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INVESTIGATION OF IMPEDANCE - DIFFERENTIAL PROTECTIVE ALGORITHM FOR EXTERNAL FAULTS WITH CT SATURATION

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In this paper, the analysis of impedance - differential protective algorithm dedicated for transmission line protection relay is presented. Measurements of current and voltage at both line ends enable to formulate a differential impedance which constitutes efficient criterion for protection purposes. Special attention is focused on algorithm operation in case of external faults appearance, which have to be distinguished properly due to security reasons in both situations - without and with CTs saturation. The sensitivity and the reliability of the presented protection algorithm were evaluated based on simulation carried out in ATP-EMTP simulation program. References 9, tables 1, figures 3.

Key words: differential protection, transmission line, CT saturation, ATP-EMTP, simulation.

Introduction. All of following features: high selectivity for all fault types even in case of power system with multi-terminal transmission lines, toleration to high line loading [1], fast operational speed for weak infeed/no-infeed terminal or stable operation in the presence of both high frequency ac- and dc components occurred during system faults [2], characterize current differential protection (CDP). Moreover, due its simple principle which required only information about current signals, CDP is easy to apply [3]. Based on these features, the current differential protection has been widely used as a protection for transmission line of any length. However, both security and sensitivity of current differential protection can be disturbed by current transformer (CT) saturation mainly caused by a high value of fault current amplitude or/and decaying dc components in fault currents or in-rush currents with a long time constant [4]. Such situation can occur especially during external faults with heavy CT saturation and may cause redundant operation of classical differential protection. To avoid maloperation and improve its reliability several methods can be found in the literature [5], [4, 6, 7], Since this solutions do not guarantee desired effects for all situation, new protection ideas are still required to improve relay operation, especially while CTs saturation happens.

The authors of this paper present the concept of impedance - differential protection introduced in [8] which can be applied as a main protection in transmission line. Based on the voltage and current measurements from both line ends, the differential impedance is calculated. The performed investigation are focused on the evaluation of the algorithm in case of external faults with special attention to possible occurrence of CTs saturation. For this purpose, several cases of both internal and external disturbances without and with CTs saturation are depicted and analyzed. The examination of algorithm were performed using the fault data obtained from ATP-EMTP.

Analysis of impedance-differential protection. The basis of impedance - differential protective algorithm [8] is explained by utilization of single phase model of the faulted transmission line (Fig. 1). It is assumed that *d* is per unit distance from terminal S to F (fault point).

In Fig. 1 $\underline{Z}_L$ represents the lumped line impedance, while the line shunt admittance is defined in (1) and the line shunt capacitance is C_L.

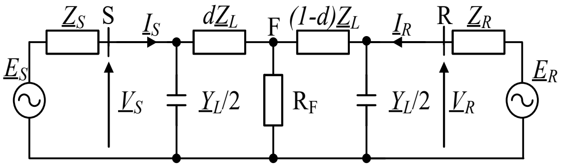

Fig. 1

$$\frac{\underline{Y}_L}{2}=\frac{j\omega C_L}{2}. \tag{1}$$

Based on Fig. 1 the following equation can be formulated:

$$\left(1+\frac{\underline{Y}_L d\underline{Z}_L}{2}\right)\underline{V}_S-\left(1+\frac{\underline{Y}_L(1-d)\underline{Z}_L}{2}\right)\underline{V}_R=\underline{Z}_L\left(d\underline{I}_S-(1-d)\underline{I}_R\right). \tag{2}$$

The voltage coefficients $\underline{V}_s$, $\underline{V}_R$ in (2) are replaced by their average value results in

$$\left(1+\frac{\underline{Y}_L\underline{Z}_L}{2}\right)(\underline{V}_S-\underline{V}_R)=d\,\underline{Z}_L\underline{I}_S-(1-d)\,\underline{Z}_L\underline{I}_R. \tag{3}$$

The differential impedance and the compensated differential impedance are expressed as follows:

$$\underline{Z}_{diff}^{comp}=\left(1+\frac{\underline{Y}_L\underline{Z}_L}{2}\right)\left(\frac{\underline{V}_S-\underline{V}_R}{\underline{I}_S-\underline{I}_R}\right)=\left(1+\frac{\underline{Y}_L\underline{Z}_L}{2}\right)\underline{Z}_{diff}. \tag{4}$$

