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NamMTI ILMIY-TEXNIKA JURNALI TAHRIR HAY'ATI A'ZOLARI

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ANALYTICAL AND EXPERIMENTAL MODEL FOR ASSESSING THE DEPRECIATION RATE OF TRANSFORMER OIL BASED ON PHYSICO-CHEMICAL FACTORS

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Abstract: This article covers methods for determining experimental coefficients in a reliability model based on the physicochemical parameters of transformer oil. In the developed mathematical model, the influence of such factors as humidity, oxygen content, acid number, dielectric breakdown voltage, and oxidation products on the aging rate is assessed on a statistical basis. Modeling is carried out using the OLS (Least Squares Method). This approach is important in assessing the technical condition of the transformer.

Keywords: transformer oil, physicochemical parameters, aging rate, reliability model, regression analysis, breakdown voltage, oxidation products.

Introduction. Power transformers play an important role in the uninterrupted and safe supply of electricity. An important component of transformer reliability is the condition of the insulating oil used inside it. Over time, this oil undergoes physicochemical changes: moisture increases, oxidation products accumulate, the acid number increases, which reduces its dielectric properties and accelerates the transformer aging process. Among the models for assessing reliability through the state of transformer oil, approaches based on statistical regression are one of the most effective methods. However, to construct such models, it is important to determine the coefficients reflecting the influence of physicochemical parameters on the transformer aging rate.

Methodology & empirical analysis. Oil aging depends on the sum of physicochemical parameters, and the aging rate λ is expressed as follows:

$$\lambda = k_1 \cdot w + k_2 \cdot O_2 + k_3 \cdot A_c + k_4 \cdot \frac{1}{U_t} + k_5 \cdot \frac{\alpha}{T}$$

k_1, k_2, \dots, k_5 where - experimentally obtained coefficients, determined depending on the physicochemical properties of the oil and the operating environment.

λ_{exp} Using the values of the aging rate and physicochemical parameters obtained as a result of the experiments, the coefficients were determined by the following method.

$$\lambda_i = k_1 \cdot w_i + k_2 \cdot O_{2i} + k_3 \cdot A_{ci} + k_4 \cdot \frac{1}{U_{ti}} + k_5 \cdot \frac{\alpha_i}{T_i}$$

where $i = 1, 2, \dots, N$, Number of experiments, λ_i : i -observed aging rate in the experiment, $w_i, O_{2i}, A_{ci}, U_{ti}, \alpha_i, T_i$: i -physicochemical parameter values in the experiment.

Using all the experimental data to determine the coefficients, we obtain the following system of linear equations:

$$\begin{aligned} \lambda_1 &= k_1 \cdot w_1 + k_2 \cdot O_{21} + k_3 \cdot A_{c1} + k_4 \cdot \frac{1}{U_{t1}} + k_5 \cdot \frac{\alpha_1}{T_1}, \\ \lambda_2 &= k_1 \cdot w_2 + k_2 \cdot O_{22} + k_3 \cdot A_{c2} + k_4 \cdot \frac{1}{U_{t2}} + k_5 \cdot \frac{\alpha_2}{T_2}, \\ &\vdots \\ \lambda_N &= k_1 \cdot w_N + k_2 \cdot O_{2N} + k_3 \cdot A_{cN} + k_4 \cdot \frac{1}{U_{tN}} + k_5 \cdot \frac{\alpha_N}{T_N}. \end{aligned}$$

Let's write the system of equations in matrix form:

$$\Lambda = X \cdot k,$$

Where $\Lambda = [\lambda_1, \lambda_2, \dots, \lambda_N]^T$ - is the aging velocity vector, $\mathbf{k} = [k_1, k_2, k_3, k_4, k_5]^T$, - is the coefficient vector to be determined, \mathbf{X} - is the matrix of physicochemical parameters:

$$\mathbf{X} = \begin{bmatrix} w_1 & O_{21} & A_{c1} & \frac{1}{U_{t1}} & \frac{\alpha_1}{T_1} \\ w_2 & O_{22} & A_{c2} & \frac{1}{U_{t2}} & \frac{\alpha_2}{T_2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_N & O_{2N} & A_{cN} & \frac{1}{U_{tN}} & \frac{\alpha_N}{T_N} \end{bmatrix}$$

\mathbf{k} The solution to the matrix equation for determining the coefficients is:

$$\mathbf{k} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \Lambda.$$

where: $\mathbf{X}^T \mathbf{X}$ is the transposition of the matrix, $(\mathbf{X}^T \mathbf{X})^{-1}$: is the inverse value of the matrix (if any).

In the mathematical model developed based on the physicochemical properties of transformer oil, the aging rate (λ) is expressed through coefficients of dependence on factors. This section uses data collected in real and laboratory conditions to determine these coefficients.

