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# DIFFERENTIAL PROTECTION OF POWER TRANSFORMERS BASED ON NEGATIVE SEQUENCE CURRENTS DETECTION

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**ABSTRACT:** Due to the current increase of electrical power consumption from the mining equipment, followed by corresponding increase of fault current the subsequent damage and deterioration of reliable power supply have to be expected. In order to reduce the damage caused by internal faults and to prevent cases of false operations, protection devises with high sensitivity, selectivity and minimal operation time are required. Solution to the problems of differential protection relay sensitivity and speed requires the selection and validation of informative parameters from the operating signals of relay protection followed by development of internal damage detection algorithms and evaluation of tripping. This paper represents the dynamic current signals analysis using the generalized symmetrical components. The dynamic behavior of positive and negative sequence amplitudes of the differential currents for the cases of internal and external faults, transformer inrush currents and the supply voltage was studied. Analysis of relation between positive and negative sequence amplitudes of the differential currents for cases of various transients in power transformer allowed formulating algorithm for inter turn fault detection. On the basis of the phase shift between the negative sequences components of the first harmonic of currents in transformer high and low voltage was formulated. Developed and tested model of differential protection based on phase criteria, have the sensitivity 0.1% of the transformer rated current, which corresponds to 1% of the short-circuited turns of transformer winding. Time of the computation by protection device does not exceed the half of supply voltage period.

**Key words**: differential protection, transformer, negative sequence.

## ДИФЕРЕНЦИАЛНА ЗАЩИТА НА СИЛОВИ ТРАНСФОРМАТОРИ, ОСНОВАНА НА РАЗПОЗНАВАНЕ НА ОТРИЦАТЕЛНИ ТОКОВИ ВЕРИГИ

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**РЕЗЮМЕ:** Поради засиленото потребление на електроенергия от минното оборудване, последвано от съответното увеличаване на ток при повреда, трябва да се очаква и последваща повреда и влошаване на надеждното електрозахранване. За да се намалят щетите от вътрешни къси съединения и да се предотвратят случаи на фалшиви работни операции, са нужни предпазни устройства с висока чувствителност, избирателност и минимално време за работа. Решаването на проблемите с чувствителността и скоростта на релетата за диференциална защита изисква подбирането и валидирането на информативни параметри от работните сигнали на предпазното реле, последствани от разработването на вътрешни алгоритми за разпознаване на повредата и оценка на прекъсването на захранването. Докладът представя анализ на динамични токови сигнали, използвайки обобщени симетрични компоненти. Разгледани са динамичното поведение на положителни и отрицателни амплитуди на веригата от диференциални токове при случаи на вътрешни и външни къси съединения, отскока на тока при трансформатори и захранващото напрежение. Анализът на връзката между положителните и отрицателните амплитуди на веригата от диференциални токове при случаи на различни променливи в захранващия трансформатор позволява формулирането на алгоритъм за установяване на междунавивково късо съединение. Въз основа на смяната на фазите между компонентите на отрицателната верига на първата хармонична функция на токовете в трансформатора, се формулират високото и ниското напрежение. Разработеният и тестван модел за диференциална защита, основан на критерия фаза, има чувствителност 0.1% от номиналния ток на трансформатора, което съответства на 1% от съединените на късо намотки на трансформатора. Времето за изчисляване с предпазни устройства не надвишава половината от периода на захранващото напрежение.

**Ключови думи:** диференциална защита, трансформатор, отрицателна верига.

## Introduction

Power transformers are critical elements of the electric power system, which largely affect the efficiency and reliability of power supply of consumers. However, the transformer reliability is not sufficient to ensure continuous operation of plants. This is due to the imperfection of relay operation. Disadvantages are manifested in the refusal of the relay if there is an internal fault in the transformer and in unjustified tripping due to the emergence of false signals caused by the advent of the three-phase asymmetry of the system outside the protected zone.

Thus, during the examination of 9302 transformers rated at 110kV by power company UES Russia in the year 2009 the number of recorded accidents reached 542, and in 320 cases transformer failures were caused by windings turn-to-turn faults. In another test group of 3020 transformers rated from 35 to 110kV protection devices failed to operate properly in 168 cases per year (Konovalova E.V., 2003). According to CIGRE statistic, failures or false tripping of protective devices take place in every three cases out of a hundred.

In connection with the current trend of growing capacity of mining equipment, the negative consequences of failing the relay performance will lead to further vulnerability of power transformers due to a corresponding increase in fault currents leading to a large-scale damage to the transformer.

