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DETERMINATION OF ENERGY LOSS IN THE MAGNETIC CORE OF OIL POWER TRANSFORMERS UNDER LONG-TERM OPERATION CONDITIONS

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Abstract: The article analyzes energy losses resulting from long-term operation in magnetic cores of oil power transformers. In the study, magnetic losses in no-load mode - losses due to hysteresis and eddy currents - are of particular importance. This work describes the calculation methodology based on existing standards, provides measurement-based approaches and formulas for calculating time-dependent energy losses. In addition, based on the regression equations depending on the magnetic induction, it was possible to determine the specific losses of magnetic core materials. The proposed approach is important for assessing the technical condition of operating transformers, determining the need for major repairs, and choosing a new transformer.

Keywords: oil power transformer, magnetic core, no-load losses, hysteresis, eddy current, service life, regression method, energy efficiency, overhaul.

Introduction. Currently, 5-10 percent of the electricity generated in power plants is lost in the magnetic cores of electrical machines [1]. Losses in transformers and autotransformers make up to 20 percent of the total loss of electricity transmitted through electric networks.

The magnetic core, which is one of the main structural elements of transformers, also has the above situation, i.e., magnetic losses. These losses are called permanent losses because they do not depend on the load. As a result of long-term operation, a decrease in magnetic properties is observed in the magnetic core as a result of thermal processes, asymmetrical voltages and mechanical stresses, and a change in magnetic losses is observed.

Literature Review. According to GOST 14209-97, three-phase transformers with a rated power of $S_{nom} \leq 2500\ kVA$ are classified as distribution transformers. Depending on their power rating and nominal voltage, distribution transformers are divided into the following dimensions [2]:

Table 1. Dimensions of distribution transformers.

Dimensions	**Rated power (S_{nom}) kVA**	**Rated voltage (U_{nom}) kV**
I	25 – 100 kVA	≤ 35
II	160 – 630 kVA	≤ 35
III	1000 – 2500 kVA	≤ 35

In [3], the following quality indicators are defined for distribution power transformers [3]:

- specific weight relative to nominal power, *kg/ kVA;*
- service life $T_{service}$, years (reliability indicator);
- no-load power losses (*NLL*) ΔP_{NL}, *kW;*
- load power losses (*LL*) ΔP_{LL}, *kW;*
- no-load current, I_{NLL} *percent*

One of the requirements set out above is that the no-load power losses of transformers must be constant and not exceed a specified value. In oil-immersed power transformers, no-load power losses are observed due to hysteresis phenomena and eddy currents that occur as a result of magnetization and demagnetization in the magnetic core.. The following factors contribute to an increase in power losses in idle mode [4]:

- ✓ deterioration of the varnish insulation between steel sheets and metal corrosion;
- ✓ poor mixing;
- ✓ overheating of the magnetic circuit above the norm;
- ✓ use of low-quality steel grades;
- ✓ mechanical damage to steel sheets during overhaul and repair of the magnetic circuit.

The service life of power transformers also affects the increase in electricity losses and their reliability indicators. Long-term transformers are characterized by greater power losses, which is associated with an increase in operating losses without load [5], One of the indicators of the technical condition of power transformers is the presence of capital repairs. According to statistical data on the repair of power transformers, only 25% of 6 and 10 kV power transformers undergo major repairs with the dismantling of the magnetic core. The results of post-repair tests of power transformers show that for some power transformers, the power losses measured in the magnetic circuit are two or more times higher than the nominal values, therefore, the installation of a new power transformer is often preferable to the option of further operation of the transformer, which is periodically repaired [6].

Summarizing the data collected on power transformers with a voltage of 6-10 kV, we can conclude that after overhaul, the magnetic circuits of transformers of various nominal powers have increased no-load energy losses. In addition, it was found that the lower the nominal power of power transformers, the greater the difference between the certified and measured values of power losses in the magnetic core. In most cases, damaged transformers are repaired, after which they are put into operation again [7]. No-load operation after repair increases energy losses.

Periodic monitoring of no-load parameters is especially important for power transformers that have been in operation for more than 20 years.

