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INVESTIGATION OF IMPEDANCE-DIFFERENTIAL PROTECTION'S ALGORITHM AS A FAULT LOCATOR FOR DOUBLE-CIRCUIT TRANSMISSION LINE

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This paper deals with an analysis of impedance-differential protection algorithm applied to locate faults on a double-circuit transmission line. In particular, the study of fault location accuracy for the case of using the relation between currents for negative-sequence not for zero-sequence, as it was presented so far, is provided. It results from the well-known fact that zero-sequence impedances are in practice considered as quite unreliable data. Therefore, one has to limit usage of zero-sequence impedance parameters as much as possible. Such approach was applied in this paper and therefore the use of the additional relation of currents for negative-sequence is under investigation. The fault signals from ATP-EMTP simulation on the sample double-circuit transmission line was applied for evaluating the fault location accuracy. References 8, figures 4, table 1.

Keywords: double-circuit line, transmission line, fault location, ATP-EMTP, simulation, algorithm, negative and zero sequences

Introduction. Due to their economic and environmental advantages, double-circuit transmission lines have been extensively utilised in modern power systems. However, 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 complicated than for single-circuit lines [1]. Different protection schemes for the double-circuit line [2, 3] have been proposed which face problems, mostly due to mutual coupling between the circuits. It causes that the relay becomes overreached or underreached depending on the network characteristics, operating status and fault location [3].

In this paper, an analysis of impedance-differential protective algorithm of transmission line [4] is presented. The considered protection [4] utilises the measurements of both currents and voltages from line ends. Based on the voltage and current measurements, the differential impedance is calculated. This method provides reliable internal faults detection. In addition, the impedance-differential protection method allows for fault location, which is indisputably a great advantage. The distance to fault determination [5] can be utilised for an inspection-repair purpose. This paper is analysing the fault location feature of the impedance-differential algorithm. In particular, a comprehensive evaluation of fault location accuracy with the use of the simulation data is presented.

The following sections of this paper briefly recalled the concept of impedance-differential algorithm for single-circuit transmission line initially described in [4] and improved in [6]. Then, in order to implement investigated algorithm for double-circuit line, its modification is described. The method presented in this paper replaces the usage of a zero sequence component analysis [7] for consideration of the mutual coupling existence between lines by the usage of a negative sequence component analysis. Next, testing results of the proposed distance to fault calculation in double-circuit lines are compared with the method presented in [7].

Analysis of impedance-differential algorithm. The evaluated impedance - differential protection algorithm dedicated for a single-circuit line was primary introduced in [4] and improved in [6]. Although, authors in [7] adapted this algorithm for utilisation in a double-circuit line. The modification of the algorithm [7] is presented in this chapter.

At the beginning of impedance-differential protection algorithm, information concerning each phase voltages and currents from both line ends is collected, and next, the fault detection criterion is verified. This allows discriminating normal and faulty conditions in the protected line. The criterion is stated as:

$$\left|\underline{I}_{S\phi}\right| + \left|\underline{I}_{R\phi}\right| > I_{SET}\,, \tag{1}$$

where I_{SET} is the threshold value and $I_{R\varphi}$, $I_{S\varphi}$ is the current in phase φ at the line terminal S, R. If the fault condition is fulfilled, the algorithm checks whether the fault is internal or external based on the phase difference between the phase angle of the calculated positive sequence impedances [6]. Then, the compensated differential impedance (2) is expressed according to:

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

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

$$\underline{V}'_{S(R)\phi} = \underline{V}_{S(R)\phi} - \frac{\underline{Z}_{0L} - \underline{Z}_{1L}}{\underline{Z}_{0L}} \underline{V}'_{S(R)0} . \tag{3}$$

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:

