ATP-EMTP INVESTIGATION OF FAULT LOCATION ALGORITHM APPLYING SIGNALS OF CURRENT DIFFERENTIAL RELAYS OF DOUBLE-CIRCUIT SERIES-COMPENSATED TRANSMISSION LINE

Murari Saha
ABB AB
Västerås, Sweden
murari.saha@se.abb.com

Eugeniusz Rosolowski
Wroclaw University of Technology
Wroclaw, Poland
eugeniusz.rosolowski@pwr.wroc.pl

Jan Izykowski
Wroclaw University of Technology
Wroclaw, Poland
jan.izykowski@pwr.wroc.pl

Abstract – This paper presents an accurate fault location algorithm for a double-circuit series-compensated lines associated with current differential relays. Use of two-end currents and one-end voltage to fault location has been considered. The algorithm applies two subroutines designated for locating faults on particular line section, and additionally the procedure for selecting the valid subroutine. The developed algorithm has been tested and evaluated using signals taken from ATP-EMTP versatile simulations of faults. The presented sample results of the testing show the validity of the presented fault location algorithm and its high accuracy.

Keywords: double-circuit transmission line, series capacitor compensation, current differential protection, fault location, fault simulation

1 INTRODUCTION

Accurate location of faults on power lines [1]–[8] is a very important task. It is especially of utmost importance for series-compensated lines, which are spreading over few hundreds of kilometers and are vital links between the energy production and consumption centers. Series compensation can be accomplished with use of fixed capacitors (considered in this paper) [2]–[6] or thyristor controlled capacitors [7].

Among the known methods, the approach based on an impedance principle is the most popular. In particular, the algorithms utilizing one-end current and voltage measurements have been presented in [1]–[2]. In turn, in [3] use of two-end currents and voltages, measured synchronously with the aid of PMUs, has been considered for fault location. Use of the unsynchronized measurements has been proposed in [4]. In [5] the method for application with current differential protective relays of a single series-compensated transmission line was introduced. The other fault location techniques for such lines are based on knowledge based approaches [6]–[7].

In this paper a new impedance-based fault location algorithm for a double-circuit series-compensated line (Figures 1 and 2) is presented. For this purpose the approach from [5] was taken for further development and adaptation to double-circuit line application.

It is considered that fixed series capacitors (SCs) are installed in each line circuit (Figure 1). The SCs are usually equipped with MOVs (Metal Oxide Varistors) for overvoltage protection (Figure 1). The other details for the capacitor bank, as not important for the conducted considerations, are not shown here.

Innovative contribution of the proposed fault location technique relies on using the following specific incomplete two-end measurements (Figure 1):

- currents from protective differential relays, i.e. phasors $\{\underline{I}_{AA}\}$, $\{\underline{I}_{BA}\}$ of three-phase currents from both ends of the faulted line circuit,
- three-phase voltage $\{v_A\}$ measured locally, i.e.: at the bus AA, where the fault locator FL_A is consider as to be embedded into the relay DIFF REL_A,
- zero-sequence current i_{AB0} from the healthy parallel line, provided for compensating for the mutual coupling between the line circuits.

Such set of the fault locator input signals has been assumed with the aim of embedding the fault locator into current differential protective relays. Phasors $\{\underline{I}_{AA}\}$, $\{\underline{I}_{BA}\}$ of three-phase currents measured synchronously are exchanged by the current differential relays via the communication channel.

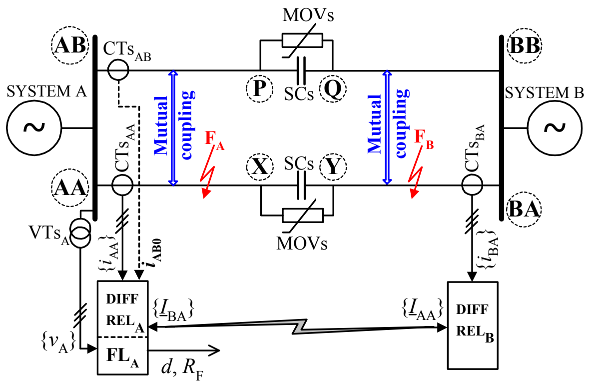

Figure 1: Fault location with use of fault locator FL_A embeded into the relay at one end.

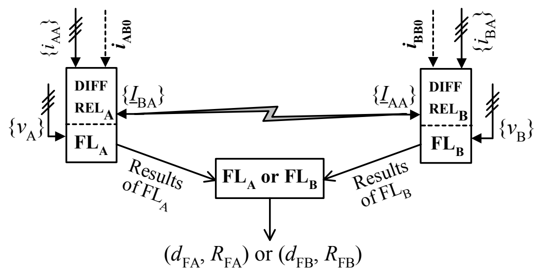

Figure 2: Idea of fault location with use of two fault locators embedded into the relays at both line ends.

The fault location function can be embedded into the differential relay at one end (Figure 1) or into the relays at both ends (Figure 2). In the latter case much superior fault location can be performed.

2 FAULT LOCATION ALGORITHM

A fault is of a random nature and can appear at any line section, i.e. between the bus AA and the capacitor bank (fault FA) or between the bus BA and the bank (fault FB) – Figures 1 and 2. Therefore, two subroutines: SUB_A, SUB_B are utilised for locating these hypothetical faults FA and FB, respectively. The final result is selected with use of the selection procedure.