Materials and methods. The article used statistical methods, electrical engineering theory, and regression analysis methods.

Results and discussion. It is known that the total energy losses in a two-winding power transformer consist of no-load and load losses. The total energy losses can be determined by expression (1):

$$\Delta W_{TL} = \Delta W_{NLL} + \Delta W_{LL} \tag{1}$$

where, ΔW_{TL} – total electrical energy losses, kWh; ΔW_{NLL} – transformer no-load energy losses, kWh; ΔW_{LL} - load energy losses, kWh [9].

The no-load energy losses of oil-immersed power transformers over time are assumed to be constant over time T and can be determined by formula (2).

$$\Delta W_{NLL} = \Delta P_{NLL} \cdot T \tag{2}$$

wher, ΔP_{NLL} – active power losses in no-load operation of the transformer, kW; T - calculated time period (hour).

Load losses of electrical energy in the transformer (ΔW_{LL}) for the period T are calculated as follows.

$$\Delta W_{LL} = \Delta P_{LL} \cdot T \tag{3}$$

where, ΔP_{QT} – active power losses in the transformer under load mode

$$\Delta P_{LL} = \frac{P_T^2 + Q_T^2}{U_{nom}^2} \cdot R_T \tag{4}$$

where, R_T – is the active resistance of the transformer, (Ω); P_{T} – active load in the T period; Q_{T} – reactive load in period T

$$R_T = \Delta P_{LL} \cdot \frac{U_{nom}^2}{S_{nom}^2} \tag{5}$$

The active (P_T) and reactive (Q_T) loads of transformers during the period T do not remain constant, but vary in accordance with the actual consumer load schedule, which can consist of n identical time intervals of time Δt, each of which corresponds to certain constant values of (P_T) and (Q_T). Based on this, for any interval Δt we have:

$$\Delta W_{NLL} = \Delta P_{NLL} \cdot \Delta t \tag{6}$$

$$\Delta W_{LL} = \frac{\Delta P_{\Delta t}^2 + \Delta Q_{\Delta t}^2}{U_{nom}^2} \cdot \Delta P_{LL} \cdot \frac{U_{nom}^2}{S_{nom}^2} \Delta t = \frac{S_{\Delta t}^2}{S_{nom}^2} \cdot \Delta P_{LL} \cdot \Delta t = k_{\Delta t}^2 \cdot \Delta P_{LL} \cdot \Delta t \tag{7.1}$$

$$\Delta W_{LL} = k_{\Delta t}^2 \cdot \Delta P_{LL} \cdot \Delta t \tag{7.2}$$

where, $k_{\Delta t}$ – transformer load factor; S_{nom} – nominal power of the transformer, kVA; $S_{\Delta t}$ – full load power of the transformer during time Δt, kVA.

By appropriately substituting expressions (6) and (7) into expression (1), we can obtain expression (8):

$$\Delta W_{TL} = \Delta P_{NLL} \cdot \Delta t + k_{\Delta t}^2 \cdot \Delta P_{LL} \cdot \Delta t \tag{8}$$

A mathematical expression (8) is obtained that allows determining the total energy losses of power transformers over time Δt.

As a result of the study of existing methods for calculating no-load losses in power transformers, it was found that the existing programs for determining energy losses use reference data, because the passport data for transformers is lost.

The active power losses ΔP_{NLL} of the transformer in the no-load operation mode occur under the influence of various physical and constructive factors. These losses are formed mainly as a result of the formation of hysteresis and eddy currents in the magnetic core. According to the current calculation methodology, they are expressed by expression (9) as follows [10]:

$$\Delta W_{NLL} = \Delta P_{NLL} \sum_{i=1}^{m} T_i \left(\frac{U_i}{U_{HV.nom}}\right)^2 \tag{9}$$

where, T_i – operating hours in i-mode, hours; U_i – operating voltage in i-mode, kV; $U_{HV.nom}$ – nominal high voltage, kV; ΔP_{NLL} – no-load power loss in the transformer passport, W.

