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DIAGNOSTICS OF WINDING DEFORMATION IN A SINGLE-PHASE POWER TRANSFORMER WITH AN UNLOADED TERTIARY WINDING IN OPERATIONAL MODE

Sergey DOROZHKO, Andrey KRIVUNEV*

Stavropol State Agrarian University, Russia

The presented paper is focused on the development of an algorithm and software implementation of this algorithm into diagnostics of winding deformation in a single-phase power transformer with an unloaded tertiary winding in operational mode. To implement the algorithm, it is necessary to measure instantaneous values of input voltage and current, output voltage and current, and voltage across the unloaded tertiary winding by means of the electric power quality analyzer PQA – 824. This tool is utilized for signal filtering. The inductances of T-shaped equivalent circuit of the transformer were calculated. Relative deviations of the obtained inductance values were determined on the basis of transformer in operation; these deviations were compared with pre-determined set-points. If the inductances deviate from the set-points, the transformer must be repaired. Modern mathematical software package Mathcad 14 is designed to implement the algorithm. As a result of laboratory tests, the error of the proposed algorithm does not exceed 2% in comparison with the exact method.

Keywords: single-phase power transformer; equivalent circuit; windings; operational mode; power quality analyzer

The reliability of electrical equipment largely determines the reliability of power distribution systems. Emergency damage, often accompanied by the destruction of equipment, leads to electric power failure and economic damage. Significant losses occur due to failures of power transformers.

Nearly 50% of transformer substations of rural distribution network in Russia have reached their expected service life (Makarova, 2012). The annual failure rate of power transformers in these networks is up to 55.2% due to the turn shortenings in windings (Davidenko et al., 2008). Usually, the turn shorting is a result of windings deformation. A transformer with significant deformation of the windings must be taken out for repair. This step will eliminate the transformer failure. Therefore, the reduction of accident rate of power transformers due to the deformation of windings is an urgent task.

Even nowadays, the evaluation of actual power transformer state according to the results from diagnostic measurements is not simple to perform. Traditional methods for deformation detection (Low Voltage Impulse (LVI) method, Frequency Response Analysis (FRA), reactance measurement, etc.) require switching off the transformer (Chen et al., 2002; Miyazaki et al., 2017; IEEE, 1995). Moreover, for the measurement itself, precision instruments and trained personnel are also essential.

The deformation of the windings can be diagnosed by changes in element parameters of the L-shaped equivalent circuit of the transformer (Dorozhko, 2015) and in parameters of longitudinal branches of the T-shaped equivalent circuit of the transformer without disconnection from the electric

network (Zasyppkin and Dorozhko, 1995). The following papers also try to find a solution to this issue: Xu and Li (1998), Reddy and Rajpurohit (2014), Can et al. (2016). Taking into account the impacts of neglecting this problem, it is necessary to carry out such diagnostic measurements on all transformers in agricultural enterprises and rural distribution networks (Pristavka and Bujna, 2014).

In power networks, both three-phase transformers and single-phase transformers are used; however, there is considerably lower number of three-phase transformers in operation. Therefore, it is reasonable to consider the performance of the transformer diagnostics only for single-phase transformers and subsequent application of results in three-phase transformers. The aim of the paper is to devise an algorithm and subsequent software implementation of this algorithm into diagnosis of winding deformation in single-phase power transformer with an unloaded tertiary winding in operational mode.

Material and methods

In order to determine the parameters of T-shaped equivalent circuit elements in a single-phase transformer with unloaded tertiary winding in operational mode, it is necessary to measure the arrays of instantaneous values of input voltage $|u_1(t_j)|$ (V), input current $|i_1(t_j)|$ (A), output voltage $|u_2(t_j)|$ (V), output current $|i_2(t_j)|$ (A) and voltage across the tertiary unloaded winding $|u_3(t_j)|$ (V), where $t_j = t_1, t_2, \dots, t_N$ (s); N – number of samples of instantaneous values within the given period (Fig. 1). The measurements were

Contact address: Andrey Krivunev, Stavropol State Agrarian University, Russia, e-mail: dusikasss26@mail.ru

performed by means of the electric power quality analyzer PQA – 824 (here and after analyzer) (HT-ITALIA, 2007; Dorozhko, 2011). The analyzer can simultaneously record 4 current signals with accuracy $\pm 0.5\%$ readings plus 0.06% full scale clamp and 4 voltage signals with accuracy $\pm 0.5\%$ readings plus 2 no. of digits. Analog-to-digital converter (ADC) resolution is 256 samples per 50 Hz.