Hence, the locational differential impedance is obtained

$$\underline{Z}_{LOC} = 2\left(\underline{Z}_{diff}^{comp} - \frac{\underline{Z}_L}{2}\right)\left(\frac{\underline{I}_S - \underline{I}_R}{\underline{I}_S + \underline{I}_R}\right) = \underline{Z}_L\left(2d - 1\right). \tag{5}$$

Therefore, the fault location is described using (6) where *real* part is considered to exclude imaginary part which can appear in case of measurements and calculations errors

$$d = \frac{1}{2}\operatorname{Re}\left(\frac{\operatorname{Im}\left(\underline{Z}_{LOC}\right)}{\operatorname{Im}\left(\underline{Z}_{1L}\right)} + 1\right). \tag{6}$$

Moreover, in case of external faults, the locational differential impedance is equal to 0. Therefore, it allows to distinguish if the fault occurs in or outside the protected line. For the sake of briefness the calculations of asymmetrical faults in three phase system are not presented in this paper. However, the locational differential impedance is almost the same what is proved in [8].

In accordance to (5) when the fault appears in the middle of the line, the compensated differential impedance is equal to $\underline{Z}_L/2$ - the same as in case of external faults. It forces to define additional criterion to overcome this problem. In [9] the authors have been proposed to calculate the integrated impedance ($\underline{Z}_{II}$) for faulty phase (φ)

$$\underline{Z}_{II} = \frac{\underline{V}_{S\phi} + \underline{V}_{R\phi}}{\underline{I}_{S\phi} + \underline{I}_{R\phi}}. \tag{7}$$

The sign of imaginary parts of integrated impedance, both during external faults and normal system operation, is negative [9]. While internal fault occurs, the sign of imaginary part of $\underline{Z}_{II}$ is always positive [9].

The evaluated protective algorithm is presented in [8]. At the beginning, synchronized information about voltages and currents from both line sides is collected. Based on current signals, the fault detection criterion is checked (**1st condition**). This criterion is expressed in (8) where I_{SET} is a threshold value. In case of fault condition, the algorithm analyzes whether the fault is internal or external

$$\left|\underline{I}_{S\phi}\right| + \left|\underline{I}_{R\phi}\right| > I_{SET}. \tag{8}$$

Subsequently, $\underline{Z}_{LOC}$ and d are evaluated. The compensated differential impedance is computed according to:

$$\underline{Z}_{diff}^{comp} = \left(1 + \frac{\underline{Y}_L}{2}\underline{Z}_L\right)\left(\frac{\underline{V}_S^{'} - \underline{V}_R^{'}}{\underline{I}_S - \underline{I}_R}\right), \tag{9}$$

where voltages ($\underline{V}_S^{'}, \underline{V}_R^{'}$) are calculated from (10), where 0, 1 mean zero- and positive-sequence components.

$$\underline{V}_{S\phi}^{'} = \underline{V}_{S\phi} - \frac{\underline{Z}_{0L} - \underline{Z}_{1L}}{\underline{Z}_{0L}}\underline{V}_{S0}. \tag{10}$$

Thereafter, regarding (6) the fault location can be determined. If calculated distance is equal to half of line length which can be achieved in case of midpoint and external faults (**2nd condition**), the criterion including calculation of integrated impedance imaginary part is used (**3rd condition**).

Simulation results. The main aim of simulation was to assess operation of the evaluated algorithm if CTs saturation takes place. The simulation tests have been done for a representative model of a power system with 400 kV transmission line developed in EMTP-ATP (Fig. 1). The overhead transmission line is modeled as transposed one with distributed parameters (positive sequence line impedance - Z_{1L}=0.0276+j0.315, and capacitance - C_{1L}= 0.013uF, zero sequence line impedance - Z_{0L}=0.275+j1.0265, and capacitance, C_{0L}=0.0085uF). The line is supplied from both sides, 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). Additionally, the developed model includes CTs (1000/1 5P30 30 VA) with adequate magnetizing characteristic, that are installed on the sending and receiving sides of transmission line unit.

