Transformer Fault Analysis Using Instantaneous Symmetrical Components

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***Abstract*— Symmetrical components analysis of time-dependent variables is a well-known tool for calculation of power quality in electrical grids. This paper deals with analysis of power transformer internal faults by means of time-dependent symmetrical components of currents. Described method allows calculation of symmetrical components during transient and under non-sinusoidal conditions. Those components were implemented in relay protection algorithms for identification of internal faults in transformers. Various examples of transformer faults were studied and illustrated.**

Keywords—Differential protection, transformer, instantaneous symmetrical components, negative sequence

I. INTRODUCTION

Power transformers are important part of any electric power system, and it`s reliability largely affect the sustainability and reliability of power supply. The transformer reliability is dependent on effective relay protection operation. Main problems in relay protection are failures in case of turn-to-turn fault in the transformer and in unjustified tripping in case of the three-phase asymmetry of the system outside the protected zone.

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 and prevent the shutdowns of equipment due to false relay operations, protection devices should have high level of sensitivity to detect the fault at early stages of its development in the background of noise signals.

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 especially in the case high harmonics of current are present [1] ,[2],[3].

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.

II. POWER TRANSFORMER SIMULATION

Modeling of power supply system and differential relay FOR the power transformer 35\6 kV, 6 MVA (Fig.1) has been carried out by means of 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.

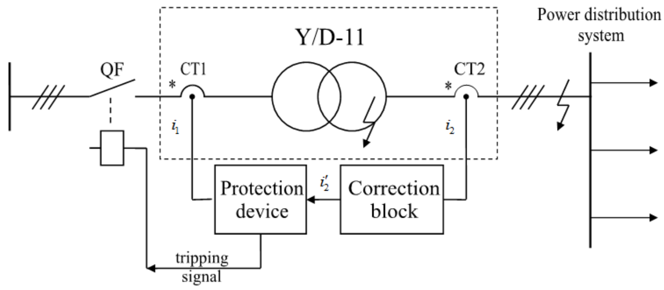

Fig. 1. Circuit breaker state control subsystem.

A. *Differential protection simulation*

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 $\overline{i_2} \rightarrow \overline{i_2'}$ 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 $I_{d0} = \left|\overline{i_{d0}}\right|$ defines the lower limit of detecting internal faults [4], [5].

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 differential currents [6], [7].

B. Generalized symmetrical components analysis

Generalized symmetrical components analysis [8] covers the case of nonsinusoidal and asymmetric dynamic systems of three-phase variables forming the vector: $x_{pno} = \left[x_p, x_n, x_o\right]^T$. Instantaneous components of positive and negative sequences $x_p(t)$ и $x_n(t)$ are complex variables $x_p = x_{pr} + jx_{pi}$, $x_n = x_{nr} + jx_{ni}$, zero sequence component is a real value $x_o(t)$. Symmetrical components of vector x_{pno} are calculated by this equation:

$$\begin{pmatrix} x_p(t) \\ x_n(t) \\ x_o(t) \end{pmatrix} = \begin{pmatrix} x_{pr}(t) + j\cdot x_{pi}(t) \\ x_{pr}(t) - j\cdot x_{pi}(t) \\ x_o(t) \end{pmatrix} = \frac{1}{\sqrt{3}} \cdot \left[\begin{pmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} x_a(t) \\ x_b(t) \\ x_c(t) \end{pmatrix}\right] \qquad (1)$$

Analysis periodical signals t can be implemented by means of Fourier analysis over a sliding window of one cycle of the specified frequency that is used for processing of three input signals $x_k(t)$. 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.

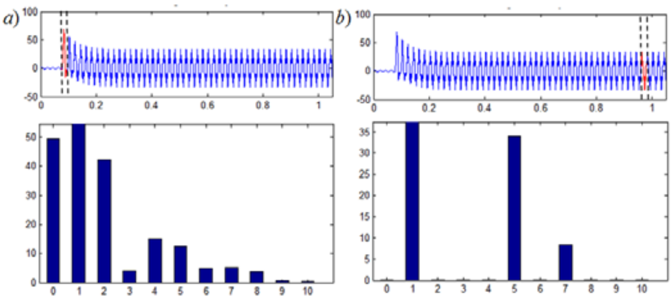

Fig. 2. Circuit breaker model with electric arc implementation.

At the beginning of 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 spectrum 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.

Calculation of symmetrical components in model of differential protection device

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 [9]. These symmetrical components were calculated for the first harmonic of current by means of discrimination of firs harmonic by low-pass filter and compensating elements implementing phase shift $\pm120°$. Transfer factor of phase-shifting link is calculated as:

$$H_\phi(f, K_\phi) = -0.5 + K_\phi \cdot \frac{1 - j\dfrac{f}{f_1}}{1 + j\dfrac{f}{f_1}} \qquad (2)$$

where $f_1 = 50$ Hz – circuit voltage frequency.

Phase shift at frequency f_1 for $K_\phi = -0.5\sqrt{3}$ is equal to 120 °. For $K_\phi = 0.5\sqrt{3}$ phase shift is equal to $-120°$.