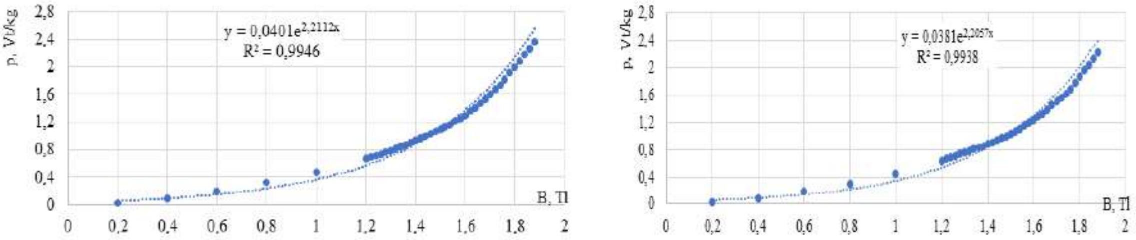
The active power loss ΔP_{NLL} of the designed transformer in the no-load operating mode was determined by (10) [11]:

$$\Delta P_{NLL} = [k_{p.r} k_{p.z} \left(p_c G_c + p_{ya} G_{ya} - 4 p_{ya} G_y + \frac{p_c + p_{ya}}{2} k_{p,u} G_{ya}\right) + \sum p_z n_z \Pi_z] \cdot k_{p.ya} k_{p.p} k_{p.sh} \tag{10}$$

Expression (11) was obtained as a result of algebraic replacement of the components of expression (10) for calculating the power loss of the transformer in no-load operation;

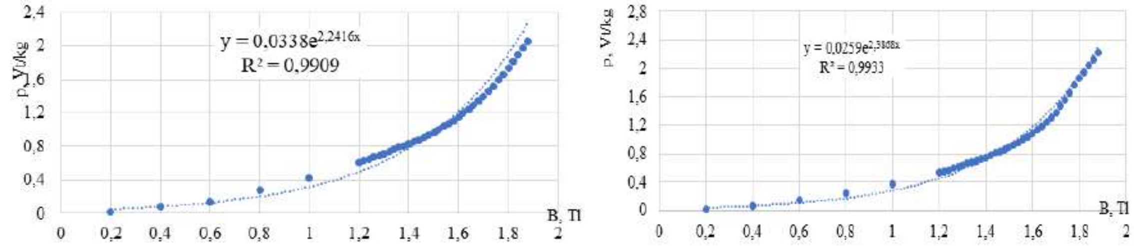
$$\Delta P_{NLL} = \left[[k_{p.r} k_{p.z} \left(p_c \cdot \left(c \Pi_c l_c \gamma_{st} + c\left(\Pi_c a_{1ya} \gamma_{st} \cdot 10^{-3} - \right.\right.\right.\right.$$
$$\left.\left. - k_z V_y \gamma_{st} 10^{-6}\right)\right) + p_{ya}(2(c-1) c \Pi_{ya} \gamma_{st} + 4(k_z V_y \gamma_{st} 10^{-6})/2) - 4 p_{ya} k_3 V_y \gamma_{st} 10^{-6} +$$
$$\left. \left. + \frac{p_c + p_{ya}}{2} k_{p.u} k_z V_y \gamma_{st} 10^{-6}\right) + \sum p_z n_z \Pi_z] \cdot k_{p.ya} k_{p.p} k_{p.sh}\right] \tag{11}$$

where, $k_{p.r}$ – coefficient of increase in losses under the influence of mechanical forces, $k_{p.r}$=1,05; $k_{p.z}$ – additional losses arising when cutting steel sheets $k_{p.z} = 1 \div 1.02$; p_c, p_{ya} – specific losses for 1 kg of steel rod and half, depending on the inductions B_c and B_{ya}, the grade and thickness of the steel; Π_c - rod active cross-section surface, m^2; Π_{ya} - active cross section surface, m^2; c – the number of active sturgeons; l_c – length of the rod, m; γ_{st} – density of transformer steel, kg/m^3; V_{ya}- size of steel of magnetic core angle; $k_{п.y}$ – coefficient taking into account the increase in losses at the corners of the core; k_z - filling coefficient; $k_{p.ya}$ - coefficient of increase in loss depending on the shape of the cross-section of the shaft; $k_{p.p}$ – depending on the power of the transformer, the coefficient taking into account the effect of pressure on losses and no-load operating current. $k_{p.sh}$ – coefficient that takes into account the losses caused by re-mixing of the upper part of the magnetic core when installing coils [11, 12].