The instantaneous values of output current, output voltage and voltage across the tertiary unloaded winding are reduced to the first side of the transformer:

$$|i'_2(t_j)| = \frac{W_2}{W_1} |i_2(t_j)|, |u'_2(t_j)| = \frac{W_1}{W_2} |u_2(t_j)|, |u'_3(t_j)| = \frac{W_1}{W_3} |u_3(t_j)| \quad (1)$$

where:

W_1, W_2, W_3 – the number of turns of the primary, secondary and tertiary windings of the transformer

Fig. 1 T-shaped single-phase transformer circuit
 R_1 – active resistance of the primary winding; X_1 – inductive resistance of the primary winding; X_0 – inductive resistance magnetizing; R_0 – resistance to magnetic losses; R'_2 – reduced active resistance of the secondary winding; X'_2 – reduced inductive resistance of the secondary winding

Since there is no current flowing through the tertiary unloaded winding, there is no drop in the voltage due to its resistance. Consequently, the voltage $|u_3(t_j)|$ is proportional to the electromotive force (EMF) of magnetization:

$$|u_0(t_j)| = |u'_3(t_j)|$$

Using the second Kirchhoff law, the array of voltage instantaneous values on the first longitudinal resistance of the equivalent circuit was determined using the following expression:

$$|\Delta u_1(t_j)| = |u_1(t_j)| - |u_0(t_j)| \quad (2)$$

The differentiation of the array of input current instantaneous values at the given period of time was performed using:

$$\left| \frac{di_1(t_j)}{dt} \right| = \frac{i_1(t_j) - i_1(t_{j-1})}{\Delta t} \quad (3)$$

where:

Δt – sampling interval of the array of instantaneous values of the input current in time, s

Since the resistance of the longitudinal branches of the transformer replacement circuit is linear, the known relation

for the voltage drop in the circuit with active resistance and inductance will be equal to:

$$u_1(t_j) = R_1 i_1(t_j) + L_1 \frac{di_1(t_j)}{dt} \quad (4)$$

where:

R_1 – active resistance of the primary winding

L_1 – inductance of the primary winding

This equation contains two unknown variables R_1 and L_1 . The equation applies to the particular time instant t_j ; therefore, there are several such equations for the given period of time. In order to determine the inductance of the primary winding L_1 , it is necessary to solve the equation for the instants of time t_{11} and t_{12} when $i_1(t_j) = 0$.

Inductance was calculated using expressions:

$$L_1(t_{11}) = \frac{u_1(t_{11})}{\frac{di_1(t_{11})}{dt}} (H)$$

$$L_1(t_{12}) = \frac{u_1(t_{12})}{\frac{di_1(t_{12})}{dt}} (H)$$

Mean values of the primary winding inductive resistance for the period of time were calculated using Eq. (5):

$$L_{1av} = \frac{L_1(t_{11}) + L_1(t_{12})}{2} \quad (5)$$

Using the second Kirchhoff law, the array of instantaneous values of voltage on the second longitudinal resistance of the equivalent circuit reduced to the first circuit was determined using the following expression:

$$|\Delta u'_2(t_j)| = |u_0(t_j)| - |u'_2(t_j)| \quad (6)$$

The differentiation of the instantaneous value array of the reduced output current at the given time was performed using expression:

$$\left| \frac{di'_2(t_j)}{dt} \right| = \frac{i'_2(t_j) - i'_2(t_{j-1})}{\Delta t}$$

Then time points when $i_2(t_j) = 0$ (two time points t_{21} and t_{22}) were recorded.