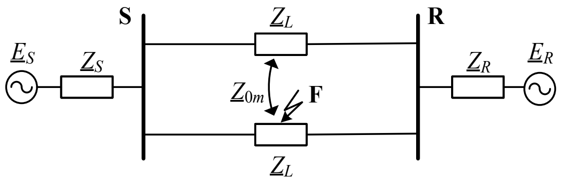

Fig. 1

$$d = \frac{1}{2}\left(\frac{\mathrm{Im}\left(\underline{Z}_{LOC}\right)}{\mathrm{Im}\left(\underline{Z}_{1L}\right)} + 1\right) \tag{4}$$

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

$$\underline{Z}_{LOC} = 2\left(\underline{Z}_{diff}^{comp} - \frac{\underline{Z}_{1L}}{2}\right)\left(\frac{\underline{I}_{S\phi} - \underline{I}_{R\phi}}{\underline{I}_{S\phi} + \underline{I}_{R\phi}}\right) = \underline{Z}_{1L}\left(2d - 1\right). \tag{5}$$

However, the formula (3) cannot be applied directly for a double-circuit line, see Fig. 1 (schematic diagram of power network with a double-circuit line), because in this case it is required to consider the existence of mutual coupling between lines during single phase-to-earth faults.

For this aim, the symmetrical components analysis is utilised. Fig. 2 represents the positive, negative, and zero sequence network for a double-circuit line.

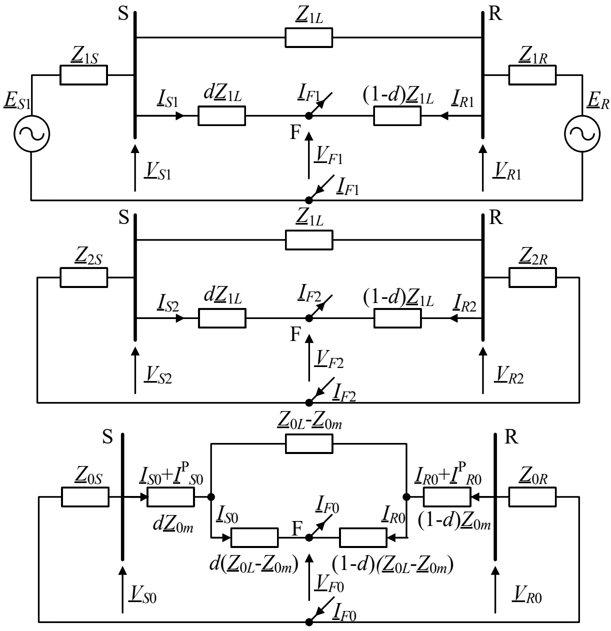

Fig. 2

From Fig. 2, the following relation can be stated:

$$\begin{aligned}
&\underline{V}_{F1} = \underline{V}_{S1} - d\,\underline{Z}_{1L}\underline{I}_{S1} = \underline{V}_{R1} - (1-d)\underline{Z}_{1L}\underline{I}_{R1}\\
&\underline{V}_{F2} = \underline{V}_{S2} - d\,\underline{Z}_{1L}\underline{I}_{S2} = \underline{V}_{R2} - (1-d)\underline{Z}_{1L}\underline{I}_{R2}\\
&\underline{V}_{F0} = \underline{V}_{S0} - d\,\underline{Z}_{0L}\underline{I}_{S0} - d\,\underline{Z}_{0m}\underline{I}^{P}_{S0} = \underline{V}_{R0} -\\
&\qquad - (1-d)\underline{Z}_{0L}\underline{I}_{R0} - (1-d)\underline{Z}_{0m}\underline{I}^{P}_{R0}
\end{aligned} , \tag{6}$$

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

Considering that the fault occurs in phase $L1$, with the implementation of symmetrical component properties, it can be obtained from (6):

$$\begin{aligned}
&\underline{V}_{SL1} - \underline{V}_{RL1} - d\left(\underline{Z}_{0L} - \underline{Z}_{1L}\right)\underline{I}_{S0} + \left(1-d\right)\left(\underline{Z}_{0L} - \underline{Z}_{1L}\right)\underline{I}_{R0} -\\
&-d\underline{Z}_{0m}\underline{I}^{P}_{S0} + \left(1-d\right)\underline{Z}_{0m}\underline{I}^{P}_{R0} = d\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1}
\end{aligned} . \tag{7}$$