2.1 *Fault location subroutine SUB_A*

In relation to Figure 3 the following generalized fault loop model [8] for fault FA can be stated:

$$\underline{V}_{\mathrm{Ap}} - d_{\mathrm{FA}}\underline{Z}_{\mathrm{1LA}}\underline{I}_{\mathrm{Ap}} - R_{\mathrm{FA}}\underline{I}_{\mathrm{FA}} = 0 \qquad (1)$$

where:

d_{FA} – unknown distance to fault [p.u.],

R_{FA} – unknown fault resistance,

$\underline{V}_{\mathrm{Ap}}$, $\underline{I}_{\mathrm{Ap}}$ – fault loop voltage and current,

$\underline{I}_{\mathrm{FA}}$ – total fault current (fault path current),

$\underline{Z}_{\mathrm{1LA}}$ – positive-sequence impedance of the line section AA–X; Note: $\underline{Z}_{\mathrm{1LA}} = d_{\mathrm{SC}}\underline{Z}_{\mathrm{1L}}$, where: $\underline{Z}_{\mathrm{1L}}$ – positive-sequence impedance of the whole line AA–BA,

d_{SC} – relative distance from bus AA to SCs&MOVs.

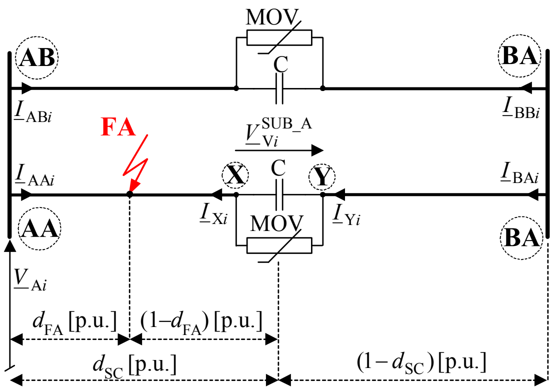

Figure 3: Scheme for subroutine SUB_A (for fault FA).

Fault loop voltage and current are composed accordingly to the fault type as follows [8]:

$$\underline{V}_{\mathrm{Ap}} = \underline{a}_1\underline{V}_{\mathrm{A1}} + \underline{a}_2\underline{V}_{\mathrm{A2}} + \underline{a}_0\underline{V}_{\mathrm{A0}} \qquad (2)$$

$$\underline{I}_{\mathrm{Ap}} = \underline{a}_1\underline{I}_{\mathrm{AA1}} + \underline{a}_2\underline{I}_{\mathrm{AA2}} + \underline{a}_0\left(\frac{\underline{Z}_{\mathrm{0LA}}}{\underline{Z}_{\mathrm{1LA}}}\underline{I}_{\mathrm{AA0}} + \frac{\underline{Z}_{\mathrm{0mA}}}{\underline{Z}_{\mathrm{1LA}}}\underline{I}_{\mathrm{AB0}}\right) \qquad (3)$$

where:

$\underline{a}_1$, $\underline{a}_2$, $\underline{a}_0$ – weighting coefficients (Table 1);

1, 2, 0 – digits in subscripts used for denoting positive-, negative- and zero-sequence components of the signals,

$\underline{Z}_{\mathrm{0LA}}$ – zero-sequence impedance of the section AA–X,

$\underline{Z}_{\mathrm{0mA}}$ – zero-sequence mutual coupling impedance for the section AA–X.

Fault type	$\underline{a}_1$	$\underline{a}_2$	$\underline{a}_0$
a-g	1	1	1
b-g	$-0.5-\mathrm{j}0.5\sqrt{3}$	$-0.5+\mathrm{j}0.5\sqrt{3}$	1
c-g	$-0.5+\mathrm{j}0.5\sqrt{3}$	$-0.5-\mathrm{j}0.5\sqrt{3}$	1
a-b, a-b-g a-b-c, a-b-c-g	$1.5+\mathrm{j}0.5\sqrt{3}$	$1.5-\mathrm{j}0.5\sqrt{3}$	0
b-c, b-c-g	$-\mathrm{j}\sqrt{3}$	$\mathrm{j}\sqrt{3}$	0
c-a, c-a-g	$-1.5+\mathrm{j}0.5\sqrt{3}$	$-1.5-\mathrm{j}0.5\sqrt{3}$	0

Table 1: Weighting coefficients used in (2)–(3).

In order to minimize an influence of line shunt capacitances on accuracy of determining the total fault current from (1), it is not calculated by direct adding the phase currents at both ends of the faulted line. Instead, it is calculated using the following generalized fault model [8]:

$$\underline{I}_{\mathrm{FA}} = \underline{a}_{\mathrm{F1}}(\Delta\underline{I}_{\mathrm{AA1}} + \Delta\underline{I}_{\mathrm{BA1}}) + \underline{a}_{\mathrm{F2}}(\underline{I}_{\mathrm{AA2}} + \underline{I}_{\mathrm{BA2}}) + \underline{a}_{\mathrm{F0}}(\underline{I}_{\mathrm{AA0}} + \underline{I}_{\mathrm{BA0}}) \qquad (4)$$

where:

$\underline{a}_{\mathrm{F1}}$, $\underline{a}_{\mathrm{F2}}$, $\underline{a}_{\mathrm{F0}}$ – share coefficients (Table 2),

$\Delta\underline{I}_{\mathrm{AA1}}$, $\underline{I}_{\mathrm{AA2}}$, $\underline{I}_{\mathrm{AA0}}$ – sequence components of currents at the bus AA,

$\Delta\underline{I}_{\mathrm{BA1}}$, $\underline{I}_{\mathrm{BA2}}$, $\underline{I}_{\mathrm{BA0}}$ – sequence components of currents at the bus BA.

