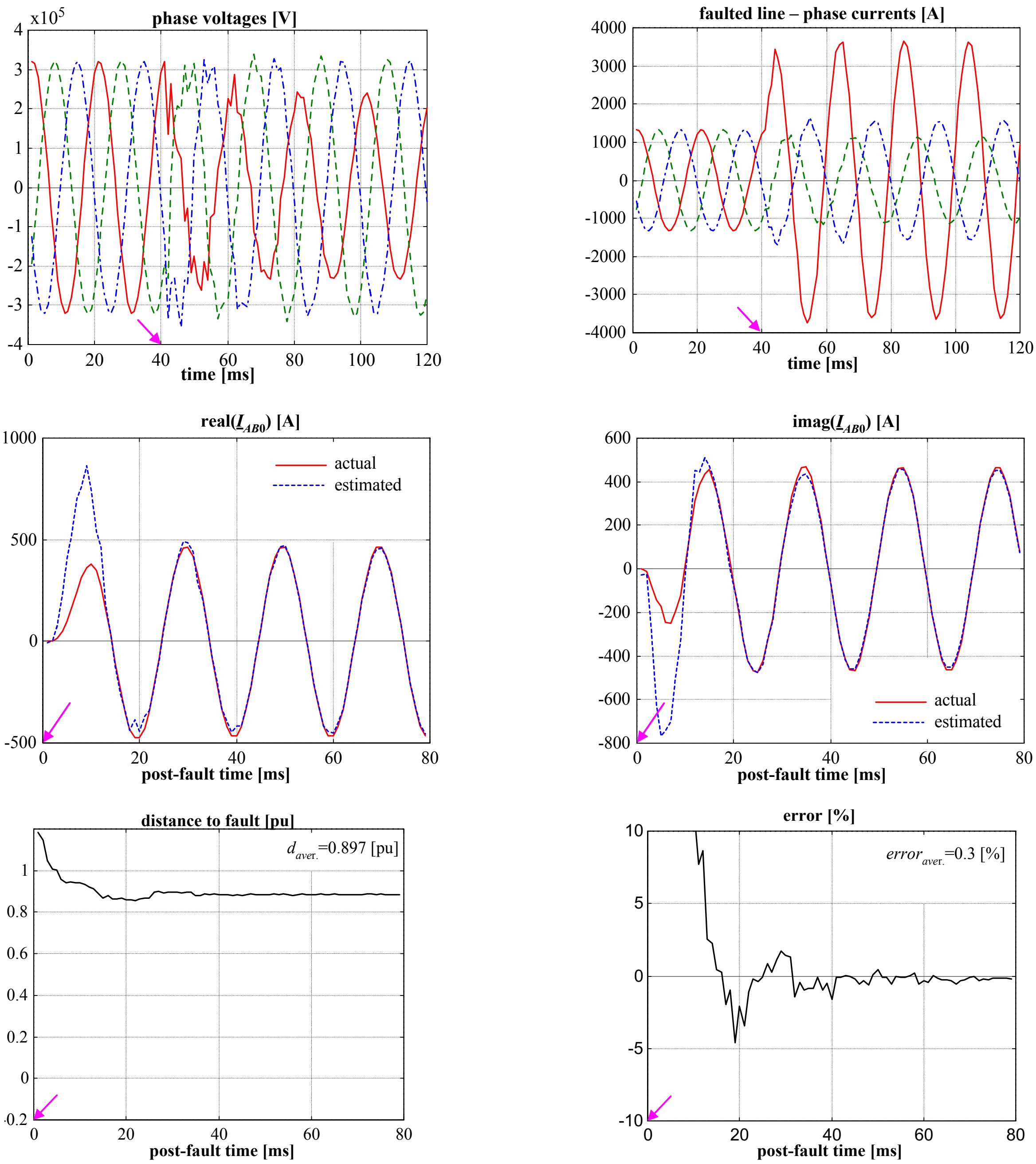

Figure 3: Example of fault location for the sample fault in 120 km transmission line – single phase-to-ground fault, fault distance: 0.9 pu, fault resistance: 10 Ω, parallel line is in operation.

Fig. 3 presents the sample results for the parallel lines of 120 km length, both in operation. The specifications of the fault are as follows: *a–g* fault, fault resistance 10 Ω, distance to fault 0.9 pu. Input signals of the fault locator have been pre-processed with full cycle Fourier filters.

The estimated zero sequence current from the healthy parallel line (its real and imaginary parts) is shown together with the actual current. The difference between these currents is high only during first cycle after fault inception. In contrast, after completing the data window of the filters (within 20 ms) the difference between the estimated and the actual currents is very small.

In order to single the results for the estimated distance to fault as well as for the estimation error the averaging within the interval 30–50 ms after fault inception has been applied. For the fault from Fig. 3 the distance to fault is estimated with the error of 0.3%.

Fig. 4 shows the errors in estimation of the distance to fault for the parallel lines of 120 km length under single phase-to-ground faults applied at different locations (0.1, 0.2,...,0.9 pu) with fault resistance of 10 Ω. The errors in case of no compensation for mutual coupling between the lines are high, what is very well known. For far end faults the error for such location exceeds 10%. In contrast, using the developed fault location algorithm the errors are quite low, especially for the case with the parallel line being in operation – the error does not exceed 0.3%. If the parallel line is switched off and earthed at both ends the errors are slightly higher, but still acceptable.

