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Impedance-Differential Protective Algorithm for Double-Circuit Transmission Lines

***Abstract.** In this paper, the evaluation of the concept of impedance differential scheme for double-circuit transmission line protection is presented. In case of single-circuit line, measurements of current and voltage at both line ends allow to formulate a differential impedance which constitutes efficient criterion for transmission lines protection. However, in case of double - circuit line, where there is a mutual coupling between the parallel lines, the algorithm should to be modified. Therefore, this paper introduced an improved protection scheme dedicated for double-circuit line in which mutual impedance between the parallel lines was taken into account. The proposed protection method enables for fault detection and also has ability to determine the fault location. For evaluating the validity of the considered protection algorithm for double-circuit line, computer simulation based on ATP-EMTP was carried out.*

***Streszczenie.** W niniejszym artykule przedstawiono algorytm impedancyjnego zabezpieczenia różnicowego dla linii przesyłowych dwutorowych. W przypadku linii jednotorowej pomiary prądu i napięcia na obu końcach linii pozwalają sformułować impedancję różnicową, która stanowi skuteczne kryterium w przypadku zabezpieczenia tego rodzaju linii. Jednak w przypadku linii dwutorowej, w której występuje wzajemne sprzężenie magnetyczne pomiędzy liniami, algorytm zabezpieczeniowy wymaga modyfikacji. W pracy tej przedstawiono impedancyjno – różnicowy algorytm zabezpieczenia dedykowany dla linii dwutorowej, w którym wzięto pod uwagę sprzężenie magnetyczne między poszczególnymi torami. Zaproponowany algorytm pozwala nie tylko wykryć zwarcie, ale umożliwia również określenie miejsca jego wystąpienia. Oceny rozważanego algorytmu zabezpieczenia dokonano na podstawie symulacji komputerowych wykonanych w programie ATP-EMTP (**Impedancyjne zabezpieczenie różnicowe dwutorowej linii przesyłowej**).*

Keywords: current differential protection, double-circuit line, transmission line, symmetrical components.
Słowa kluczowe: zabezpieczenie różnicowe, linia dwutorowa, linie przesyłowa, składowe symetryczne.

Introduction

Double-circuit transmission lines have been extensively utilized in modern power systems due to their economic and environmental advantages over single-circuit lines. The different possible configurations of double-circuit lines, the possibility of occurrence of faults involving two circuits combined with the effect of mutual coupling, makes their fault analysis much more difficult than for single-circuit lines [1]. Moreover, double-circuit power lines are most prone to faults and disturbances that are difficult to predict, forces the necessity of providing these lines with protection devices that would operate in a reliable and fast way. Since now, many various protection schemes for double-circuit line have been proposed.

The longitudinal current differential protection method is commonly used for parallel lines installed on the same tower [2]. However, such protection relay is influenced by the distributed capacitance and relies on communication channel [3]. The distance protection dedicated for parallel line presented in [4, 5] faces some problems, mostly due to mutual coupling between the circuits. It causes the relay become over reached or under reached depending on the network characteristics, operating status and fault location [5]. To improve the relay performance an application of adaptive protection principles is proposed in [6-9]. Other available protection solutions for double-circuit line concern current transverse differential protection including directional transverse differential protection [10-14]. Their operation is not based on communication channel but exit a long successive operating zone. Moreover, in case of parallel lines, travelling wave based protection scheme was also investigated as it is described in [15].

This paper deals with impedance-differential protective algorithm providing effective protection of transmission lines [16]. The traditional current differential relays [17] apply measurements of three-phase currents at the line ends, while the considered one [16] utilizes the measurements of both currents and voltages from the line ends. Thus, more information on the fault is provided. Based on the voltage and current measurements from both line ends, the differential impedance is calculated. This method is able to detect reliably internal faults regardless of the transmission line length. In addition, the impedance-differential protection method allows for fault location which is indisputably a great advantage.

The following sections of this paper briefly recalled the concept of impedance-differential protection for single-circuit transmission line – this method was precisely described in [16] and improved in [18]. Then, in order to implement investigated algorithm for double-circuit line, its modification is described. Next, the testing results of the proposed algorithm concerning double-circuit lines are presented and discussed.