Note that in (4) instead of using positive-sequence components $\underline{I}_{\mathrm{AA1}}$, $\underline{I}_{\mathrm{BA1}}$ taken from the fault time interval, the superimposed positive-sequence currents are applied:

$$\Delta\underline{I}_{\mathrm{AA1}} = \underline{I}_{\mathrm{AA1}} - \underline{I}_{\mathrm{AA1}}^{\mathrm{pre}} \qquad (5a)$$

$$\Delta\underline{I}_{\mathrm{BA1}} = \underline{I}_{\mathrm{BA1}} - \underline{I}_{\mathrm{BA1}}^{\mathrm{pre}} \qquad (5b)$$

where the subtracted currents are taken from the pre-fault time interval (superscript: pre).

Usage of the superimposed quantities (5a)–(5b) and not the fault quantities is advantageous since lower errors arise due to neglecting line shunt capacitances.

Fault type	$\underline{a}_{\mathrm{F1}}$	$\underline{a}_{\mathrm{F2}}$	$\underline{a}_{\mathrm{F0}}$
a-g	0	3	0
b-g	0	$-1.5+\mathrm{j}1.5\sqrt{3}$	0
c-g	0	$-1.5-\mathrm{j}1.5\sqrt{3}$	0
a-b	0	$1.5-\mathrm{j}0.5\sqrt{3}$	0
b-c	0	$\mathrm{j}\sqrt{3}$	0
c-a	0	$-1.5-\mathrm{j}0.5\sqrt{3}$	0
a-b-g	$1.5+\mathrm{j}0.5\sqrt{3}$	$1.5-\mathrm{j}0.5\sqrt{3}$	0
b-c-g	$-\mathrm{j}\sqrt{3}$	$\mathrm{j}\sqrt{3}$	0
c-a-g	$1.5-\mathrm{j}0.5\sqrt{3}$	$1.5+\mathrm{j}0.5\sqrt{3}$	0
a-b-c a-b-c-g	$1.5+\mathrm{j}0.5\sqrt{3}$	$1.5-\mathrm{j}0.5\sqrt{3}$ *)	0
*) $\underline{a}_{\mathrm{F2}} \neq 0$, however, negative-sequence component is not present			

Table 2: Share coefficients used in fault model (4)

The recommended share coefficients (Table 2) assures that the zero-sequence currents are not involved ($\underline{a}_{F0} = 0$) in total fault current calculations.

After resolving (3) into the real and imaginary parts, and eliminating the unknown fault resistance (R_{FA}), the sought fault distance (d_{FA}) is determined as:

$$d_{FA} = \frac{\mathrm{real}(\underline{V}_{Ap})\,\mathrm{imag}(\underline{I}_{FA}) - \mathrm{imag}(\underline{V}_{Ap})\,\mathrm{real}(\underline{I}_{FA})}{\mathrm{real}(\underline{Z}_{1LA}\underline{I}_{Ap})\,\mathrm{imag}(\underline{I}_{FA}) - \mathrm{imag}(\underline{Z}_{1LA}\underline{I}_{Ap})\,\mathrm{real}(\underline{I}_{FA})} \tag{6}$$

Having the fault distance calculated (6), the fault resistance R_{FA} can be also determined, as for example from the real part of (1) as:

$$R_{FA} = \frac{\mathrm{real}(\underline{V}_{Ap}) - d_{FA}\mathrm{real}(\underline{Z}_{1LA}\underline{I}_{Ap})}{\mathrm{real}(\underline{I}_{FA})} \tag{7}$$

2.2 Fault location subroutine SUB_B – case with one fault locator

In relation to Figure 4 one can perform the analytical transfer of voltage from the bus AA up to the point X (at the capacitor bank). This can be accomplished for the individual positive-, negative- and zero-sequence components:

$$\underline{V}_{X1} = \underline{V}_{A1} - d_{SC}\underline{Z}_{1L}\underline{I}_{AA1} \tag{8a}$$

$$\underline{V}_{X2} = \underline{V}_{A2} - d_{SC}\underline{Z}_{1L}\underline{I}_{AA2} \tag{8b}$$

$$\underline{V}_{X0} = \underline{V}_{A0} - d_{SC}\underline{Z}_{0L}\underline{I}_{AA0} - d_{SC}\underline{Z}_{0m}\underline{I}_{AB0} \tag{8c}$$

where:

$\underline{Z}_{1L}$, $\underline{Z}_{0L}$, $\underline{Z}_{0m}$ – positive- (and also negative-), zero- and mutual zero-sequence impedance for the whole length of the line.