Taking into account the third equation from (6) concerning zero sequence components, the equation (7) can be rewritten as:

$$\begin{aligned}
&\underline{V}_{SL1} - \underline{V}_{RL1} + \underline{V}_{R0} - \underline{V}_{S0} - \underline{Z}_{1L}\underline{I}_{R0} + d\,\underline{Z}_{1L}\left(\underline{I}_{S0} + \underline{I}_{R0}\right) =\\
&= d\,\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1} .
\end{aligned} \tag{8}$$

The missing d can be derived from negative sequence components analysis and can be stated as:

$$d = \frac{\underline{V}_{S2} - \underline{V}_{R2} + \underline{Z}_{1L}\underline{I}_{R2}}{\underline{Z}_{1L}\left(\underline{I}_{S2} + \underline{I}_{R2}\right)} . \tag{9}$$

Thus, equation (8) can be rewritten as:

$$\underline{V}_{SL1} - \underline{V}_{RL1} + \underline{V}_{R0} - \underline{V}_{S0} - \underline{Z}_{1L}\underline{I}_{R0} + \frac{\left(\underline{I}_{S0} + \underline{I}_{R0}\right)\left(\underline{V}_{S2} - \underline{V}_{R2} + \underline{Z}_{1L}\underline{I}_{R2}\right)}{\left(\underline{I}_{S2} + \underline{I}_{R2}\right)} = d\underline{Z}_{1L}\underline{I}_{SL1} - (1-d)\underline{Z}_{1L}\underline{I}_{RL1} . \tag{10}$$

Finally, the voltage difference $\underline{V}'_{S\varphi} - \underline{V}'_{R\varphi}$ from the equation (2) can be written for phase $\varphi = L1$:

$$\underline{V}'_{SL1} - \underline{V}'_{RL1} = \underline{V}_{SL1} - \underline{V}_{RL1} + \underline{V}_{R0} - \underline{V}_{S0} - \underline{Z}_{1L}\underline{I}_{R0} + \frac{\left(\underline{I}_{S0} + \underline{I}_{R0}\right)\left(\underline{V}_{S2} - \underline{V}_{R2} + \underline{Z}_{1L}\underline{I}_{R2}\right)}{\left(\underline{I}_{S2} + \underline{I}_{R2}\right)} . \tag{11}$$

For the remaining single-phase-to-earth faults ($L2$–E, $L3$–E) analogous equations are valid.

Simulation results. For assessing the presented algorithm, the model of the 400 kV, double-circuit transmission line supplied from both ends has been investigated. The simulation tests were performed in ATP-EMTP [8], while the fault location algorithm was implemented in MATLAB. The sending equivalent system S is assumed to be strong ($S''_{kS} = 30GVA$), while the receiving one R is weak ($S''_{kR} = 5GVA$). The model includes ideal CTs and currents and voltages are filtered by anti-aliasing filters of $1kHz/3 = 330Hz$ cut off frequency. The currents and voltages phasors estimation is done using the DFT. The data of the considered transmission line for positive and zero sequences are: $\underline{Z}_{1L} = (0.0267 + j0.3151)\Omega/km$, $\underline{C}_{1L} = 0.013\mu F/km$, $\underline{Z}_{0L} = (0.0275 + j1.0265)\Omega/km$, $\underline{C}_{0L} = 0.085\mu F/km$, $\underline{Z}_{0m} = (0.1896 + j1.5671)\Omega/km$.

In order to test the proposed algorithm, short-circuit simulations have been conducted inside the line, for two different line lengths – 50 km, 100 km. The faults have been applied inside the protected zone, referring to S side at distances of $d = 0.1; 0.2;\ldots 0.9$ [p.u.] The studies included phase-to-earth ($L1$-E) faults. Presented results in Table concern $L1$-E faults, in view of different line lengths. The example: $L1$-E fault at 40% of 50 km line, $R_f = 1\ \Omega$, is presented in Fig. 3 – 4. In Fig. 3 are presented currents at busbar S and R and in Fig. 4 is indicated the computed distance.