Impedance-differential protection – formulation for single-circuit line

The evaluated impedance - differential protection algorithm introduced in [16] and improved in [18] is composed of the following steps, see Figure 1. In Table 1 the description of used variables is indicated.

Table 1. Signals and Variables used in Protective Algorithm

$\underline{I}_{S\varphi}$	current at the line terminal S
$\underline{I}_{R\varphi}$	current at the line terminal R
$\underline{V}_{S\varphi}$	voltage at the line terminal S
$\underline{V}_{R\varphi}$	voltage at the line terminal R
$\underline{V}_{S0}$	zero-sequence voltage at the line terminal S
$\underline{V}_{R0}$	zero-sequence voltage at the line terminal R
φ	faulty phase ($L1$, $L2$, $L3$)
$\underline{Y}_{1L}$	shunt admittance of the line
$\underline{Z}_{1L}$, $\underline{Z}_{0L}$	positive-, zero-sequence impedance of the line

In the first step, information concerning each phase voltages and currents from both line ends is collected and the fault detection criterion is verified. This stride allows to discriminate normal and faulty conditions in the protected line. The checking criterion is expressed as:

$$\left|\underline{I}_{S\varphi}\right| + \left|\underline{I}_{R\varphi}\right| > I_{SET} \quad (1)$$

where I_{SET} is a threshold value. If the fault condition is fulfilled, the algorithm checks whether the fault is internal or

external based on phase difference between phase angle of the calculated positive sequence impedances [18].
In the next step, the compensated differential impedance (2) is computed according to:

$$\underline{Z}_{diff}^{comp} = \left(1 + \frac{\underline{Y}_{1L}}{2}\underline{Z}_{1L}\right)\left(\frac{\underline{V}_{S\varphi}^{'} - \underline{V}_{R\varphi}^{'}}{\underline{I}_{S\varphi} - \underline{I}_{R\varphi}}\right) \quad (2)$$

where $\underline{V}_S{}'$ and $\underline{V}_R{}'$ are obtained from the following equation:

$$\underline{V}_{S\varphi}^{'} = \underline{V}_{S\varphi} - \frac{\underline{Z}_{0L} - \underline{Z}_{1L}}{\underline{Z}_{0L}}\underline{V}_{S0} \quad (3)$$

$$\underline{V}_{R\varphi}^{'} = \underline{V}_{R\varphi} - \frac{\underline{Z}_{0L} - \underline{Z}_{1L}}{\underline{Z}_{0L}}\underline{V}_{R0} \quad (4)$$

It is assumed that the fault (F) is on the line S-R, at the relative distance d [p.u.], counted from the bus S. Thereafter, the fault location can be determined using:

$$d = \frac{1}{2}\left(\frac{\operatorname{Im}(\underline{Z}_{LOC})}{\operatorname{Im}(\underline{Z}_{1L})} + 1\right) \quad (5)$$

where $\underline{Z}_{LOC}$ is calculated from:

$$\underline{Z}_{LOC} = 2\left(\underline{Z}_{diff}^{comp} - \frac{\underline{Z}_{1L}}{2}\right)\left(\frac{\underline{I}_{S\varphi} - \underline{I}_{R\varphi}}{\underline{I}_{S\varphi} + \underline{I}_{R\varphi}}\right) = \underline{Z}_{1L}(2d - 1) \quad (6)$$

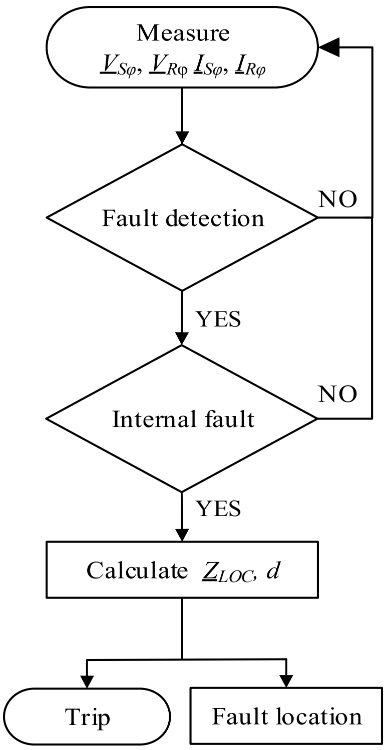

Fig. 1. Block diagram of the improved impedance-differential protection

Impedance-differential protection for double-circuit line

However, the formulas (3) and (4) cannot be implemented for double-circuit line, see Figure 2 , because in this case it is required to take into consideration the existence of mutual coupling between lines during single phase-to-earth faults.