If there is no internal fault within the compensating bank, then at both sides of the bank we have identical currents (Figure 4). After neglecting the line shunt capacitances we get:

$$\underline{I}_{Y1} = \underline{I}_{X1} = \underline{I}_{AA1} \tag{9a}$$

$$\underline{I}_{Y2} = \underline{I}_{X2} = \underline{I}_{AA2} \tag{9b}$$

$$\underline{I}_{Y0} = \underline{I}_{X0} = \underline{I}_{AA0} \tag{9c}$$

In contrast, at both sides of the compensating bank there are different voltages due to presence of voltage drops across the capacitors. For calculating them, one has to determine currents (in particular phase: a, b or c) at the point X:

$$\underline{I}_{X\_a} = \underline{I}_{X0} + \underline{I}_{X1} + \underline{I}_{X2} \tag{10a}$$

$$\underline{I}_{X\_b} = \underline{I}_{X0} + \underline{a}^2\underline{I}_{X1} + \underline{a}\underline{I}_{X2} \tag{10b}$$

$$\underline{I}_{X\_c} = \underline{I}_{X0} + \underline{a}\underline{I}_{X1} + \underline{a}^2\underline{I}_{X2} \tag{10c}$$

where $\underline{a} = \exp(\mathrm{j}2\pi/3)$ – operator shifting by: $2\pi/3$.

Applying the fundamental frequency equivalenting of SC&MOV bank [2] the voltage drops across it are:

$$\underline{V}_{V\_a}^{SUB\_B} = \underline{Z}_{V\_a}(|\underline{I}_{X\_a}|)\cdot\underline{I}_{X\_a} \tag{11a}$$

$$\underline{V}_{V\_b}^{SUB\_B} = \underline{Z}_{V\_b}(|\underline{I}_{X\_b}|)\cdot\underline{I}_{X\_b} \tag{11b}$$

$$\underline{V}_{V\_c}^{SUB\_B} = \underline{Z}_{V\_c}(|\underline{I}_{X\_c}|)\cdot\underline{I}_{X\_c} \tag{11c}$$

where:

$\underline{I}_{X\_a}$, $\underline{I}_{X\_b}$, $\underline{I}_{X\_c}$ are phasors of the currents flowing through the bank of SC&MOV in particular phase (a, b or c) and by "$|\underline{X}|$" the amplitude of the phasor $\underline{X}$ is denoted.

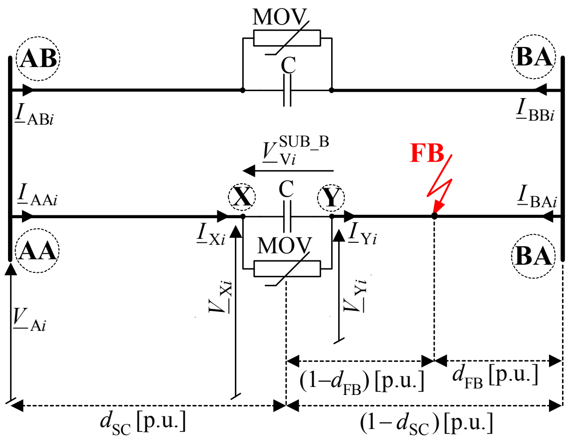

Figure 4: Scheme for subroutine SUB_B (for fault FB).

Having the phase voltage drops (25)–(27) one determines the sequence components of this voltage drop:

$$\underline{V}_{V1}^{SUB\_B} = \frac{1}{3}\left(\underline{V}_{V\_a}^{SUB\_B} + \underline{a}\underline{V}_{V\_b}^{SUB\_B} + \underline{a}^2\underline{V}_{V\_c}^{SUB\_B}\right) \tag{12a}$$

$$\underline{V}_{V2}^{SUB\_B} = \frac{1}{3}\left(\underline{V}_{V\_a}^{SUB\_B} + \underline{a}^2\underline{V}_{V\_b}^{SUB\_B} + \underline{a}\underline{V}_{V\_c}^{SUB\_B}\right) \tag{12b}$$

$$\underline{V}_{V0}^{SUB\_B} = \frac{1}{3}\left(\underline{V}_{V\_a}^{SUB\_B} + \underline{V}_{V\_b}^{SUB\_B} + \underline{V}_{V\_c}^{SUB\_B}\right) \tag{12c}$$

The sequence voltages at point Y (Figure 4) are:

$$\underline{V}_{Y1} = \underline{V}_{X1} - \underline{V}_{V1}^{SUB\_B} \tag{13a}$$

$$\underline{V}_{Y2} = \underline{V}_{X2} - \underline{V}_{V2}^{SUB\_B} \tag{13b}$$

$$\underline{V}_{Y0} = \underline{V}_{X0} - \underline{V}_{V0}^{SUB\_B} \tag{13c}$$

As a result of the performed analytic transfer of currents (9a)–(9c) and voltages (13a)–(13c) it is possible to formulate the generalized fault loop model for the subroutine SUB_B (Figure 4). This fault loop contains the line section from the point Y up to the fault FB and fault path resistance R_{FB}:

$$\underline{V}_{Yp} - (1-d_{FB})\underline{Z}_{1LB}\underline{I}_{Yp} - R_{FB}\underline{I}_{FB} = 0 \tag{14}$$

where:

$\underline{V}_{Yp}$, $\underline{I}_{Yp}$ – fault loop voltage and current composed analogously as in the case of the subroutine SUB_A,

$\underline{I}_{FB} = \underline{I}_{FA}$ – total fault current, determined as in (4).

Solution of (14) for the unknowns d_{FB} and R_{FB} can be obtained analogously as presented for fault FA.