In order to reduce the damage along with preventing the shutdowns of equipment due to false relay operations, protection devices should have high level of sensitivity and selectivity to detect the fault at early stages of its development in the background of noise signals along with the necessity of short response time 5 - 14ms (Alexsandrov A.M., 2011) to exclude the melting of short circuited turns.

The most widespread digital differential relays use percentage linear-wise restraint curves that are characterized by threshold of sensitivity 20-30% of rated transformer current.

This value of threshold is too large for detecting the initial stage of the fault which is accompanied by differential current less than 5% of rated current.

To meet the stringent requirements of sensitivity and selectivity digital differential relays start to use special handling of current signals designed to identify the components that are more sensitive to internal defects and less sensitive to false differential currents (Gajić Z. *et al*., 2005; Abniki H. *et al*., 2010; Guzmán A. *et al*., 2011).

The paper considers analysis of power transformer currents under various conditions of operation, including inner and outer faults, on the basis of generalized symmetrical components and working out of differential relay algorithm that uses amplitude and phase criteria of tripping

## Modeling the power transformer performance under different operational conditions

Analysis of power supply system and differential relay of the power transformer 35\6kV, 6MVA (Fig.1) has been carried out with assistance of computer models built up in Simulink MatLab environment. Transformers, lines, breakers and faults outside the protected zone were modeled with appropriate elements from SimPowerSystems library. Internal faults were reproduced by a short-circuiting of taps of the transformer windings.

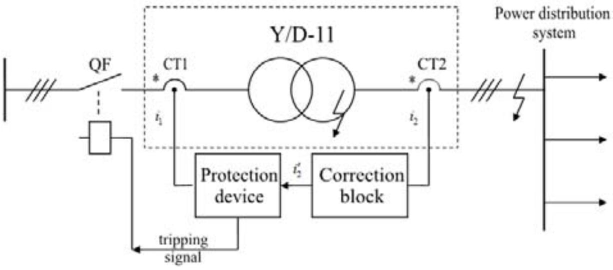

**Fig. 1. Differential protection system of a power transformer**

In order to compensate for amplitude and phase differences between current transformers outputs $\overline{i_1} = [i_{1a} \quad i_{1b} \quad i_{1c}]^T$, $\overline{i_2} = [i_{2a} \quad i_{2b} \quad i_{3c}]^T$ and to make a differential current in normal modes of operation close to zero the protection device involves a correction block that implements transformation $\overline{i_2} \to \overline{i_2'}$ [5] so that differential current $\overline{i_d} = \overline{i_1} - \overline{i_2'}$ in ideal case would be equal to zero. However, input signals of the protection device are unbalanced due to the following reasons: errors of current transformers CT1, CT2, imprecision of amplitude and phase correction of currents $\overline{i_1}, \overline{i_2}$, finite value of the power transformer excitation current, no constant value of a transformation ratio due to regulation of output voltage of the power transformer via switching taps of windings. Finite value of the differential current of a healthy transformer $I_{d0} = |\overline{i_{d0}}|$ defines the lower limit of detecting internal faults.

Conditions of tripping may occur for a healthy transformer in some power system operational modes such as energizing the transformer with inrush currents, increase in an input voltage, switching off a damaged line etc. Elimination of tripping in case of false differential currents is achieved by several methods using for instance comparison of spectrum of real and false differential currents currents (Ivanchenko D.I., Shonin O.B., 2012; Guzmán A. *et al*., 2000).

In the protection device (Fig. 1) the analysis of input signals $\overline{i_1}, \overline{i_2'}$ and differential signal $\overline{i_d} = \overline{i_1} - \overline{i_2'}$ has been carried out on the basis of their decomposition into series of generalized symmetrical components of positive $i^{(+)}(t)$, negative $i^{(-)}(t)$ and zero $i^{(0)}(t)$ sequences (Haque M.T., Hosseini S.H., 2001). The applied method covers analysis of asymmetrical no sinusoidal currents and three-phase transient processes.

The analysis has been implemented with assistance of a 3-phase sequence analyzer block which includes a Fourier analysis over a sliding window of one cycle of the specified frequency that is used for three input signals processing. Harmonics phasors derived from a windowed Fourier transform are functions of time due to sliding a window by different fragments of a signal with a complex form. Illustration of Fourier analyzer data as applied to the inrush current $i_a(t)$ in phase $a$ is given in Fig. 2.