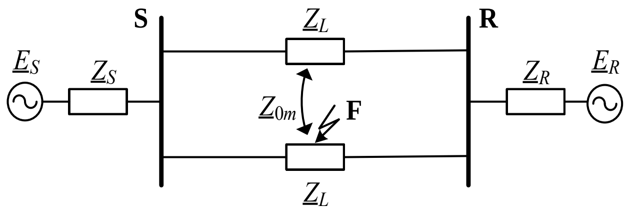

Fig.2. Schematic diagram of power network with double-circuit overhead line terminated at both ends at common buses

For this purpose, in this paper, the symmetrical components analysis is utilized. Figure 3 represents the positive-, negative-, and zero-sequence network for a double-circuit line. From Figure 2 the following relationships can be stated:

$$\begin{aligned}
&\underline{V}_{F1} = \underline{V}_{S1} - d\underline{Z}_{1L}\underline{I}_{S1} = \underline{V}_{R1} - (1-d)\underline{Z}_{1L}\underline{I}_{R1}\\
&\underline{V}_{F2} = \underline{V}_{S2} - d\underline{Z}_{1L}\underline{I}_{S2} = \underline{V}_{R2} - (1-d)\underline{Z}_{1L}\underline{I}_{R2}\\
&\underline{V}_{F0} = \underline{V}_{S0} - d\underline{Z}_{0L}\underline{I}_{S0} - d\underline{Z}_{0m}\underline{I}_{S0}^{P}\\
&= \underline{V}_{R0} - (1-d)\underline{Z}_{0L}\underline{I}_{R0} - (1-d)\underline{Z}_{0m}\underline{I}_{R0}^{P}
\end{aligned} \quad (7)$$

where $\underline{Z}_{0m}$ is mutual coupling zero-sequence impedance, $\underline{I}^{P}_{S0}$, $\underline{I}^{P}_{R0}$ is zero-sequence current from parallel line at the terminal S and R, respectively.

Considering that the fault occurs in phase $L1$, and after implementation of symmetrical component properties, it can be obtained from (7):

$$\begin{aligned}
&\underline{V}_{SL1} - \underline{V}_{RL1} - d(\underline{Z}_{0L} - \underline{Z}_{1L})\underline{I}_{S0} + (1-d)(\underline{Z}_{0L} - \underline{Z}_{1L})\underline{I}_{R0}\\
&- d\underline{Z}_{0m}\underline{I}_{S0}^{P} + (1-d)\underline{Z}_{0m}\underline{I}_{R0}^{P} = d\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1}
\end{aligned} \quad (8)$$

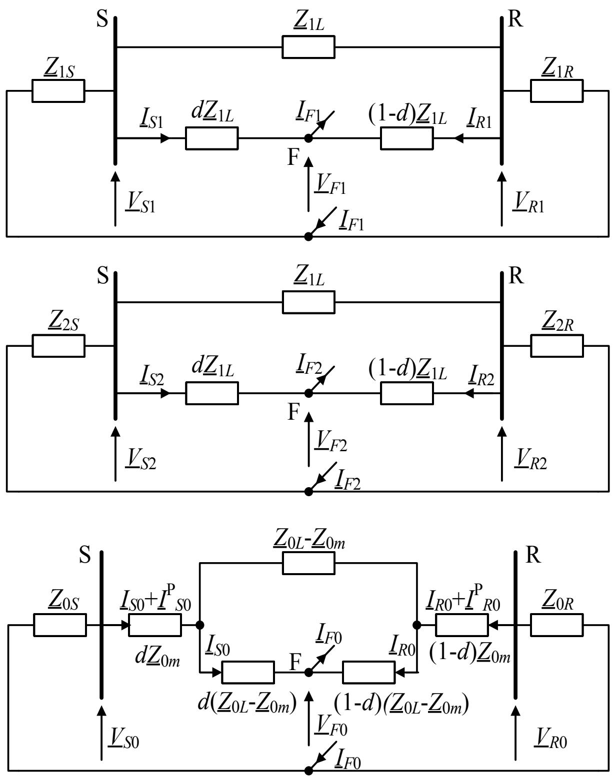

Fig.3. Equivalent circuit diagram of double-circuit line for: positive-, negative- and zero-sequence components

