NEW ACCURATE FAULT LOCATION ALGORITHM FOR PARALLEL LINES

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INTRODUCTION

Varieties of fault location algorithms, differing in many aspects, have been developed so far. Huge majority of them, including the algorithm presented in this paper, belongs to the family of impedance based algorithms. In these algorithms the impedance parameters of a line are taken as the measure for a distance to fault. Basically, voltages and currents from one end or from all terminals of a line are the inputs of such the algorithms. The other possibility relies on using measurements of distance relays from the line terminals as Sachdev and Agarwal (1) proposed. Travelling waves based fault location, as for example in the representative method by Gale et al (2), constitutes yet another family of algorithms.

The earlier one-end algorithms for locating faults in transposed parallel lines, as for example the algorithm introduced by Eriksson et al (3), apply phase voltages and currents from the faulted line and a zero sequence current from the healthy line as the input signals. Locating faults in untransposed traditional and series-compensated parallel lines has been presented by Saha et al in (4). For this purpose complete phase currents from both, the faulted and the healthy lines together with phase voltages are utilised as the inputs and phase co-ordinates approach is applied. The algorithm presented in this paper is based on description with symmetrical components but also applies these input signals. This brings improvement of fault location for transposed parallel lines as the derived algorithm does not require source impedances for the local and remote equivalent systems as well as avoids pre-fault measurements. This is important as the remote source impedance can not be measured locally and pre-fault measurements can be in some cases unreliable or even unavailable.

Liao and Elangovan (5), Sheng and Elangovan (6) as well as Zhang et al in (7) and (8) have also extensively investigated utilisation of the flow of all currents from the healthy parallel line for improving the fault location. However, the algorithm delivered in this paper differs from the approaches of the cited references (5)-(8). The presented algorithm - as its innovative contribution - uses generalised fault loop model and the zero sequence quantities are avoided when determining the voltage drop across the fault path. Moreover, in order to provide high accuracy of fault location in long parallel lines the compensation for shunt capacitances is introduced.

BASICS OF THE LOCATION ALGORITHM

Figure 1 presents the equivalent circuit diagrams of parallel lines for particular sequence quantities. It is assumed in Figure 1b that impedances for the negative sequence are equal to the corresponding positive sequence impedances from Figure 1a. Shunt capacitances of both lines for all the sequence components are neglected at the beginning of deriving the algorithm. Terminals of parallel lines are denoted in Figure 1 as: AA, BA, AB and BB. The first letter is used here for marking the substation while the second stands for the line. Fault location is considered as performed from the substation A and for a line A at which a fault occurs at distance (d) (point F in Figure 1). For this purpose the fault loop composed accordingly to the classified fault type is considered. It contains the faulted line segment (between points AA and F in Figure 1) and the fault path itself.

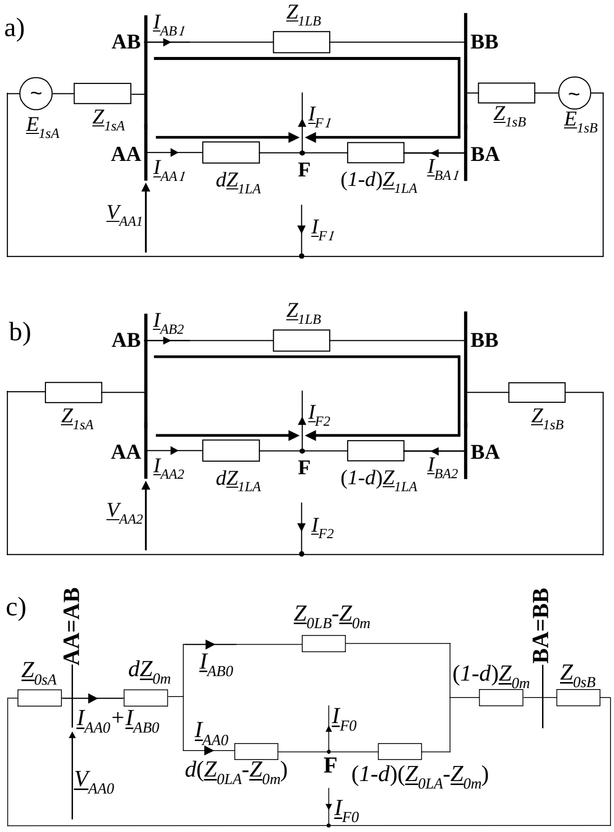

Figure 1: Equivalent circuit diagrams of parallel lines for: (a) positive sequence, (b) negative sequence, (c) zero sequence.