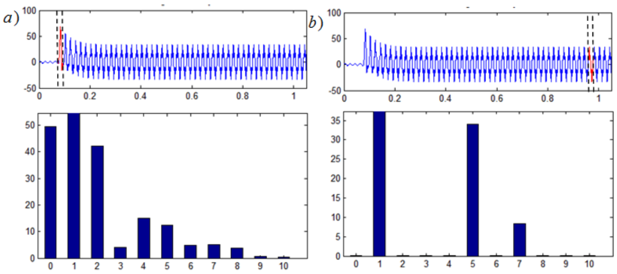

**Fig. 2. Spectrum of inrush current at the beginning of transient process - a) and in a steady state mode – b)**

At the beginning of the transient process the current's spectrum consists of a DC – component, odd and even harmonics (Fig. 2a) while in a steady state (Fig. 2b) it has only odd components. Because spectra of currents $i_a(t), i_b(t), i_c(t)$ are different, a set of 3-phase signals of each harmonic $k$ is unbalanced and can be decomposed into symmetrical components $i_k^{(+)}(t)$, $i_k^{(-)}(t)$ and $i_k^{(0)}(t)$ characterized by time-dependent phasors $\dot{I}_{mk}^{(+)}(t), \dot{I}_{mk}^{(-)}(t), \dot{I}_{mk}^{(0)}(t)$ which are outputs of 3-phase sequence analyzer.

An example of reproducing negative sequence currents of harmonics $k = 1,2,4$ of inrush currents is shown in Fig. 3.

The purpose of a power transformer study is to reveal the peculiarities of amplitude and phase relationships between dynamic phasors of symmetrical components of differential current of fundamental harmonic in order to increase in the relay's sensitivity and to facilitate the discrimination between useful and false signals. Data used for analysis are amplitudes and phases of first harmonic's symmetrical components of the protection device input currents and the same components of differential current obtained at the advent of different kinds of the 3-phase system's asymmetry.

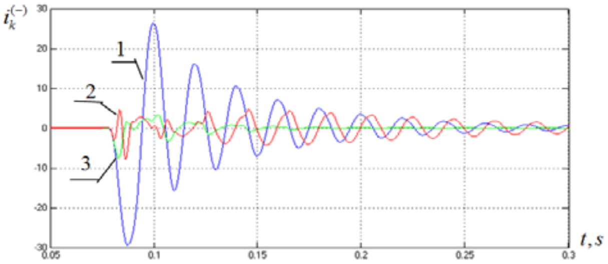

**Fig. 3. Negative sequence components of first (1), second (2) and forth (3) harmonic of the transformer inrush current**

## An amplitude criterion for tripping the transformer with internal faults

Comparative analysis of positive and negative sequences of a differential current has been carried out for the following modes: short circuiting of $W_{2sc}$ turns of the secondary winding $W_2$ in the range $\beta = W_{2sc}/W_2 = 0.01, 0.02, 0.05, 0.1$, energizing a no loaded transformer, increment of input voltage, phase-to-phase short circuiting outside the protected zone. It was found that the ratio of amplitudes of negative $I_m^{(-)}$ and positive $I_m^{(+)}$ sequences is sensitive to the type of 3-phase asymmetry.

Results of simulation demonstrate (Fig. 4) that an internal fault such as short-circuiting 5% turns of the secondary winding leads to asymmetrical 3-phase differential currents $i_{da}, i_{db}, i_{dc}$ in contrast to the form of a healthy transformer excitation current which is a part of an unbalanced differential current.

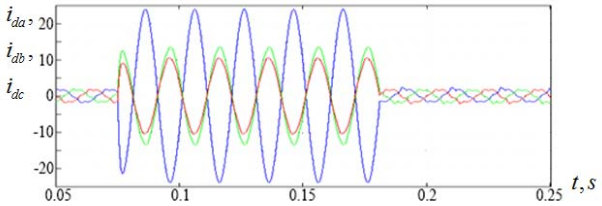

**Fig. 4. Three-phase differential currents due to turn-to-turn short-circuiting 5% of the secondary winding in the background of healthy transformer excitation currents**

Fig. 5 shows instantaneous curves of negative and positive components of a differential current (Fig. 5a) and changing of amplitudes of corresponding sequences resulted from internal short circuiting (Fig. 5b). As it is seen from Fig. 5a the negative sequence component (curve 2) of the unbalanced differential current is negligibly small as compared to a positive one (curve 1). This is due to a filtering effect of decomposing the current into symmetrical components which results in changing the number of harmonics in compared currents from $k = 1,3,5,7\ldots$ to $k = 5,11,17\ldots$ and this leads to an appropriate decrease in RMS value.