In view of zero-sequence circuit presented in Figure 3, the equation (8) can be defined as:

$$\begin{aligned}&\underline{V}_{SL1} - \underline{V}_{RL1} + \underline{V}_{R0} - \underline{V}_{S0} - \underline{Z}_{1L}\underline{I}_{R0} \\ &+ d\underline{Z}_{1L}\left(\underline{I}_{S0} + \underline{I}_{R0}\right) = d\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1}\end{aligned} \tag{9}$$

The missing d can be derived from zero-sequence components analysis for double-circuit line and can be expressed as:

$$d = \frac{\underline{V}_{R0} - \underline{V}_{S0} + \underline{Z}_{0L}\underline{I}_{R0} + \underline{Z}_{0m}\underline{I}^{P}_{R0}}{\underline{Z}_{0L}\left(\underline{I}_{S0} + \underline{I}_{R0}\right) + \underline{Z}_{0m}\left(\underline{I}^{P}_{S0} + \underline{I}^{P}_{R0}\right)} \tag{10}$$

Thus, the equation (9) can be written as:

$$\begin{aligned}&\underline{V}_{SL1} - \underline{V}_{RL1} + \underline{V}_{R0} - \underline{V}_{S0} - \underline{Z}_{1L}\underline{I}_{R0} + \\ &\frac{\underline{Z}_{1L}\left(\underline{V}_{R0} - \underline{V}_{S0} + \underline{Z}_{0L}\underline{I}_{R0} + \underline{Z}_{0m}\underline{I}^{P}_{R0}\right)}{\underline{Z}_{0L}\left(\underline{I}_{S0} + \underline{I}_{R0}\right) + \underline{Z}_{0m}\left(\underline{I}^{P}_{S0} + \underline{I}^{P}_{R0}\right)}\left(\underline{I}_{S0} + \underline{I}_{R0}\right) \\ &= d\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1}\end{aligned} \tag{11}$$

Analogous equations are valid for the remaining single-phase-to-earth faults (*L*2–*E*, *L*3–*E*). The obtained formula (11) in case of double-circuit line replaces in (2) part concerning voltage difference $\underline{V}_{S\varphi}'$-$\underline{V}_{R\varphi}'$ formulated for single line.

Simulation Results

For evaluating the presented algorithm, the representative model of the 400 kV, double-circuit transmission line supplied from both sides has been investigated. The simulation tests were performed in ATP-EMTP [19], while protection algorithm was implemented in MATLAB software. The double-end line, whereas the sending equivalent system *S* is assumed to be strong (of high short-circuit power S_{kS}"= 30 GVA), while the receiving one *R* is weak (S_{kR}"= 5 GVA). The currents and voltages phasors estimation is done by the full-cycle Fourier filtering. The developed model includes ideal CTs and the secondary currents and secondary voltages are filtered by anti-aliasing filters of 1 kHz/3=330 Hz cut off frequency. The line parameters are gathered in Table 2.

In order to test the proposed protection algorithm, short-circuit simulations have been conducted inside the line as well as beyond it. Different line lengths – 50 km, 80 km and 200 km have been taken under consideration whereas the faults have been applied inside the protected zone, referring to *S* side at distances of d = 0.1; 0.2;…0.9 p.u. The studies included four different short-circuit types: three-phase fault (*L*1-*L*2-*L*3) and different types of asymmetrical faults (phase-to-earth (*L*1-*E*), phase-to-phase (*L*1-*L*2), and phase-to-phase-to-earth (*L*1-*L*2-*E*) faults.