Accuracy of locating faults FB (Figure 4) with use of the fault loop model (14) can be worse than in the case of faults FA (Figure 3) – located using the formula (6) of the subroutine SUB_A. This is so since some additional errors may arise due to uncertainty with respect to the parameters of the compensating bank and inaccurate representation of them for the fundamental frequency. In order to eliminate completely the need for knowing and utilizing the compensating bank parameters two fault locators (Figure 2) can be applied.

2.3 Fault location subroutine SUB_B – case with two fault locators embedded into relays at both line ends

In this case the fault locator FL_B (Figure 2) can fulfil its duty by considering the fault loop seen from the bus BA, i.e. containing the line section from the bus BA up to the fault FB and fault path resistance R_{FB}. Thus, there is no need for representing the SCs&MOVs in the considered fault loop. This is advantageous from assuring high accuracy of fault location point of view. The generalized fault model for such fault loop is formulated analogously as in (1), but with utilizing the signals from the line terminals BA&BB.

2.4 Application of distributed parameter line model

In the considerations presented so far the double-circuit line under study was represented using the lumped parameter line model without accounting for the line shunt capacitances. This can be justified when the considered capacitor compensating bank is installed in midpoint of the line dividing it into two segments (on the left and right sides of the bank) of the moderate length. It is so for the line considered in the Section 3 where the quantitative analysis is presented.

If the compensating bank divides the line into segments such that the longer section exceeds some 200 km, then there is a need for applying the distributed parameter line model. This can be accomplished analogously as for the single-circuit series-compensated line presented in [5]. However, peculiarity of the double-circuit line for the zero-sequence, which is well presented in [9], has to be taken into account.

2.5 Selection procedure

The applied subroutines SUB_A, SUB_B yield the results for a distance to fault and fault resistance: (d_{FA}, R_{FA}); (d_{FB}, R_{FB}), respectively. The results from only one subroutine are consistent with the actual fault. Such subroutine is thus treated as the valid one. First, the subroutine yielding the distance to fault outside the section range and/or the fault resistance of negative value is rejected. If this appears insufficient, then one has to proceed with further selection

In the case of a single fault locator (Figure 1) the subroutine with estimated smaller fault resistance is selected as the valid one, analogously as in [2]). In vast majority of the fault cases this allows for making proper selection.

In the case of using two fault locators (Figure 2) the selection can be based on estimation of the resistance and reactance for the fundamental frequency equivalent of the compensating bank. This estimation has to be carried out for both subroutines (SUB_A and SUB_B). For this purpose the fault locator FL_A determines the auxiliary impedances:

$$\underline{Z}_{Xph}^{SUB\_A} = \frac{\underline{V}_{Xph}^{SUB\_A}}{\underline{I}_{BAph}} \tag{15a}$$

$$\underline{Z}_{Xph}^{SUB\_B} = \frac{\underline{V}_{Xph}^{SUB\_B}}{\underline{I}_{AAph}} \tag{15b}$$

where:

$\underline{V}_{Xph}^{SUB\_A}$, $\underline{V}_{Xph}^{SUB\_B}$ – voltages at the point X from any of the faulted phases (phase: ph), determined according to Figure 3 (SUB_A) and Figure 4 (SUB_B),

$\underline{I}_{BAph}$, $\underline{I}_{AAph}$ – currents at the line ends BA and AA from the faulted phase (ph), which after neglecting the line shunt capacitances are equal to currents at the capacitor bank.

The fault locator FL_B determines the auxiliary impedances:

$$\underline{Z}_{Yph}^{SUB\_A} = \frac{\underline{V}_{Yph}^{SUB\_A}}{\underline{I}_{BAph}} \tag{16a}$$

$$\underline{Z}_{Yph}^{SUB\_B} = \frac{\underline{V}_{Yph}^{SUB\_B}}{\underline{I}_{AAph}} \tag{16b}$$

where:

$\underline{V}_{Yph}^{SUB\_A}$, $\underline{V}_{Yph}^{SUB\_B}$ – voltages as in (15a)–(15b), but at the point Y (Figures 3 and 4),

$\underline{I}_{BAph}$, $\underline{I}_{AAph}$ – currents as in (15a)–(15b).

In order to calculate the voltages used for determining the auxiliary impedances (15a)–(16b) one has to start with the analytic transfer of voltages from the line terminals to the points X, Y, for the respective sequences. Then, the sequence voltages are to be transferred to the phase domain in order to get the voltages from the faulted phase (in case of multi-phase faults one takes any phase from those involved in a fault). This is so since the judgement with respect to which subroutine is valid can be performed by considering the character of the estimated fundamental frequency impedance of the compensating bank from any of the faulted phases:

$$\underline{Z}_{Vph}^{SUB\_A} = \underline{Z}_{Yph}^{SUB\_A} - \underline{Z}_{Xph}^{SUB\_A} \tag{17a}$$

$$\underline{Z}_{Vph}^{SUB\_B} = \underline{Z}_{Xph}^{SUB\_B} - \underline{Z}_{Yph}^{SUB\_B} \tag{17b}$$

Thus, determination of the impedances $\underline{Z}_{Vph}^{SUB\_A}$, $\underline{Z}_{Vph}^{SUB\_B}$ for the compensating bank require only subtracting the auxiliary impedances determined by the fault locators FL_A and FL_B from both line ends. The subroutine (SUB_A of the fault locator FL_A or SUB_B of the fault locator FL_B) which yields the estimated impedance of the series *R–C* circuit character (resistance>0 and reactance<0) [2], with the parameters from the expected range, is selected as the valid subroutine. It has been checked for huge number of fault cases that the expected range for the resistance and reactance of the compensating bank impedance is even not needed. This is so since one gets negative resistance and/or positive reactance of the compensating bank impedance only for one subroutine and it undergoes rejections as the false one.