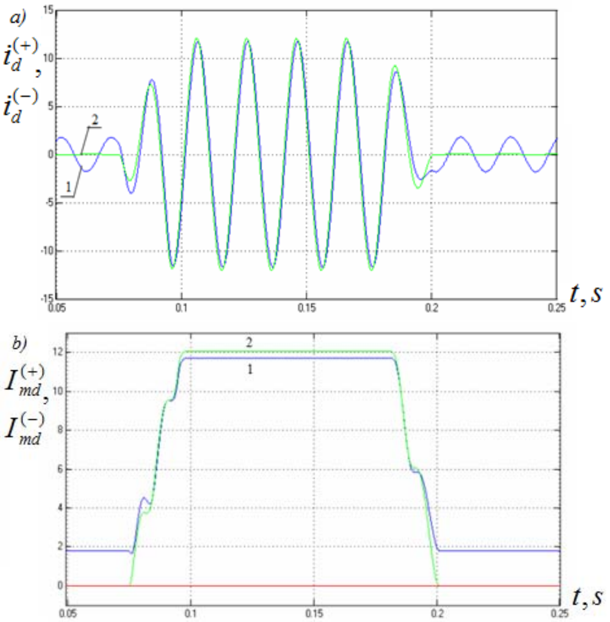

**Fig. 5. Instantaneous current's forms of positive (1) and negative (2) sequences – a) and their amplitudes' change because of internal short circuiting**

Fig. 5b shows that amplitudes of negative and positive components are practically equal so that $\hat{I}_m^{(-)} = I_m^{(-)}/I_m^{(+)} \approx 1$. This value of ratio $\hat{I}_m^{(-)}$ keeps valid if the number of short circuited turns is more than two percent, i.e. if $\beta \geq 0.02$.

Results of simulation for other modes of the transformer operation in the form used in Fig. 4 and Fig. 5 have shown that relationship $\hat{I}_m^{(-)} \approx 1$ is not the case for false differential currents. For instance, for inrush currents we have $\hat{I}_m^{(-)} \leq 0.5$. The inequality $\hat{I}_m^{(-)} \prec 1$ in varying degrees holds for other types of false differential currents: in case of external fault $\hat{I}_m^{(-)} \leq 0.4$, in case of 30% increment of input voltage $\hat{I}_m^{(-)} \leq 0.2$.

To use the obtained results for internal fault identification it is helpful to refer to a complex informative parameter expressed in the form (1):

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$$G\left(\hat{I}_m^{(-)}\right) = \frac{1-\left(\hat{I}_m^{(-)}\right)^2}{1+\left(\hat{I}_m^{(-)}\right)^2} \tag{1}$$

Dynamics of the parameter behavior during different kinds of faults is shown in Fig. 6.

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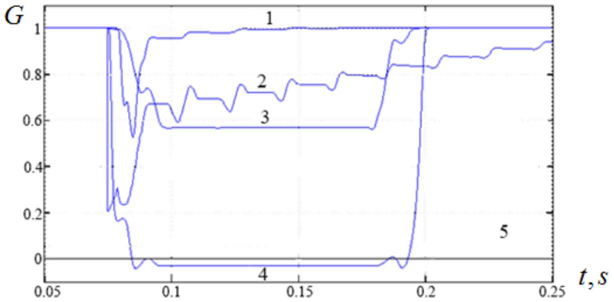

**Fig. 6. A threshold value (5) and amplitude criteria behavior for the transformer over-voltage (1), transformer energizing (2), external fault (3), inter-turn fault in the transformer winding (4).**

Examination of curves allows identifying two regions of the relay operation relatively to a threshold value $S_i = 0.05$. An area of the relay operation due to internal faults is defined by a condition $G\left(\hat{I}_m^{(-)}\right) < S_i$. Another area $G\left(\hat{I}_m^{(-)}\right) > S_i$ corresponds to false differential currents caused by external faults, inrush currents, transformer over excitation etc. In this case relay operation is blocked. Algorithm of digital protection relay operation based on revealed amplitude relations between negative and positive components of the transformer differential currents is presented in Fig. 7.