Fig. 5 shows the errors in estimation of the distance to fault for the parallel lines of 300 km length. Again, application of the developed fault location algorithm provides reasonable accuracy, especially for the case when both the lines are in operation. The errors in this case (Fig. 5) are higher than for the shorter parallel line (Fig. 4). This is so since shunt capacitances for longer line have stronger influence on fault location accuracy. Changing the algorithm to consider the shunt capacitances of parallel lines can effect in higher accuracy of fault location.

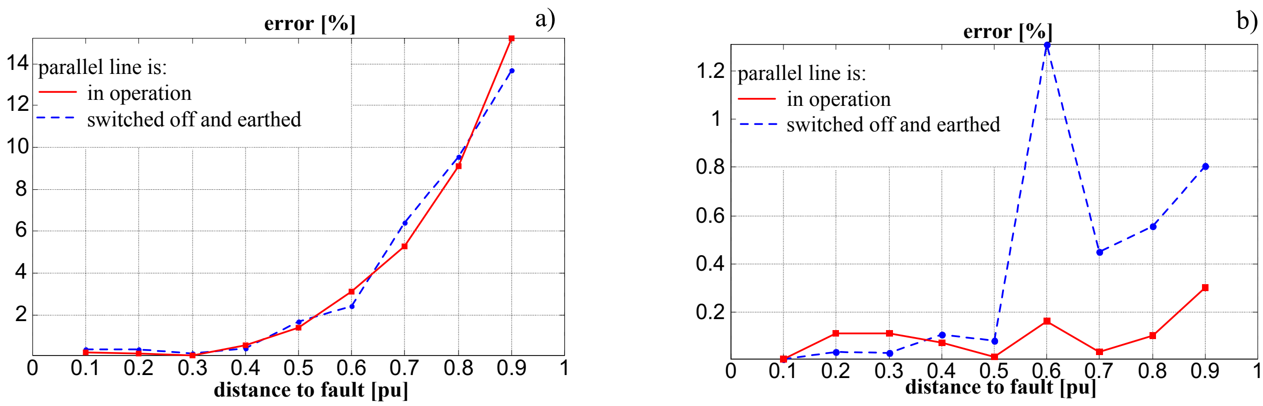

Figure 4: Error in estimated distance to fault for 120 km transmission line under: a) no mutual coupling compensation, b) with the compensation.

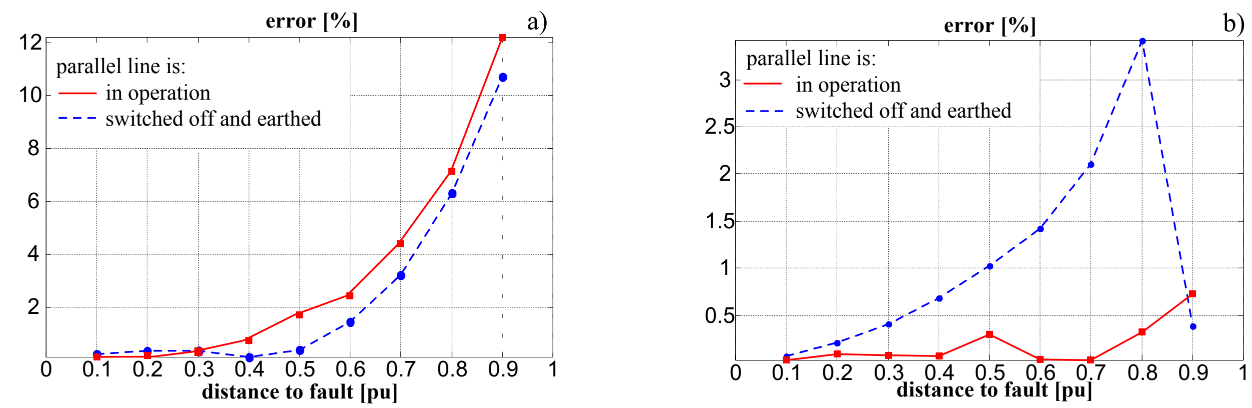

Figure 5: Error in estimated distance to fault for 300 km transmission line under: a) no mutual coupling compensation, b) with the compensation.

4 CONCLUSIONS

One-end fault location technique for parallel transmission networks not requiring measurements from the healthy parallel line circuit has been presented. The algorithm is capable of locating faults under different modes of the parallel lines operation, namely for the healthy parallel line being in operation as well as for switched off and earthed, respectively.

The developed fault location algorithm is simple and of very compact form. Setting proper complex coefficients reflects different fault types in the algorithm. Different sets of the coefficients have been derived. The distance to fault is calculated with the quadratic formula and thus in simpler way than in the earlier algorithms [8-9]. In comparison to the earlier algorithms the proposed approach requires less constant inputs of the location algorithm. In this way the uncertainty with respect to the remote source impedance for the zero sequence has no effect on fault location accuracy.

Detailed ATP-EMTP model of the considered transmission network has been developed to generate reliable fault data used for testing. The sample examples of fault location have been attached and discussed. Evaluation of location accuracy for numerous fault cases proved satisfactory performance of the algorithm, especially for the case with the healthy parallel line being in operation. Further improvement of fault location accuracy for long lines can be accomplished by compensating for shunt capacitances of parallel lines.

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