Transfer factor of low-pass filter is calculated as:

$$H(f) = \frac{-4}{\left(1 + j\dfrac{f}{f_1}\right)^4} \qquad (3)$$

Structure of described filters of positive and negative components implemented in Simulink MATLAB is presented in Fig 3.

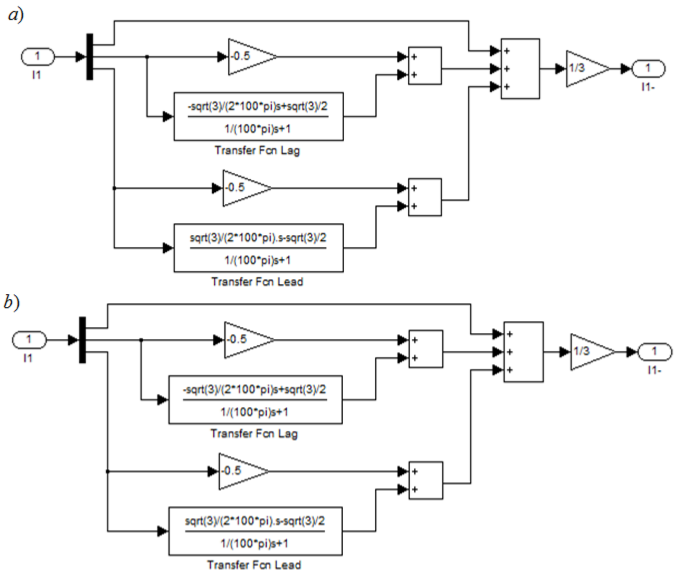

Fig. 3. Structure of described filters of positive (a) and negative (b) components.

Fig. 4 shows instaneous positive component of differential current in case of short-circuit of 7% of turns in transformer secondary winding calculated by means of SimPowerSystem

«3-phase sequence analyzer» and described filters. Diagram shows what both methods provide the same result for interval $t > 0{,}02$ s and described filters can be implemented in protection devices for calculation of symmetrical components of currents. Aperiodical component of currents can be filtered by means of rejection filter.

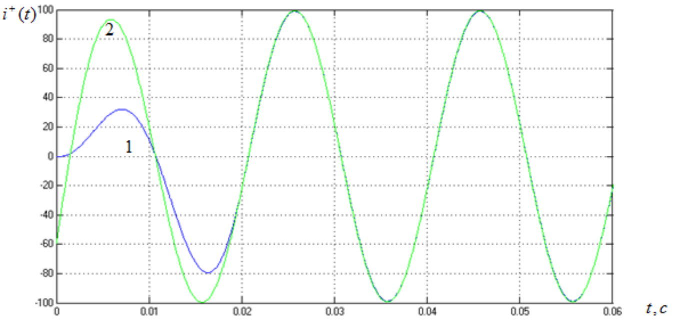

Fig. 4. Instaneous positive component of differential current in case of short-circuit of 7% of turns in transformer secondary winding calculated by means of SimPowerSystem «3-phase sequence analyzer» (1) and by low-pass filter (2).

III. BREAKER SIMULATION RESULTS

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 (Fig.5) demonstrate 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.5 shows instantaneous curves of negative and positive components of a differential current (Fig. 6) and changing of amplitudes of corresponding sequences resulted from internal short circuiting (Fig.7). As it is seen from Fig. 6 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.

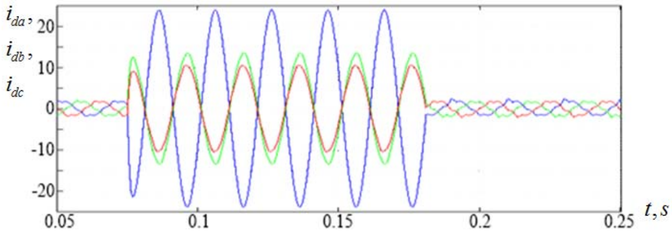

Fig. 5. Three-phase differential currents due to turn-to-turn short-circuiting 5% of the secondary winding in the background of healthy transformer excitation currents.

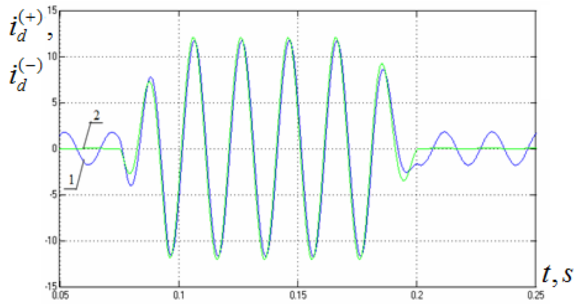

Fig. 6. Instantaneous current's forms of positive (1) and negative (2) sequences change because of internal short circuiting.