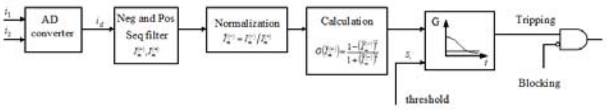

**Fig. 7. Block-diagram of the algorithm for detecting internal faults in a power transformer**

## Detecting internal faults of the transformer on the basis of a current's phase shift angle criterion

The distribution of currents in equivalent circuits for symmetrical components depends on whether an equivalent voltage source is located in the protected zone or not. Consequently, a phase shift between transformer currents of negative sequence should be sensitive to the location of the fault relatively to the protected zone (Gajić Z. *et al.*, 2005; (Ivanchenko D.I., Shonin O.B., 2012).

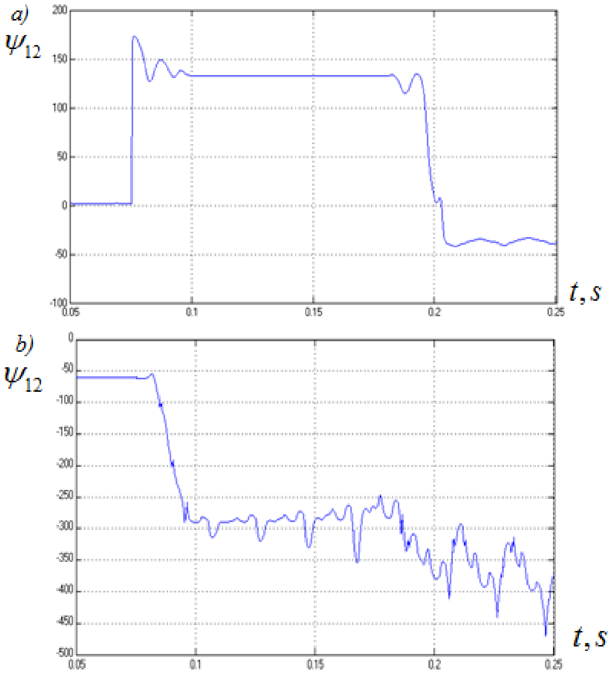

**Fig. 8. The phase shift angle between the negative sequences of first harmonic of currents in case of internal fault – a) and in case of input voltage increment – b)**

Substantiation of a phase angle criterion for detecting internal faults of power transformer has been conducted via measurement and analysis of a phase shift between negative sequence components of the transformer input and output currents $\psi_{12} = \psi_1^{(-)} - \psi_2^{(-)}$. Indexes 1, 2 relate to high and low voltage sides of the transformer, respectively. The phase shift was determined by means of two blocks «Sequence Analyzer» and a block «Summer». Results of simulation have shown that at internal faults the phase shift angle is $\psi_{12} = 135°$ (Fig. 8a). In ideal, *RL* elements-free network, the phase shift becomes close to $\psi_{12} = 180°$. This reflects the fact that the fictitious sources of negative sequence voltage are at the point of occurrence of the asymmetry of the three-phase system within the protected zone. In this case, the transformer currents caused by these sources will have opposite directions. In case of energizing the transformer an average value of the phase shift angle is $\psi_{12} = -20°$, in case of primary winding overvoltage – $\psi_{12} = -80°$ (Fig. 8.b)

The obtained results show that measuring the phase angle between the negative sequences of the transformer phase currents enables to construct a criterion of internal fault's detection in the form of an inequality $125° \prec \psi_{12} \prec 235°$ which has been used in a digital relay algorithm shown in Fig. 9.

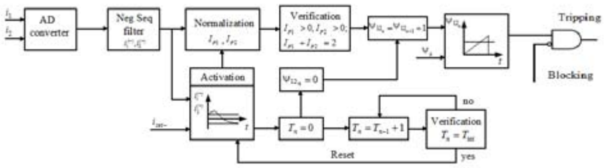

**Fig. 9. Structural diagram of a transformer's differential relay based on the phase criterion of internal faults detection.**

Consider the algorithm for measuring the phase shift between the currents of negative sequences. The phase criterion for relay operation can be rewritten as follows: $|\psi_{12}| > \psi_s$, where $\psi_s = 125^0$ is a threshold value. Conversions of negative sequence signals, the phase shift measurement and comparison of obtained results with the threshold are represented in fig. 10.