Graph of the specific losses of cold-rolled 3404 steel with a thickness of 0.35 mm versus magnetic induction

Graph of the specific losses of cold-rolled 3404 steel with a thickness of 0.30 mm versus magnetic induction



Graph of the specific losses of cold-rolled 3405 steel with a thickness of 0.30 mm versus magnetic induction

Graph of the magnetic induction dependence of the specific losses of cold-rolled M4X steel with a thickness of 0,28 mm

Figure 1. Regression analysis of the dependence of the specific losses of transformer magnetic sheets on magnetic induction

Table 2. Regression equations of dependence of pc, pya and pz specific losses on magnetic induction for cold-rolled 3404, 3405 and M4X steel grades

	Dependence of relative losses of pc and pya on magnetic induction			
	Steel type	**Sheet thickness, mm**	**Regression equation**	**Approximation**
1	3404	0,35 мм	$p = 0{,}0401e^{2{,}2112B}$	$R^2 = 0{,}9946$
2		0,30 мм	$p = 0{,}0381e^{2{,}2057B}$	$R^2 = 0{,}9938$
3	3405	0,30 мм	$p = 0{,}0338e^{2{,}2416B}$	$R^2 = 0{,}9909$
4	M4X	0,28 мм	$p = 0{,}0259e^{2{,}3868B}$	$R^2 = 0{,}9933$
	Dependence of specific losses pz on magnetic induction			
	Single-plate	$p_3 = 0{,}4317\ln(B) + 0{,}2319$		$R^2 = 0{,}9737$
	Double-plate	$p_3 = 0{,}4672\ln(B) - 1{,}6282$		$R^2 = 0{,}9606$

The actual expression for calculating the power losses of a transformer during no-load operation was obtained by algebraically substituting the expressions in (9) (10) and (11) into (12);

$$\Delta P_{NLL} = \Delta P_{NLLn}\left(\frac{U_i}{U_{YK}}\right)^2 T_i = \Big[\big[k_{p.r}k_{p.z}\Big(p_{\mathrm{c}}\cdot\Big(c\Pi_c l_c\gamma_{st} + c\big(\Pi_c a_{1ya}\gamma_{st}\cdot 10^{-3} - $$

$$-k_z\, V_y\gamma_{st}10^{-6}\big)\Big)\Big) + p_{ya}(2(c-1)c\Pi_{ya}\gamma_{st} + 4(k_z\, V_y\gamma_{st}10^{-6})/2\,) - 4p_{ya}k_3\, V_y\gamma_{st}10^{-6} + $$

$$+\frac{p_{\mathrm{c}}+p_{ya}}{2}k_{p.u}k_z\, V_y\gamma_{st}10^{-6}\Big) + \sum p_z n_z\Pi_z\big]\cdot k_{p.ya}k_{p.p}k_{p.sh}\Big]\left(\frac{U_i}{U_{HV}}\right)^2\cdot T_i \qquad (12)$$

Applying the regression equations in Table 2 to the expression (12) obtained above allows us to increase the accuracy of the value of the no-load power losses of transformers.

Conclusion. In this study, a calculation methodology based on current standards was developed and formulas for determining energy losses in transformers over time were proposed based on measurement results. In particular, it was possible to assess the energy properties of magnetic core materials through regression equations describing the relationship between magnetic induction and specific power losses.

This approach serves as an important tool for comprehensive analysis of the technical condition of transformers in operation, substantiating the need for their overhaul, and selecting new energy-efficient transformers. The results of the study showed that in some transformers that have undergone overhaul, power losses in the magnetic core increase, which negatively affects the overall efficiency of the device. Therefore, special attention should be paid to the properties of magnetic core materials during consistent monitoring of energy efficiency, maintenance, and modernization processes.

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