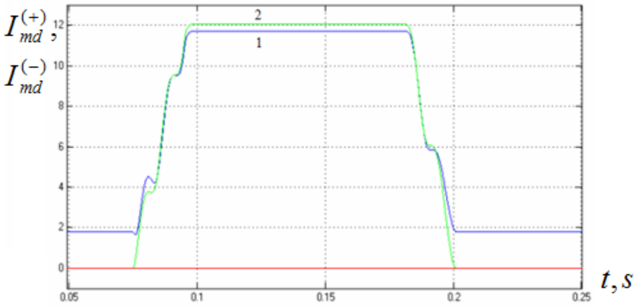

Fig. 7. Instantaneous current's amplitudes of positive (1) and negative (2) sequences change because of internal short circuiting.

Fig. 7 shows that amplitudes of negative and positive components are practically equal so that $\widehat{I}_m^{(-)} = I_m^{(-)}/I_m^{(+)} \approx 1$. This value of ratio $\widehat{I}_m^{(-)}$ 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 $\widehat{I}_m^{(-)} \approx 1$ is not the case for false differential currents. For instance, for inrush currents we have $\widehat{I}_m^{(-)} \leq 0.5$. The inequality $\widehat{I}_m^{(-)} \prec 1$ in varying degrees holds for other types of false differential currents: in case of external fault $\widehat{I}_m^{(-)} \leq 0.4$, in case of 30% increment of input voltage $\widehat{I}_m^{(-)} \leq 0.2$.

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

$$G\left(\hat{I}_m^{(-)}\right)=\frac{1-\left(\hat{I}_m^{(-)}\right)^2}{1+\left(\hat{I}_m^{(-)}\right)^2}, \qquad (6)$$

Dynamics of the parameter behavior during different kinds of faults is shown in Fig. 8.

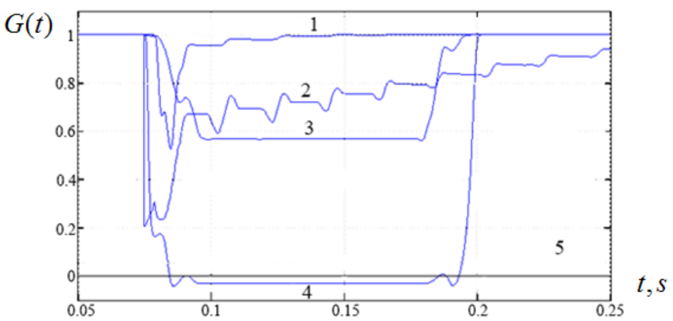

Fig. 8. A threshold value (5) and amplitude criteria behavior for the transformer over-voltage (1), transformer energizing (2), external fault (3), inter-turn fault in the transformer winding (4).

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 to be prevented.

IV. Conclusions

The paper deals with analysis of the power transformer's fault currents under different conditions of operation using Simulink MATLAB. 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.

Low-pass filter with correction link was proposed for calculation of symmetrical components of first harmonic of differential current.

Comparative analysis of dynamic phasors shows the sensitivity of amplitudes of negative and positive sequences of differential currents to fault location and allows formulation of algorithm for detecting internal faults in the transformer windings.

References

[1] Gajić Z., Brnčić I., Hilström B., Mekić F., Ivanković I. "Sensitive Turn-To-Turn Fault Protection For Power Transformers", Proceedings of the 32nd Annual Western Protective Relay Conference, Spokane, WA, October 2005.

[2] Shklyarskiy Ya.E., Skamyin A.N. "Compensation of the reactive power in the presence of higher voltage harmonics at coke plants". Coke and Chemistry. vol. 59, 2016, pp 163-168. DOI:10.3103/S1068364X16040062.

[3] Abniki H., Majzoobi A., Monsef H., Dashti H., Ahmadi H., Khajavi P. "Identifying Inrush Currents from Internal Faults using Symmetrical Components in Power Transformers", Proceedings of the International Symposium: Modern Electric Power Systems (MEPS), 2010, 20-22 Sept. 2010, 1-6 pp.

[4] Guzmán A., Fischer N., Labuschagne C. "Improvements in Transformer Protection and Control", Journal of Reliable Power Volume 2 Number 3 September 2011, Pullman, Washington USA, 19-35pp

[5] Guzmán A., Zocholl S., Altuve H.. "Performance analysis of traditional and improved transformer differential protective relays", USA, SEL Paper, 2000, 162-171pp.

[6] Alexsandrov A.M. *Differentsial`naya zashita transformatoriv: Uchebnoe posobie* [Differential protection of transformers: training aids], St.Petersurg, FSEE, 2011, p. 223 (In Russian)

[7] Ivanchenko D.I., Shonin O.B. Application of Kalman filter for digital differential protection relay of power transformers, *Zapisky gornogo instituta* [Proceedings of the Mining Institute], vol. 195, 2012, pp. 255-258 (In Russian)

[8] Paap G.C. "Symmetrical components in the time domain and their application to power network calculations", IEEE Transactions on power systems, vol. 15, №. 2, May 2000, 522 – 528 pp.

[9] Haque M. T., Hosseini S. H. "A control strategy for unified power quality conditioner (UPQC) using instantaneous symmetrical components theory", Second Intl. Conf. on Electrical and Electronics Engineering (ELECO' 2001), 7-11, Nov. 2001, Bursa-Turkey, pp. 152-156