3 ATP-EMTP BASED TESTING OF THE FAULT LOCATION ALGORITHM

The 300-km, 400-kV transmission line compensated in the middle (d_{SC}=0.5 p.u.), at the degree of 70%, was modelled using ATP-EMTP [10]. The line impedances and capacitances were assumed as:

$\underline{Z}_{1L}$=(8.28+j94.5) Ω,

$\underline{Z}_{0L}$=(82.5+j307.9) Ω,

$\underline{Z}_{0m}$=(63+188.5) Ω,

C_{1L}=13 nF/km, C_{0L}=8.5 nF/km, C_{0m}=5 nF/km.

The supplying systems A and B (Figure 1) were modelled taking for them the impedances: $\underline{Z}_{1SA}=\underline{Z}_{1SB}$=(1.31+j15)Ω, $\underline{Z}_{0SA}=\underline{Z}_{0SB}$=(2.32+j26.5)Ω; the e.m.f. of the system B as delayed by 30^{o} with respect to the system A.

The MOVs with the common approximation:

$$i = P\left(\frac{v}{V_{REF}}\right)^{q} \qquad (18)$$

were modelled taking: P=1 kA, V_{REF}=150 kV, q=23.

The model includes the Capacitive Voltage Transformers (CVTs) and the Current Transformers (CTs). The analog filters with 350 Hz cut-off frequency were also included. The sampling frequency of 1000 Hz was applied and the phasors were determined with use of the DFT algorithm.

In Figures 5 through 7 the results for the example fault location are presented.

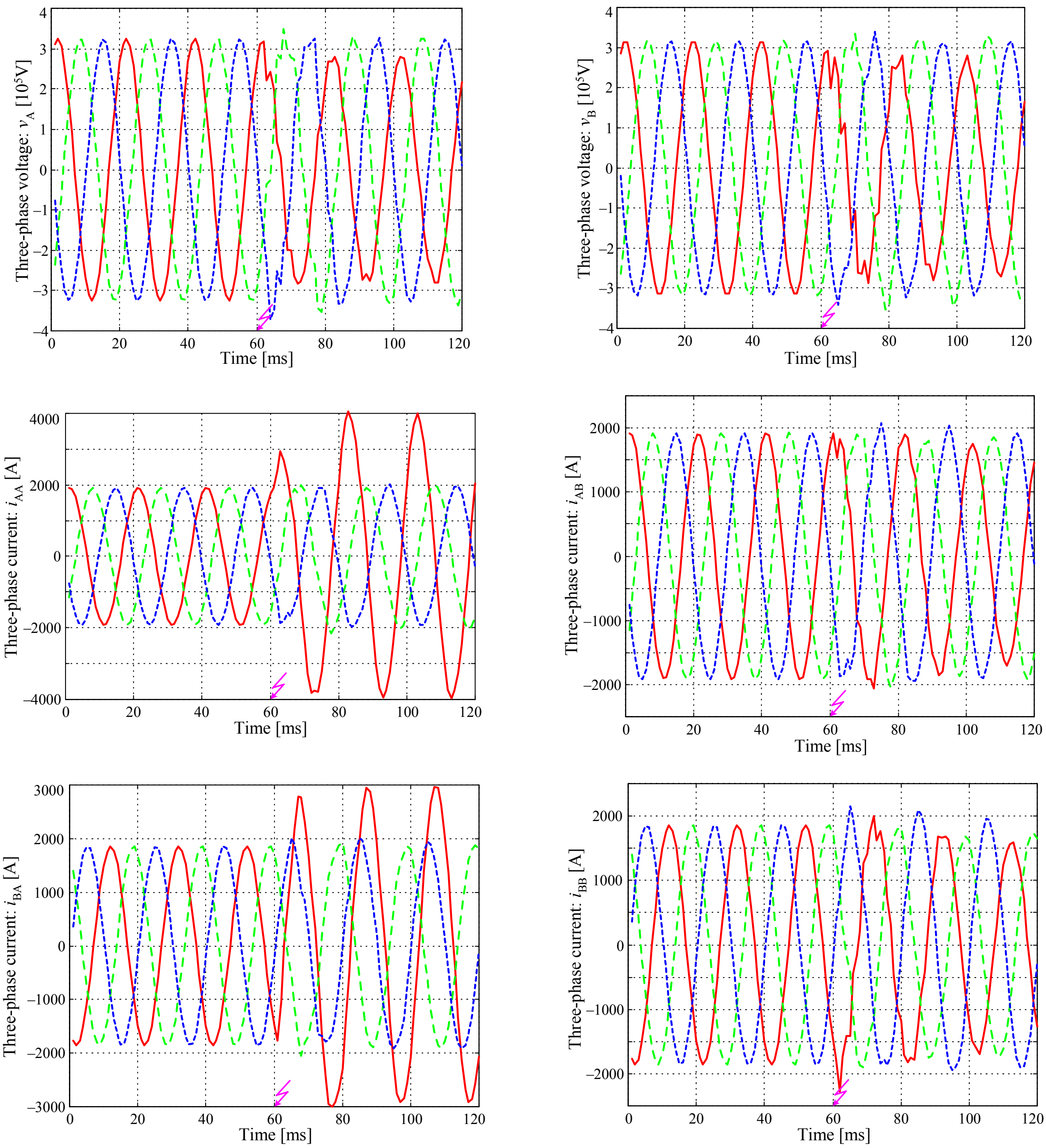

Figure 5: The example: three-phase voltages and currents from both ends of the faulted double-circuit line.