A generalised model for this fault loop is stated as:

$$\underline{V}_{AA\_p} - d\,\underline{Z}_{1LA}\,\underline{I}_{AA\_p} - R_F \sum_{i=0}^{2} \underline{a}_{Fi}\,\underline{I}_{Fi} = 0 \qquad (1)$$

where:

d – unknown and sought distance to fault,

$\underline{Z}_{1LA}$ - positive sequence impedance of the faulted line,

$\underline{V}_{AA\_p}$, $\underline{I}_{AA\_p}$ - fault loop voltage and current composed according to the fault type,

R_F - fault resistance,

$\underline{I}_{Fi}$ - sequence components of the total fault current ($i=0$ – zero sequence, $i=1$ positive sequence, $i=2$ – negative sequence),

$\underline{a}_{Fi}$ - weighting coefficients (Table 2),

Fault loop voltage and current can be expressed in terms of the local measurements and with using the coefficients ($\underline{a}_0$, $\underline{a}_1$, $\underline{a}_2$) gathered in Table 1:

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

$$\underline{I}_{AA\_p} = \underline{a}_1\underline{I}_{AA1} + \underline{a}_2\underline{I}_{AA2} + \underline{a}_0\frac{\underline{Z}_{0LA}}{\underline{Z}_{1LA}}\underline{I}_{AA0} + \underline{a}_0\frac{\underline{Z}_{0m}}{\underline{Z}_{1LA}}\underline{I}_{AB0} \qquad (3)$$

where:

AA, AB – subscripts used for indicating measurements acquired from the faulted line (AA) and from the healthy line (AB), respectively,

$\underline{Z}_{0LA}$, $\underline{Z}_{0m}$ - impedance of the faulted line and mutual coupling between the lines for the zero sequence, respectively.

Voltage drop across the fault path (as shown in the third term in Equation (1)) is expressed using sequence components of the total fault current ($\underline{I}_{F0}$, $\underline{I}_{F1}$, $\underline{I}_{F2}$). Determining this voltage drop requires establishing the weighting coefficients ($\underline{a}_{F0}$, $\underline{a}_{F1}$, $\underline{a}_{F2}$). These coefficients can accordingly be determined by taking the boundary conditions for particular fault type. However, there is some freedom for that. Thus, it is proposed firstly to utilise this freedom for avoiding zero sequence quantities. This is well known that the zero sequence impedance of a line is considered as unreliable parameter. This is so due to dependence of this impedance upon the resistivity of a 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 the usage of zero sequence quantities when determining the voltage drop across the fault path. This can be accomplished by setting $\underline{a}_{F0} = 0$ as shown in Table 2, where the alternative sets of the weighting coefficients are gathered. Secondly, the freedom in establishing the weighting coefficients can be utilised for determining the preference for using particular quantities. The negative sequence (Table 2, set I) or the positive sequence (Table 2, set II) can be preferred as well as possibly both types of the quantities (Table 2, set III) can be used for determining the voltage drop across the fault path.

TABLE 1 - Coefficients for determining signals defined in Equation (2) and Equation (3)

Fault type	$\underline{a}_1$	$\underline{a}_2$	$\underline{a}_0$
a-g	1	1	1
b-g	a^2	a	1
c-g	a	a^2	1
a-b, a-b-g a-b-c, a-b-c-g	$1 - a^2$	$1 - a$	0
b-c, b-c-g	$a^2 - a$	$a - a^2$	0
c-a, c-a-g	$a - 1$	$a^2 - 1$	0
$a = exp(j2\pi/3)$			

TABLE 2 – Alternative sets of weighting coefficients for determining the voltage drop across the fault path

Fault type	Set I			Set II			Set III		
	$\underline{a}_{F1}$	$\underline{a}_{F2}$	$\underline{a}_{F0}$	$\underline{a}_{F1}$	$\underline{a}_{F2}$	$\underline{a}_{F0}$	$\underline{a}_{F1}$	$\underline{a}_{F2}$	$\underline{a}_{F0}$
a-g	0	3	0	3	0	0	1.5	1.5	0
b-g	0	$3a$	0	$3a^2$	0	0	$1.5a^2$	$1.5a$	0
c-g	0	$3a^2$	0	$3a$	0	0	$1.5a$	$1.5a^2$	0
a-b	0	$1-a$	0	$1-a^2$	0	0	$0.5(1-a^2)$	$0.5(1-a)$	0
b-c	0	$a-a^2$	0	a^2-a	0	0	$0.5(a^2-a)$	$0.5(a-a^2)$	0
c-a	0	a^2-1	0	$a-1$	0	0	$0.5(a-1)$	$0.5(a^2-1)$	0
a-b-g	$1-a^2$	$1-a$	0	$1-a^2$	$1-a$	0	$1-a^2$	$1-a$	0
b-c-g	a^2-a	$a-a^2$	0	a^2-a	$a-a^2$	0	a^2-a	$a-a^2$	0
c-a-g	$a-1$	a^2-1	0	$a-1$	a^2-1	0	$a-1$	a^2-1	0
a-b-c-g (a-b-c)	$1-a^2$	0	0	$1-a^2$	0	0	$1-a^2$	0	0