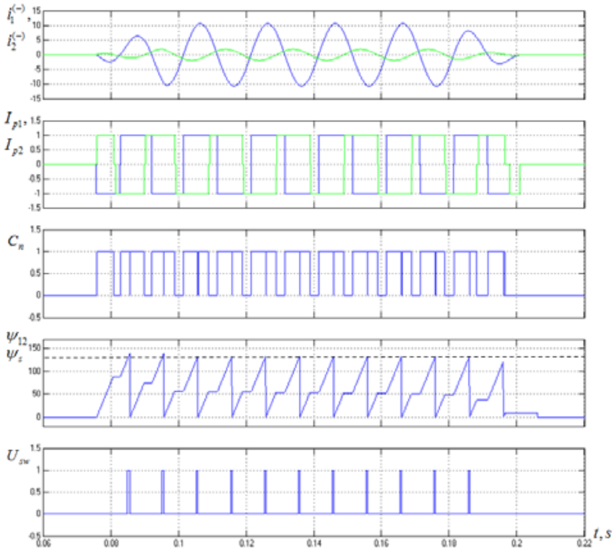

**Fig. 10. Calculation of trapping's signal for a case of the transformer's internal fault with 4% short-circuited turns in secondary winding**

In order to illustrate operation of the protection algorithm Fig. 10 shows several cycles of measurement cycles and generation of tripping signals without energizing the circuit breakers. In order to measure the phase shift between negative sequence components of input signals of the protection device $i_1^{(-)}(t)$, $i_2^{(-)}(t)$ the signals are converted into a sequence of bipolar rectangular pulses $I_{p1}(t), I_{p2}(t)$ according to the formula:

$$I_{p1}(t)=\begin{cases}1, & i_1^{(-)} > Is_\psi\\ 0, & -Is_\psi \le i_1^{(-)} \le Is_\psi,\\ -1, & i_1^{(-)} < -Is_\psi\end{cases} \qquad (2)$$

$$I_{p2}(t)=\begin{cases}1, & i_2^{(-)} > Is_\psi\\ 0, & -Is_\psi \le i_2^{(-)} \le Is_\psi\\ -1, & i_2^{(-)} < -Is_\psi\end{cases}$$

The protection algorithm activation threshold $Is_\psi$ corresponds to 1% of short circuited secondary winding turns.

The difference between signals $I_{p1}(t), I_{p2}(t)$ is converted into a sequence of rectangular pulses of unit amplitude $C(t)$ in accordance with the expression:

$$C_n(t)=\begin{cases}1, & \left|I_{p1}(t)-I_{p2}(t)\right| = 2\\ 0, & \left|I_{p1}(t)-I_{p2}(t)\right| \ne 2\end{cases} \qquad (3)$$

The duration of the signal $C(t)$ corresponds to the time interval during which the signals $i_1^{(-)}(t)$, $i_2^{(-)}(t)$ in any half-cycle are of opposite signs.

Integration of the signal $C(t)$ over half a period $T_i = T/2$ gives the value of a phase shift $\psi_{12}$. If the calculation of the time delay $\Delta T$ and corresponding phase angle $\psi_{12}$ is performed in discrete form, the operation of integration is replaced by summation of discrete values $C_{nj}$ of the signal with a predetermined sampling period $T_S$.

$$\Delta T = \sum_{j=1}^{T_i}\left(T_S \cdot C_{nj}\right),\quad \psi_{12} = \frac{\Delta T}{T_i}\cdot 180^0 \qquad (4)$$

By comparing the measured values $\psi_{12}$ with the set point $\psi_s$ the tripping signal $U_{sw}$ is formed.

Results of calculation represented in Fig. 10 have been obtained with a Matlab S-function written in the C++ programming language. Signal processing time does not exceed half a period of the system voltage $T_i \le 10\,ms$.

## Conclusion

1. The paper deals with analysis of the power transformer's currents under different conditions of operation using a SimPowerSystems' model and Matlab S-functions. Analysis was carried out on the basis of decomposition of analyzed currents to generalized symmetrical components by means of a sequence analyzer which output signals in the form of dynamic phasors of each harmonic which were used to reconstruct instantaneous values of currents' positive, negative and zero sequences.

2. Comparative analysis of dynamic phasors enabled to reveal the sensitivity of the negative and positive sequences' amplitude ratio to the origin of differential currents which allowed suggesting algorithm for detecting internal faults in the transformer windings in the background of false differential currents.

3. It has been shown that the reliable detection of 1-2% short-circuited turns of the transformer winding can be realized by comparing the set point with the measured phase angle between positive and negative sequences of the input and the output currents of the transformer. Signal processing in the relay is illustrated by a series of transformations performed by using S-function, specially compiled in the programming language C ++.

4. Both algorithms can be used separately or simultaneously for improvement of the relay operation reliability.

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