Subsequently, inductance values were calculated using:

$$L'_2(t_{21}) = \frac{u'_2(t_{21})}{\frac{di'_2(t_{21})}{dt}} (H)$$

$$L'_2(t_{22}) = \frac{u'_2(t_{22})}{\frac{di'_2(t_{22})}{dt}} (H)$$

The mean inductive resistance values of the secondary winding for the given period of time were calculated by means of the following formula:

$$L'_{2av} = \frac{L'_2(t_{21}) + L'_2(t_{22})}{2} \quad (7)$$

It was necessary to determine the relative deviations of inductance of the primary winding $\Delta L_1 = \frac{|L_{1serv} - L_{1av}|}{L_{1serv}} \cdot 100\%$ and inductance of the secondary winding $\Delta L_2 = \frac{|L'_{2serv} - L'_{2av}|}{L'_{2serv}} \cdot 100\%$ from the values obtained from transformers in operation (L_{1serv} and L'_{2serv}). Finally, obtained deviations were compared with the set-points. If the inductances deviate from the set-points, the transformer must be repaired.

The numerical differentiation of the array of input current instantaneous values at time $\left| \frac{di_1(t_j)}{dt} \right|$, reduced by the value of output current $\left| \frac{di_2'(t_j)}{dt} \right|$, can result in very small values.

The determination of the change in inductive resistance of windings can result in significant errors (Dorozhko and Dubkov, 2010). Further calculations are carried out with filtered signals. According to the foregoing algorithm, a program in modern mathematical packet Mathcad 14 is developed.

In order to verify this algorithm, measurements were performed on the laboratory specimen of T-shaped single-phase transformer with the following technical data: rated power 0.4 kW; primary winding voltage 220 V; secondary winding voltage 230 V; the voltage of unloaded tertiary winding 12 V.

Fig. 2 Diagnostic diagram of winding deformation of single-phase power transformer with unloaded tertiary winding in operational mode
TV1, TV2 – voltage transformers (accuracy class 0.2); TA1, TA2 – current transformers (from the kit of electric power quality analyzer PQA – 824, the main reduced error of 1%); inputs of electric power quality analyzer PQA – 824: I1, I2 – for connection of current circuits, B1–B4 – for connection of voltage circuits, BE – for connection of earthing

For this purpose, the instantaneous values of voltages from all windings, and the primary and secondary currents were measured in operational mode of the transformer close to nominal. The mean value of the inductance of the primary winding of the transformer L_{1av} was calculated by means of Eq. (5). Then, the choke with the known choke inductance

value L_{ch} measured by precise instrument was installed to series with the primary winding. Then, the testing of the instantaneous values of voltages from all windings and the primary and secondary currents were repeated; the mean value of the primary winding inductance for the given period of time L'_{1av} was determined using Eq. (5); the choke inductance value was calculated using expression $L_{ch,c} = L'_{1av} - L_{1av}$. Test results were statistically processed after 5–7 cycles (Korenko et al., 2013).

Results and discussion

Experiment results are shown in Fig. 3. There is a description of inductance dependences of the choke, which was processed using L_{ch} – value of choke inductance calculated from the choke inductance by means of algorithm; $L_{ch,c}$ – value measured by a precise instrument; and $L_{h,c}$ – value of the winding inductance of the transformer measured in the short circuit experiment in accordance with IEEE (1995).

Fig. 3 Diagnostics results of windings deformation of single-phase power transformer with unloaded tertiary winding in operational mode: direct curve 1 – ideal; curve 2 – experimental

In regards to the changes in the choke inductance L_{ch} depending on the transformer winding, $L_{h,c} = 1 \div 8\%$, the error rate (the difference between straight line 1 and curve 2) did not exceed 2% in average. The data allow recording insignificant changes in the inductances of the windings, and thus also changes in inductive resistances of the windings. This leads to the conclusion that it is possible to monitor the winding deformation in single-phase power transformer with an unloaded tertiary winding in operational mode.

The results are consistent with the research of Russian scientists Khrennikov and Shlegel (2004), as well as foreign scientists Bengtsson and Abeywickrama (2012). The task of performing the diagnostics of the winding deformation in vital transformers in rural distribution networks is considerably beneficial from the economic perspective if it is taken into account that this task requires only usage of

the simple algorithm and electric power quality analyzer PQA – 824, which can be also used for other measurements.

Conclusions

Laboratory tests proved that it is possible to diagnose the winding deformation in single-phase power transformer with an unloaded tertiary winding in operational mode by means of the algorithm proposed in the paper.

It is possible to diagnose the deformation of the windings for each phase of the three-phase transformers with unloaded windings in such a manner.

The electric power quality analyzer PQA – 824 can be replaced by another similar device.

In the transformer substations lacking the current and voltage transformers, it is necessary to install additional current and voltage transformers.

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