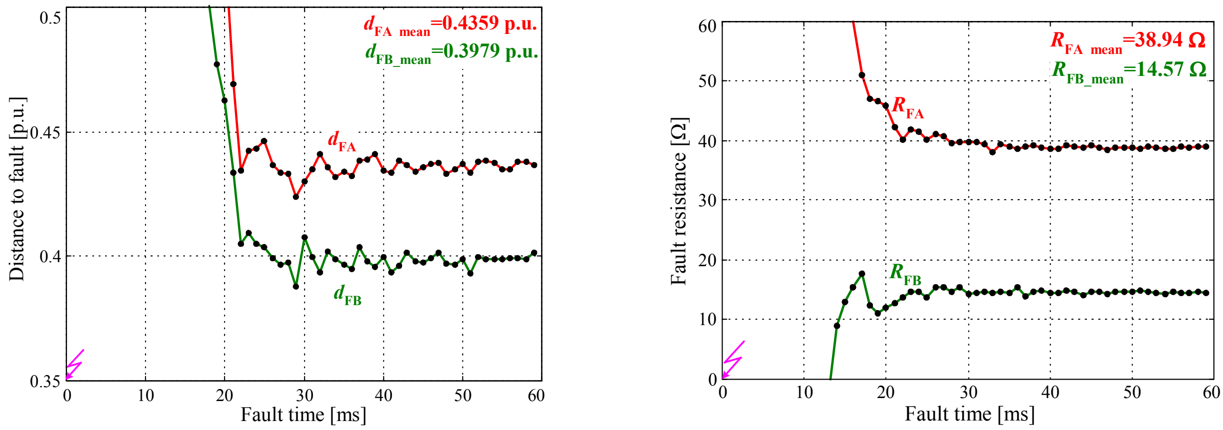

Figure 6: The example: estimated distance to fault and fault resistance according to subroutines SUB_A, SUB_B.

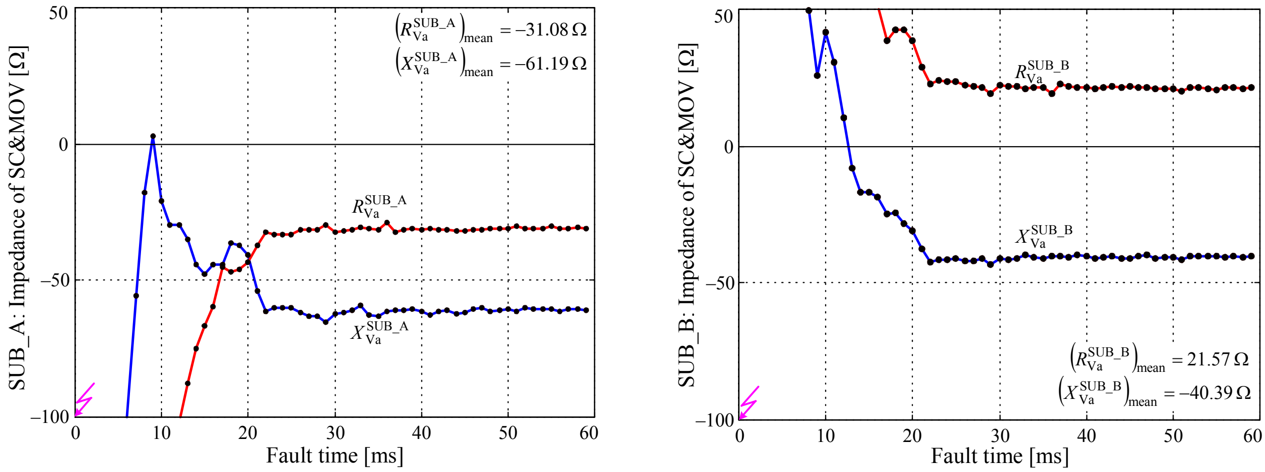

Figure 7: The example: estimated fundamental frequency impedance of the compensating bank from the faulted phase 'a' according to subroutines SUB_A (to be rejected) and SUB_B (to be selected as the valid subroutine).

The specifications for the presented example are:

- fault type: a-g,
- fault location: d_{FB_actual}=0.4 p.u. (at 60 km from the bus BA on the section BA–Y),
- fault resistance: R_{FB}=15 Ω,
- fault incipience time: t_{flt}=60 ms.

Three-phase voltage from two ends of the line and three-phase currents from both line circuits and from two line ends are shown in Figure 5. For the applied fault resistance (R_{FB}=15 Ω) there is rather low increase of currents in both line circuits in comparison to load current. As a result of that the MOV from the faulted phase conducts a current only partly and the series capacitor does not undergo short circuited completely. However, for inter-phase faults involving low fault resistances one obtains effective shunting of series capacitor by its MOV.