Table 2. Unit Parameters of the Transmission Line Model

Parameter	R' [Ω/km]	$\omega_1 L'$ [Ω/km]	C' [nF/km]
Zero sequence	0.1812	0.764	8.50
Positive sequence	0.0235	0.288	13.0
Mutual sequence	0.1563	0.476	12.0

Presented results in Table 3 concern phase-to-phase (*L*1-*L*2) faults, in view of different line lengths. The results indicating phase-to-earth (*L*1-*E*) faults, regarding to the fault resistance, are presented in Table 4 and Table 5. Computed distance to fault is defined as an average of all obtained values within third cycle of fault interval. The error of protection algorithm is defined as:

$$error(\%) = \left(d_{computed} - d_{actual}\right) * 100 \tag{12}$$

Table 3. Computed Fault Location - *L*1-*L*2 Fault, R_F=0.02 Ω

Fault loc. [p.u]	50km		80km		200km	
	$d_{comp.}$ [p.u]	*error* [%]	$d_{comp.}$ [p.u]	*error* [%]	$d_{comp.}$ [p.u]	*error* [%]
0.1	0.1001	0.0140	0.0998	0.0162	0.0989	0.1081
0.2	0.1998	0.0209	0.1995	0.0498	0.1984	0.1624
0.3	0.2995	0.0475	0.2993	0.0685	0.2983	0.1654
0.4	0.3993	0.0670	0.3992	0.0763	0.3987	0.1332
0.5	0.4992	0.0815	0.4992	0.0776	0.4992	0.0820
0.6	0.5991	0.0929	0.5992	0.0757	0.5997	0.0328
0.7	0.6990	0.1031	0.6993	0.0737	0.7001	0.0076
0.8	0.7989	0.1137	0.7993	0.0745	0.8004	0.0364
0.9	0.8987	0.1257	0.8992	0.0800	0.9003	0.0296
Max.	-	0.1257	-	0.0800	-	0.1654
Avg.	-	0.0740	-	0.0658	-	0.0842

The example (case 1) is presented in Figure 4 – Figure 5, while Figure 6 indicates computed fault location. The specifications of the case 1 are as follows: phase-to-phase (*L*1-*L*2) fault at 40% of 50 km line, fault resistance R_f = 0.02 Ω.

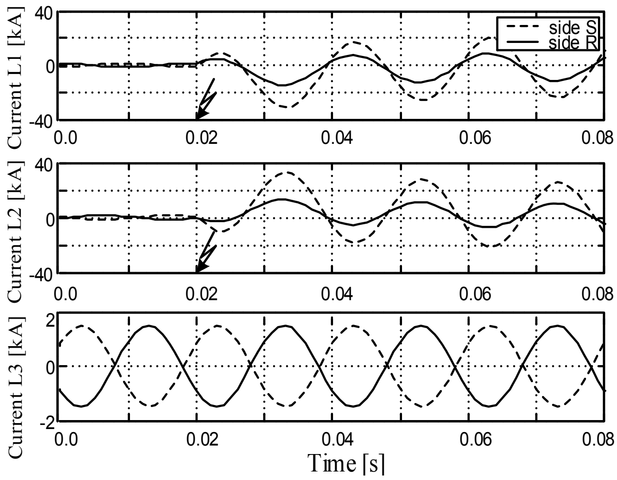

Fig. 4. The case 1 – Current waveshapes of protected line

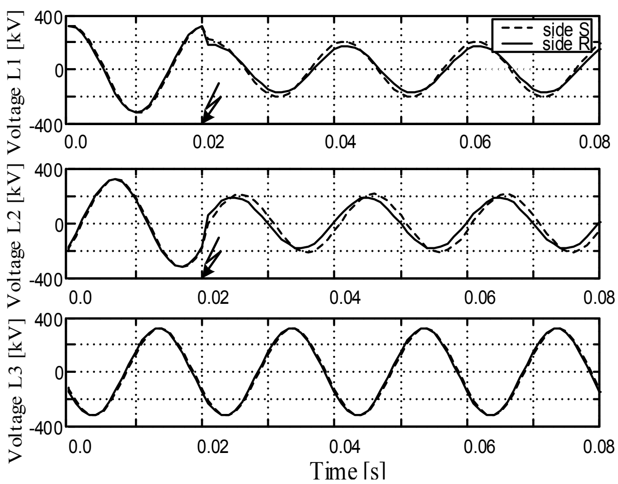

Fig. 5. The case 1 – Voltage waveshapes of protected line

For the investigation concerning fault resistance changes, the following values of resistance were applied: 2 Ω, 10 Ω, 25 Ω, 50 Ω. In this section only chosen examples are presented.