For example, considering *a-g* fault one has:

$\underline{I}_F = \underline{I}_{Fa}$, $\underline{I}_{Fb} = 0$, $\underline{I}_{Fc} = 0$

Thus, symmetrical components of a fault current are:

$\underline{I}_{F1} = \frac{1}{3}\underline{I}_{Fa}$, $\underline{I}_{F2} = \frac{1}{3}\underline{I}_{Fa}$

Therefore, one can establish for this type of a fault:

$\underline{I}_F = \underline{I}_{Fa} = 3\underline{I}_{F1} = 3\underline{I}_{F2} = 1.5\underline{I}_{F1} + 1.5\underline{I}_{F2}$

Similarly, the weighting coefficients were derived for the other fault types as shown in Table 2.

Application of Equation 1 for fault location requires determining the positive and the negative sequence components of the fault path current. Considering the two different paths in the circuits of Figure 1a and Figure 1b: - the faulted line segment adjacent to the local substation, - the healthy line together with the remote segment of the faulted line, one obtains:

$$\underline{I}_{F1} = \frac{\underline{I}_{AA1} - \frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{I}_{AB1}}{1-d} \tag{4}$$

$$\underline{I}_{F2} = \frac{\underline{I}_{AA2} - \frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{I}_{AB2}}{1-d} \tag{5}$$

Substituting Equation (4) and Equation (5) into Equation (1) and considering Equation (2) together with Equation (3) yields:

$$\underline{A}_2 d^2 - \underline{A}_1 d + \underline{A}_0 - R_F\,\underline{A}_{00} = 0 \tag{6}$$

where:

$$\underline{A}_2 = \underline{Z}_{1LA}\left(\underline{a}_1\underline{I}_{AA1} + \underline{a}_2\underline{I}_{AA2} + \underline{a}_0\frac{\underline{Z}_{0LA}}{\underline{Z}_{1LA}}\underline{I}_{AA0} + \underline{a}_0\frac{\underline{Z}_{0m}}{\underline{Z}_{1LA}}\underline{I}_{AB0}\right)$$

$$\underline{A}_1 = \underline{A}_2 + \underline{a}_1\underline{V}_{AA1} + \underline{a}_2\underline{V}_{AA2} + \underline{a}_0\underline{V}_{AA0}$$

$$\underline{A}_0 = \underline{a}_1\underline{V}_{AA1} + \underline{a}_2\underline{V}_{AA2} + \underline{a}_0\underline{V}_{AA0}$$

$$\underline{A}_{00} = \underline{a}_{F1}\left(\underline{I}_{AA1} - \frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{I}_{AB1}\right) + \underline{a}_{F2}\left(\underline{I}_{AA2} - \frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{I}_{AB2}\right)$$

Eliminating fault resistance (R_F) from Equation (6) one obtains the formula for a distance to fault (d):

$$B_2 d^2 - B_1 d + B_0 = 0 \tag{7}$$

where:

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

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

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

The required complex quantities ($\underline{A}_2$, $\underline{A}_1$, $\underline{A}_0$, $\underline{A}_{00}$) are obtained according to Equation (6) with use of the local measurements of phase currents acquired from both, the faulted and the healthy lines as well as phase voltages. The applied coefficients dependent on the fault type are gathered in Table 1 and Table 2.

Compensation for shunt capacitances

The fault location algorithm as in Equation (7) has been derived under neglecting shunt capacitances of lines. However, providing high accuracy for locating faults in long parallel lines requires compensating for these capacitances. Figure 2 presents circuit diagram of parallel lines for the positive sequence with included shunt admittances. In this case the voltage drop across the faulted line segment can be calculated with the current ($\underline{I}^C_{AA1}$) obtained from the measured current ($\underline{I}_{AA1}$) after deducing the shunt current:

$$\underline{I}^C_{AA1} = \underline{I}_{AA1} - 0.5d\,\underline{B}_{1LA}\underline{V}_{AA1} \tag{8}$$

where:

$\underline{B}_{1LA} = j\omega_1 C_{1LA}$ - positive sequence admittance of the whole faulted line,

ω_1 - fundamental frequency pulsation,

C_{1LA} - shunt capacitance of the faulted line for the positive sequence.