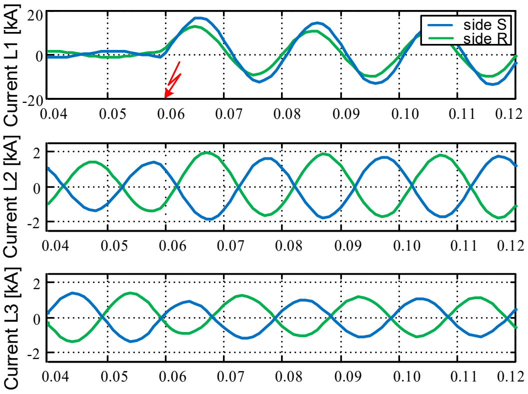

Fig. 3

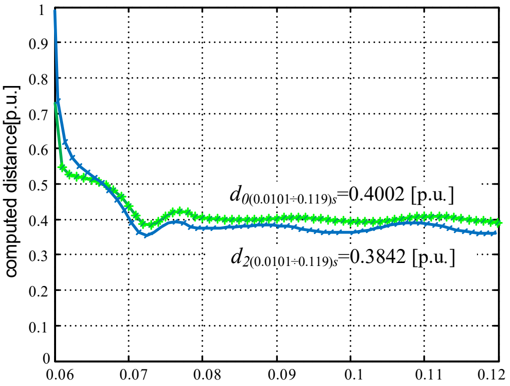

Fig.4

The computed distance to fault is defined as an average of all obtained values within the third cycle of fault interval. The error of the protection algorithm is defined as:

$$error(\%) = \left(d_{comp.} - d_{act.}\right) * 100, \qquad (12)$$

where $d_{act.}$ is the actual (used in simulation) distance to fault referring to the S side in [p.u.] and $d_{comp.}$ is calculated distance to fault in [p.u.]. The presented results (Table) concern phase-to-earth ($L1$-E) faults inside the line, whereas the fault location errors were determined as follows: $error_0$ – use of zero sequence component analysis (as presented in [7]), $error_2$ – use of negative sequence component analysis.

	50km				100km			
$d_{act.}$	The algorithm used in [7]		Presented algorithm		The algorithm used in [7]		Presented algorithm	
[p.u]	$d_{comp.}$[p.u]	$error_0$[%]	$d_{comp.}$[p.u]	$error_2$[%]	$d_{comp.}$[p.u]	$error_0$[%]	$d_{comp.}$[p.u]	$error_2$[%]
0.1	0.1003	0.0284	0.0732	2.6754	0.0985	0.1452	0.0649	3.5146
0.2	0.2003	0.0267	0.1769	2.3119	0.1989	0.1127	0.1696	3.0362
0.3	0.3002	0.0245	0.2805	1.9494	0.2993	0.0675	0.2746	2.5445
0.4	0.4002	0.0210	0.3841	1.5885	0.3998	0.0214	0.3795	2.0529
0.5	0.5002	0.0152	0.4877	1.2305	0.5002	0.0241	0.4844	1.5614
0.6	0.6001	0.0060	0.5912	0.8764	0.6006	0.0618	0.5892	1.0786
0.7	0.6999	0.0074	0.6947	0.5271	0.7009	0.0857	0.6939	0.6108
0.8	0.7997	0.0254	0.7982	0.1832	0.8009	0.0899	0.7984	0.1647
0.9	0.8995	0.0476	0.9016	0.1558	0.9007	0.0701	0.9025	0.2549
Max.	-	0.0476	-	2.6754	-	0.1452	-	3.5146
Avg.	-	0.0225	-	1.2776	-	0.0754	-	1.6465

From Table, it is visible that computations concerning negative sequence component enabled the algorithm to locate faults in double-circuit line, however, were less accurate than in case of zero sequence component analysis. The accuracy of the presented fault location algorithm raised according to the increasing length of the line. The maximal error obtained by the presented algorithm exceeded 2.6% for 50 km line and 3.5% in the case of 100 km line. In contrast, the results concerning maximal error calculated in case of the algorithm based on zero sequence components analysis was smaller than 0.2%. The average error for the proposed algorithm did not exceed 1.7% and for the algorithm presented in [7] was smaller than 0,14%. What is more, better results concerning average error computations are obtained for a shorter line, in case of both algorithms. It can be concluded that the impedance based fault location algorithm works correctly for all simulated cases.