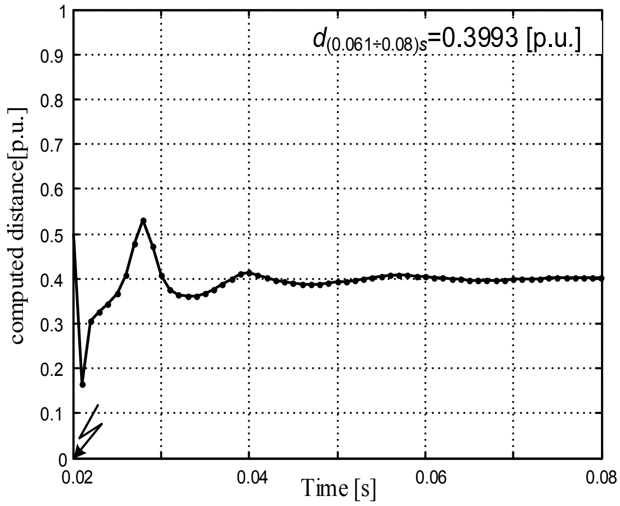

Fig. 6. The case 1 – computed distance and its average

Table 4. Fault Location - *L*1-*E* Fault, 50 km line

Fault loc. [p.u]	10 Ω		50 Ω	
	$d_{computed}$ [p.u]	*error* [%]	$d_{computed}$ [p.u]	*error* [%]
0.1	0.1009	0.0868	0.1014	0.1387
0.2	0.2006	0.0589	0.2010	0.0989
0.3	0.3004	0.0360	0.3006	0.0632
0.4	0.4002	0.0166	0.4003	0.0303
0.5	0.5001	0.0001	0.5000	0.0014
0.6	0.5998	0.0169	0.5997	0.0333
0.7	0.6997	0.0334	0.6993	0.0670
0.8	0.7995	0.0514	0.7990	0.1038
0.9	0.8993	0.0718	0.8985	0.1452
Max.	-	0.0868	-	0.1452
Avg.	-	0.0413	-	0.0758

Based on the obtained results, it can be concluded that the average error is greater for phase-to-earth faults than for phase-to-phase faults. Despite this, the error is relatively small, and its maximal value is approximately equal to 0.29% in case of single-phase to earth fault, arisen at the 90% of the 200 km line length. In addition, the average computed error for all investigated cases does not achieve 0.18%.

Table 5. Fault Location - *L*1-*E* Fault, 200 km line

Fault loc. [p.u]	10 Ω		25 Ω	
	$d_{computed}$ [p.u]	*error* [%]	$d_{computed}$ [p.u]	*error* [%]
0.1	0.0981	0.1878	0.0987	0.1291
0.2	0.1975	0.2460	0.1981	0.1872
0.3	0.2977	0.2251	0.2983	0.1686
0.4	0.3985	0.1486	0.3990	0.0976
0.5	0.4996	0.0381	0.5000	0.0025
0.6	0.6008	0.0832	0.6011	0.1077
0.7	0.7019	0.1934	0.7020	0.1952
0.8	0.8027	0.2706	0.8024	0.2427
0.9	0.9029	0.2946	0.9023	0.2291
Max.	-	0.2946	-	0.2427
Avg.	-	0.1875	-	0.1236

After consideration of various fault resistance values, see Table 4 - 5, it can be concluded that the impedance based protection algorithm works correctly for all simulated cases. The accuracy of the fault locations computation remains on the same level for all of the investigated line lengths. The computed error obtained for all considered fault resistances does not exceed 0.3% in any of investigated cases. Moreover, the maximal computed error, with respect to different fault resistance, is higher for longer lines and in case of 50 km line does not exceed 0.15%. What is more, better results concerning average error computations are obtained for shorter line, but in both cases this values are lesser than 0.3%.

The example (case 2) concerning phase-to-earth fault, at 20% of 50 km line, R_f = 10 Ω is depicted in Figure 7 – Figure 8 and the calculated distance is shown in Figure 9.