The large number of simulations have been performed to verify the presented protection method for exhibiting their results in statistical manner. Different line lengths – 50, 150 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; 0.1; 0.2;…1 p.u. and also beyond the protected zone, behind both terminals *S* and *R*, respectively. The studies included four different short-circuit types: three-phase fault (L1-L2-L3) and different types of asymmetrical faults (phase-to-earth (L1-E), phase-to-phase (L1-L2), and phase-to-phase-to-earth (L1-L2-E) faults).The examples inserted in Table concerning faults occurred at line terminal (d = 0) as well as external faults (EX.). The obtained results indicate if 1st, 2nd and 3rd conditions of protective algorithm are fulfilled.

As it is presented in Table, the protective algorithm enables to detect all of occurred inner faults, even this located at the beginning and at the end on the line. This situation is caused by the fact that threshold value of current is exceeded and 1st condition is fulfilled. The obtained results in case of external faults (with CTs saturation) are not in accordance with theoretical assumptions as it is presented in Table. In case of short line, it means for 50 km line, trip signal of protective relay is sent independently of fault type. The fault detection signal is forced by the fact that calculated current fulfilled 1st condition. Moreover, for this instance, the distance calculations done by investigated algorithm are incorrect and obtained values are different than expected value equal to half of the line length. It indicates that also 2nd condition is also fulfilled and the 3rd condition (dedicated for external faults) is useless. The situation is different in case of longer lines when the observed currents is not such deeply saturated in comparison with short lines. Nonetheless, in many cases, the fault criterions are also verified as a true and the trip signal is also issued.

The sample example concerning phase-to-phase external fault at busbar *R* (fault resistance 0 Ω) for 200 km line is depicted in Fig. 2, while the fault detection is indicated in Fig. 3. It can be seen that CT get into saturation three periods after fault inception time, which is especially seen at the sending side (Fig. 2) – note that small CT saturation is observed. It can be concluded that even for this external fault the incorrect decision is obtained which means that tripping signal was sent to breakers (Fig. 3).

Line length, km	Place	Fault	Fault detection	Comments
50	S (EX.)	L1- E	YES	Incorrect decision
		L1-L2	YES	Incorrect decision
		L1-L2-E	YES	Incorrect decision
		L1-L2-L3	YES	Incorrect decision
50	R (EX.)	L1- E	YES	Incorrect decision
		L1-L2	YES	Incorrect decision
		L1-L2-E	YES	Incorrect decision
		L1-L2-L3	YES	Incorrect decision
50	d = 0	L1- E	YES	Correct decision
		L1-L2	YES	Correct decision
		L1-L2-E	YES	Correct decision
		L1-L2-L3	YES	Correct decision
200	R (EX.)	L1- E	NO	Correct decision
		L1-L2	YES	Incorrect decision
		L1-L2-E	YES	Incorrect decision
		L1-L2-L3	YES	Incorrect decision
200	S (EX.)	L1- E	NO	Correct decision
		L1-L2	NO	Correct decision
		L1-L2-E	NO	Correct decision
		L1-L2-L3	YES	Incorrect decision