Figure 6 presents estimated fault distances (d_{FA}, d_{FB}) and fault resistances (R_{FA}, R_{FB}) according to subroutines SUB_A, SUB_B. It is considered that there are two fault locators FL_A and FL_B at both line ends (Figure 2). Both locators determine the fault position as within their sections (distance<1 p.u.) and fault resistances of positive real numbers:

- FL_A: d_{FA_mean}=0.4359 p.u., R_{FA_mean}=38.94 Ω,
- FL_B: d_{FB_mean}=0.3979 p.u., R_{FB_mean}=14.57 Ω.

Note: 'mean' in the subscripts of the above results denote that the mean values of the estimated quantities from the interval of 30 to 50 ms of the fault time (Figure 6) were determined.

Thus, having only the results for the fault distance and fault resistance from the fault locators FL_A and FL_B a dilemma which fault locator yields the valid results, i.e. the results consistent with the actual fault, arises. This dilemma can be resolved by estimating the fundamental frequency equivalent impedance for the compensating bank. Resistance and reactance for this impedance in the faulted phase 'a' – relevant for the subroutines SUB_A (17a) and SUB_B (17b) are presented in Figure 7. For the subroutine SUB_A we get unrealistic result since the estimated resistance is evidently negative (–31.08 Ω), while in reality it is positive. In turn, the subroutine SUB_B yields the realistic results: resistance of positive value (21.57 Ω) and reactance of capacitive character (–40.39 Ω). On the base of these results one can clearly judge that the subroutine SUB_A be rejected as the false one, while the subroutine SUB_B s the valid subroutine. This valid subroutine yields d_{FB_mean}=0.3979 p.u. Thus, fault location is performed with small error (equal to 0.21%).

In Figure 7 the estimated impedances of the compensating bank according to both subroutines are presented for consecutive samples from fault interval. In practice the mean values for the fault location results are calculated. For the purpose of selecting the valid subroutine the fault locator FL_A determines the following mean values of the auxiliary impedances:

$$\left(\underline{Z}_{\text{Xph}}^{\text{SUB\_A}}\right)_{\text{mean}} = (54.30 + 61.52\text{i})\,\Omega \qquad (15\text{a})$$

$$\left(\underline{Z}_{\text{Xph}}^{\text{SUB\_B}}\right)_{\text{mean}} = (43.80 - 39.67\text{i})\,\Omega \qquad (15\text{b})$$

In turn, the fault locator FL_B yields:

$$\left(\underline{Z}_{\text{Yph}}^{\text{SUB\_A}}\right)_{\text{mean}} = (23.22 + 0.34\text{i})\,\Omega \qquad (16\text{a})$$

$$\left(\underline{Z}_{\text{Yph}}^{\text{SUB\_B}}\right)_{\text{mean}} = (22.51 + 0.92\text{i})\,\Omega \qquad (16\text{b})$$

In order to get the impedances of the compensating bank determined for both subroutines one has to subtract the relevant auxiliary impedances:

- for the subroutine SUB_A:

$$\begin{aligned}\left(\underline{Z}_{\text{Vph}}^{\text{SUB\_A}}\right)_{\text{mean}} &= (23.22 + 0.34\text{i}) - (54.30 + 61.52\text{i}) \\ &= (-31.08 - 61.18\text{i})\,\Omega\end{aligned} \qquad (17\text{a})$$

- for the subroutine SUB_B:

$$\begin{aligned}\left(\underline{Z}_{\text{Vph}}^{\text{SUB\_B}}\right)_{\text{mean}} &= (43.80 - 39.67\text{i}) - (22.51 + 0.92\text{i}) \\ &= (21.29 - 40.59\text{i})\,\Omega\end{aligned} \qquad (17\text{b})$$

Only the compensating bank impedance (17b) has the character of *R–C* circuit and thus the subroutine SUB_B is correctly selected as the valid one.

Different specifications of faults and pre-fault power flows have been considered in the evaluation of the accuracy of the developed fault location algorithm. For the faults involving fault resistance up to 30 Ω, the maximum errors do not exceed: 0.35% for the case of the instrument transformers with ideal transformation and 1% with the real instrument transformers included. Such errors are definitely acceptable.

4 CONCLUSIONS

The presented fault location method for double-circuit series-compensated transmission lines can be accomplished by embedding fault locators into current differential protective relays. The fault location is designed to utilize the communication infrastructure of differential relays, thus not demanding additional communication links. As a result of embedding the fault location function into the differential relay its functionality is greatly increased.

It is possible to apply a single fault locator or two locators installed at both line ends. The latter option as allowing for better fault location accuracy was mainly considered in the paper. For this option the fault location calculations, i.e. distance to fault and fault resistance, according to both subroutines do not involve the parameters of the compensating bank at all. Thus, possible adverse influence of uncertainty with respect to the parameters of the bank on accuracy of the fault location results is completely avoided.

The derived selection procedure allows reliable indication of the results, which are consistent with the actual fault. The procedure is based on determining the impedances of the compensating bank for both subroutines. This requires only subtracting the respective auxiliary impedances yielded by the subroutines. Such selection procedure does not involve the parameters of the compensating bank in the performed calculations. Thus it surpasses the selection procedure proposed earlier for the fault location designed to single series-compensated lines.

The presented fault location technique has been thoroughly tested using signals taken from ATP-EMTP versatile simulations of faults on a double-circuit series-compensated transmission line. The presented example and the carried out evaluation with use of large number of the simulated fault cases show the validity and high accuracy of the developed fault location technique.

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