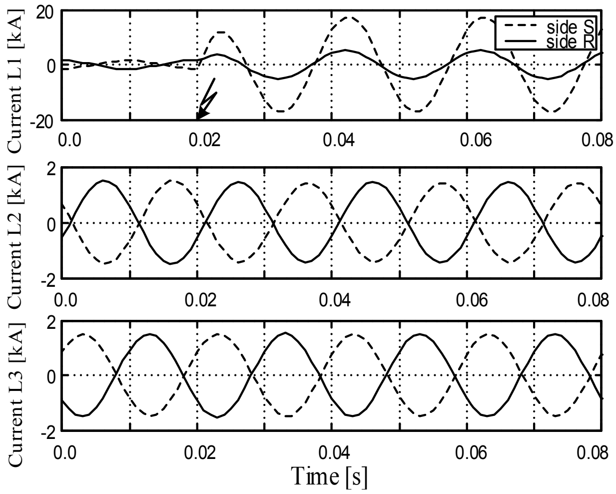

Fig. 7. The case 2 – Current waveshapes of protected line

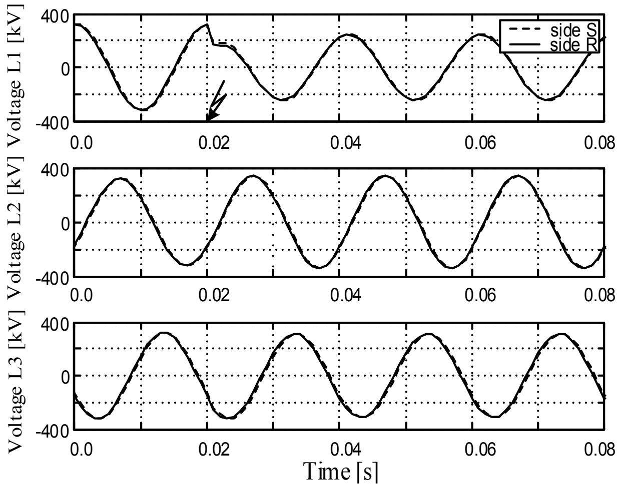

Fig. 8. The case 2 – Voltage waveshapes of protected line

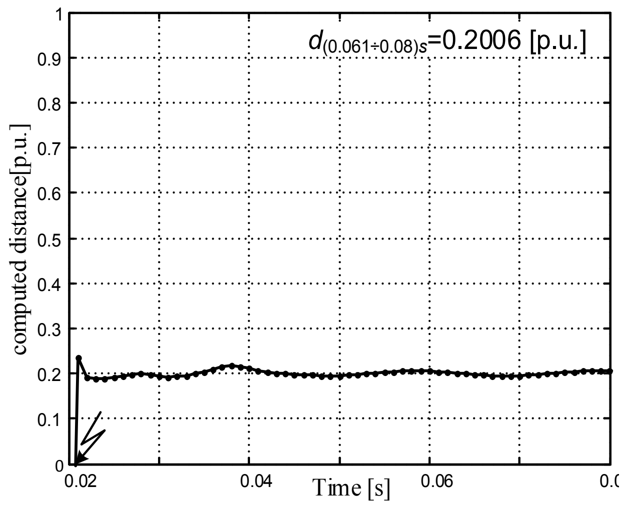

Fig. 9. The case 2 – computed distance and its average

Note, that the differential impedance algorithm enabled to locate faults in double-circuit line with maximal average error smaller than 0.20%.

As presented in Tables 3 - 5, the proposed protection algorithm for double-circuit line allows to detect faults in all conditions, regardless of fault location and fault resistance.

Conclusions

In this paper the concept of impedance-differential protection for double-circuit transmission line is presented. The demonstrated protection algorithm enables not only for internal fault detection, but can be applied also as a fault locator. Based on simulation results it can be concluded that the method can be applicable for double-circuit lines. What is more, the presented method can be used effectively for double-circuit lines with different lengths as well as it is not affected by the fault resistance changes. Since the discussed protection does not operate during external faults, the selectivity is also affirmed.

Moreover, capacitive charging current which constitutes the main drawback of current differential protection is eliminated in presented protection method and thus does not impact on the determination of fault location.

In the further investigation of the presented protection method dedicated for double-circuit transmission lines the effect of current transformers saturation should be examined.

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