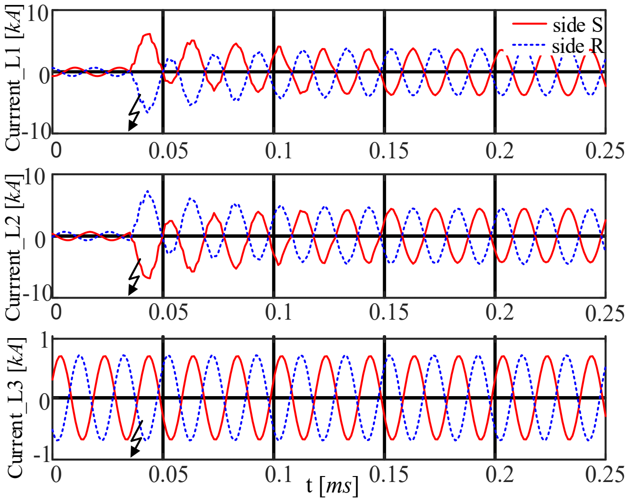

Fig. 2

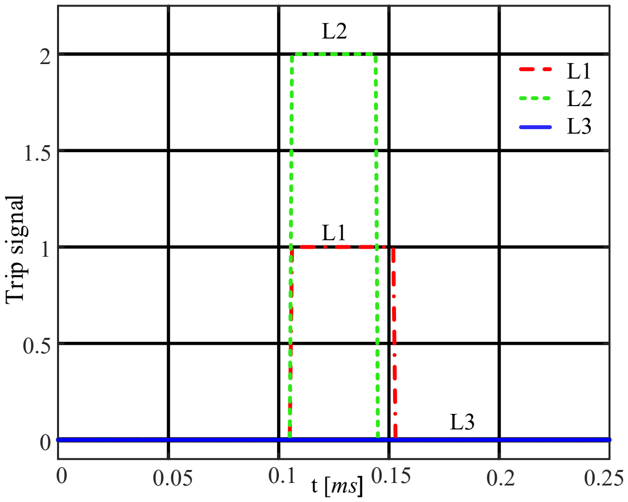

Fig. 3

Conclusions

The purpose of this paper was to examine the concept of impedance − differential protective algorithm for transmission line while CTs saturate. In normal operation condition (without CTs saturation) the demonstrated algorithm enables either for internal faults detection and for fault location.

Based on the simulation results done for short-circuits inside the protected lines, in case of CTs saturation, both features have been still retained. Nevertheless, the situation during external fault with CTs saturation is different. In many investigated cases the presented protective algorithm sends a trip signal. In view of its possible maloperation, the protection selectivity is not maintained. It indicated that presented concept has not sufficient performance to be applied in transmission line in such a form. The criterion of fault detection has to be refined to works properly in all situations (with and without CTs saturation, internal and external faults). The proposal aiming to improve the described protection algorithm is to recreate saturated current signal by using voltages from both line ends and current from not saturated side. This can be considered as the future investigations of the evaluated protection technique.

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ИССЛЕДОВАНИЕ АЛГОРИТМА ЗАЩИТЫ, ДЕЙСТВУЮЩЕЙ НА ОСНОВЕ ДИФФЕРЕНЦИАЛА ИМПЕДАНСА ДЛЯ ВНЕШНИХ КЗ, С УЧЕТОМ НАСЫЩЕНИЯ ТРАНСФОРМАТОРА ТОКА

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Проведен анализ алгоритма реле защиты линии электропередачи, действующего на основе измерения дифференцияла импеданса. Измерение тока и напряжения на обоих концах линии позволяет вычислить дифференциал импеданса, который используется как эффективный критерий функционирования защиты. Особое внимание уделяется условиям срабатывания реле в случае внешних КЗ, которые точно должны быть определены как при насыщении трансформатора тока, так и при его отсутствии. Основные характеристики реле по чувствительности и надежности были исследованы с использованием результатов модельных экспериментов, выполняемых с применением программы ATP-EMTP. Библ. 9, табл. 1, рис. 3.

Ключевые слова: дифференциальная защита, линия электропередачи, насыщение трансформатора тока, ATP-EMTP, симуляция.

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ДОСЛІДЖЕННЯ АЛГОРИТМУ ЗАХИСТУ, ЩО ДІЄ НА ОСНОВІ ДИФЕРЕНЦІАЛА ІМПЕДАНСУ ДЛЯ ЗОВНІШНІХ КЗ, З ВРАХУВАННЯМ НАСИЧЕННЯ ТРАНСФОРМАТОРА СТРУМУ

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Проведено аналіз алгоритму реле захисту лінії електропередачі, що діє на основі вимірювання диференціала імпедансу. Вимірювання струму та напруги на обох кінцях лінії дає змогу розрахувати диференціал імпедансу, який використовується як ефективний критерій функціонування захисту. Особливу увагу приділено вимогам спрацьовування реле у випадку зовнішніх КЗ, що повинні бути визначені як при насиченні трансформатора тока, так і за його відсутності. Основні характеристики реле за чутливістю та надійністю досліджено з використанням результатів модельних експериментів із застосуванням програми ATP-EMTP.

Бібл. 9, табл. 1, рис. 3.

Ключові слова: диференційний захист, лінія електропередачі, насичення трансформатора струму, ATP-EMTP, симуляція.

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