Conclusion. In this paper, the idea of impedance-differential protection for a double-circuit transmission line is presented, which enables for internal fault detection, but can also be used for faults location. The main interest of this paper is put on the fault location function compatible with the considered protection. Based on simulation results, it can be concluded that the method can be applied effectively for double-circuit lines with different lengths.

The carried out investigations has revealed that accuracy of fault location with incorporated relation of currents for negative-sequence is somehow deteriorated in comparison to the case of using the relation relevant for zero-sequence [7]. However, the accuracy is still acceptable and thus the approach introduced in this paper (use of the relation for negative-sequence) can be applied if the high level of unreliability of zero-sequence impedance data is the case. It causes that the usage of zero-sequence impedance parameters can be limited.

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ИССЛЕДОВАНИЕ АЛГОРИТМА ИМПЕДАНСНО-ДИФФЕРЕНЦИАЛЬНОЙ ЗАЩИТЫ КАК ЛОКАТОРА НЕИСПРАВНОСТЕЙ ДЛЯ ЛИНИИ ЭЛЕКТРОПЕРЕДАЧИ

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В статье проводится анализ алгоритма импедансной дифференциальной защиты, применяемой для определения места короткого замыкания в параллельной линии электропередачи. Определение дифференциального импеданса, который базируется на измерении токов и напряжений на обоих концах линии, является основой эффективного критерия для защиты одиночной линии электропередачи. Однако этот метод имеет свои недостатки в применении для параллельной ЛЭП. Из-за взаимного сопряжения между параллельными линиями он должен быть соответственно модифицирован. Кроме того, предлагаемая импедансно-дифференциальная защита может выполнять функции определения места короткого замыкания. Сигналы, полученные из проводимых компьютерных экспериментов с использованием модели участка сети с параллельной ЛЭП (применялась программа ATP-EMTP), были использованы для оценки точности локализации повреждения линии. Библ. 8, рис. 4, табл. 1.

Ключевые слова: параллельная линия электропередачи, ЛЕП, локализация короткого замыкания, ATP-EMTP, симуляция алгоритм, обратная и нулевая последовательности.

ДОСЛІДЖЕННЯ АЛГОРИТМА ІМПЕДАНСНО-ДИФЕРЕНЦІАЛЬНОГО ЗАХИСТУ ЯК ЛОКАТОРА ПОШКОДЖЕНЬ ДЛЯ ЛІНІЇ ЕЛЕКТРОПЕРЕДАЧІ

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У статті проведено аналіз алгоритму імпедансно-диференційного захисту, що застосовується для визначення місця короткого замикання у паралельній лінії електропередачі. Визначення диференціального імпедансу, який базується на вимірі струмів і напруг на обох кінцях лінії, є основою ефективного критерію для захисту одиночної лінії електропередачі. Однак цей метод має свої недоліки в застосуванні для паралельної ЛЕП. Через взаємне сполучення між паралельними лініями цей алгоритм повинен бути відповідно модифікований. Крім того, запропонований імпедансно-диференційний захист може виконувати функції визначення місця короткого замикання. Сигнали, отримані з проведених комп`ютерних експериментів з використанням моделі ділянки мережі з паралельної ЛЕП (застосовувалася програма ATP-EMTP), було використано задля оцінки точності локалізації пошкодження лінії. Бібл. 8, рис. 4, табл. 1.

Ключові слова: паралельна лінія електропередачі, ЛЕП, локалізація короткого замикання, ATP-EMTP, симуляція алгоритм, зворотна і нульова послідовності.

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