Similarly, the compensation for the segment of a faulted line, which is adjacent to the remote substation B, can be determined. As a result, the positive sequence component of a fault path current is expressed as:

$$\underline{I}^C_{F1} = \underline{M}_2 d^2 + \underline{M}_1 d + \frac{\underline{M}_0}{1-d} \tag{9}$$

where:

$$\underline{M}_2 = -0.25\underline{B}^2_{1LA}\underline{Z}_{1LA}\underline{V}_{AA1}$$

$$\underline{M}_1 = 0.5\underline{B}_{1LA}\underline{Z}_{1LA}\underline{I}_{AA1}$$

$$\underline{M}_0 = \underline{I}_{AA1} - \frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{I}_{AB1} + 0.5\left(\frac{\underline{Z}_{1LB}}{\underline{Z}_{1LA}}\underline{B}_{1LB} - \underline{B}_{1LA}\right)\underline{V}_{AA1}$$

$\underline{B}_{1LB}$ - positive sequence admittance of the healthy line.

The compensation for the remaining sequence components can be performed analogously. Finally one gets the algorithm in the form of the cubic formula for a distance to fault and without iterative calculations.

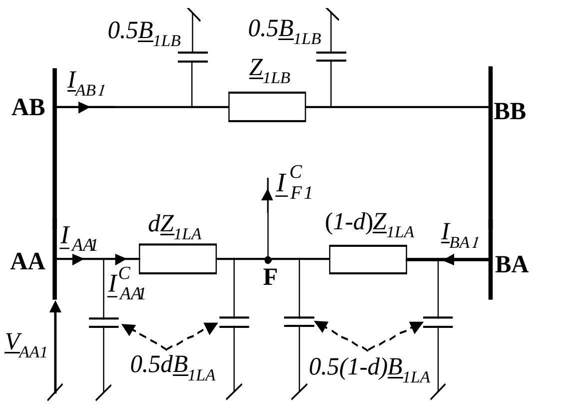

Figure 2: Positive sequence equivalent circuit diagram of parallel lines with included shunt capacitances.

EVALUATION BY USING ATP-EMTP SIMULATION

The detailed ATP-EMTP model of parallel transmission system (Figure 1) including the fault locator measurement chains has been developed. The *400* kV, *300* km parallel transmission lines were represented by the Clarke model. The model included both the Capacitive Voltage Transformers (CVTs) and the Current Transformers (CTs). The analog filters were also implemented using the *2*nd order Butterworth model. The phasors were estimated with the use of the DFT algorithm working with *20* samples per cycle.

Variety of fault cases have been generated and used in testing the fault location algorithm. In the analysis different specifications of faults, different short circuit power of the supplying systems have been taken into account. Testing proved satisfactory accuracy of fault location. Maximal fault location error does not exceed *2*% if shunt capacitances are not taken into account and *0.3*% in case of introducing the compensation.

Figure 3 presents the example of location for the following fault specifications: - fault type: *a-g*, - fault resistance: *10*Ω, - fault location: *0.167*pu. The estimated fault distance (averaged for the last *20*ms of the post-fault interval) equals *0.164*pu and thus the error is *0.3*%.

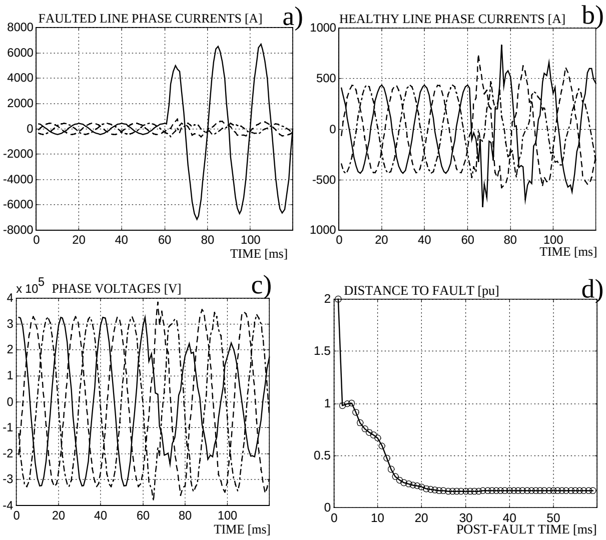

Figure 3: Example of fault location: a) phase currents from the faulted line, b) phase currents from the healthy line, c) phase voltages, d) estimated distance to a fault.

CONCLUSIONS

New accurate fault location algorithm for parallel lines is presented. The algorithm utilises one-end measurements of voltages and currents. Complete phase currents from both, the faulted and the healthy lines as well as phase voltages are the inputs of the fault locator. The flow of currents through the healthy line path is utilised for deriving the algorithm. Thus, the algorithm is capable of locating faults when both parallel lines are in operation. The presented algorithm is of compact form and does not require source impedances as well as usage of pre-fault signals is avoided. Adverse influence of uncertainty with respect to zero sequence impedance of a line is partly limited as the voltage drop across a fault path is determined with excluding zero sequence components.

In order to provide high accuracy of locating faults in long parallel lines the compensation for shunt capacitances is introduced. The evaluation performed by using a large number of ATP-EMTP simulations proved effectiveness and high accuracy of the presented fault location algorithm.

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