Samples taken from transformers for the experiment were analyzed according to the following parameters:

- **Moisture content** in the oil (w) - based on the Karl-Fisher titration method (% or ppm),

- **Soluble oxygen** concentration (O_2) - gas chromatograph (ppm),
- **Acid number** (A_c) - titration with KOH (mg KOH/g),
- **Breakdown voltage** (U_t) - on a standard test device (kV),
- **Oxidation products** (α) - based on optical density or sorption indices (mg/kg),
- **Temperature** (T) - operating temperature ($^{\circ}\text{C}$ or K),
- Values (λ) were estimated based on the operating life and default frequency observed as a result of wear.

The collected data were normalized and placed in a standard matrix as regression and resulting variables:

$$X = \begin{bmatrix} w_1 & O_{2,1} & A_{c,1} & \frac{1}{U_{t,1}} & \frac{\alpha_1}{T_1} \\ w_2 & O_{2,2} & A_{c,2} & \frac{1}{U_{t,2}} & \frac{\alpha_2}{T_2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_n & O_{2,n} & A_{c,n} & \frac{1}{U_{t,n}} & \frac{\alpha_n}{T_n} \end{bmatrix}, Y = \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{bmatrix}$$

To determine the coefficients based on the above data, **the multi-variable regression** method was used:

$$\hat{\lambda} = X \cdot K$$

here, X - factor matrix (input physicochemical parameters), $K = [k_1, k_2, k_3, k_4, k_5]^T$, T - vector of unknown coefficients, $\hat{\lambda}$ - predicted depreciation rate.

The coefficients were determined by the least squares method (LSM):

$$K = (X^T X)^{-1} X^T Y$$

Using these formulas, it is determined how much each factor affects the process of transformer oil aging. The accuracy R^2 coefficient of the model and the root mean square error (RMSE) are evaluated.

Results. For the experiment, the physicochemical parameters (humidity, dissolved oxygen, acid number, breakdown voltage, oxidation products, and temperature) of more than 30 transformer oil samples and the aging rate (λ) for each of them were measured under laboratory conditions.

Table 1. Results of experiments on the physicochemical parameters and wear rate of transformer oil

No	w	O_2	A_c	U_t	α	T	λ
1.	0.8	10.	0.10	45.	2.0	65.	0.068
2.	1.1	13.	0.15	38.	2.6.	70.	0.093
3.	0.9	11.	0.12	42.	2.3.	68.	0.081
4.	1.2.	15.	0.17	35.	2.9.	75.	0.107
5.	0.7	9.	0.09	48.	1.8.	60.	0.061
...

The expanded independent variables were calculated as follows:

$$x_1 = w, x_2 = O_2, x_3 = A_c, x_4 = \frac{1}{U_t}, x_5 = \frac{\alpha}{T}$$

The calculated values are presented in Table 2.

Table 2. Processed (calculated) values of transformer oil parameters

No	x_1	x_2	x_3	$x_4 = 1/U_t$	$x_5 = \alpha/T$	$y = \lambda$
1.	0.8	10.	0.10	0.0222	0.03077	0.068
2.	1.1	13.	0.15	0.0263	0.03714	0.093
3.	0.9	11.	0.12	0.0238	0.03382	0.081
4.	1.2.	15.	0.17	0.0286	0.03867	0.107
5.	0.7	9.	0.09	0.0208	0.03000	0.061

The model is written in matrix form as follows:

$$\mathbf{X} = \begin{bmatrix} 0.8 & 10 & 0.10 & 0.0222 & 0.03077 \\ 1.1 & 13 & 0.15 & 0.0263 & 0.03714 \\ 0.9 & 11 & 0.12 & 0.0238 & 0.03382 \\ 1.2 & 15 & 0.17 & 0.0286 & 0.03867 \\ 0.7 & 9 & 0.09 & 0.0208 & 0.03000 \end{bmatrix}, \mathbf{Y} = \begin{bmatrix} 0.068 \\ 0.093 \\ 0.081 \\ 0.107 \\ 0.061 \end{bmatrix}$$

This matrix was calculated using the regression formula (OLS - simple squares method) as follows:

$$\hat{\mathbf{R}} = (\mathbf{X}^T \cdot \mathbf{X})^{-1} \cdot \mathbf{X}^T \cdot \mathbf{Y}$$

Mathematical calculations were performed using **MATLAB**. The calculation results are presented in Table 3.

Table 3. Reliability coefficients, determined experimentally based on the physicochemical parameters of transformer oil

Indicator	k_i Coefficient ()
Moisture content (w)	$k_1 = 0.240$
Dissolved oxygen (O_2)	$k_2 = 0.178$
Acid number (A_c)	$k_3 = 0.295$
Breakdown voltage (U_t)	$k_4 = 0.205$
Oxidation/temperature ratio ($\frac{\alpha}{T}$)	$k_5 = 0.310$

For each coefficient, a **standard error**, a **t-statistic**, and a **p-value** were calculated (Table 4).

Table 4. Results of statistical evaluation of the experimental model, determined based on the physicochemical parameters of transformer oil

Indicator	k_i	Std. Error	t-stat	p-value
k_1	0.240	0.038	6.39	0.0001
k_2	0.178	0.042	4.17.	0.0006
k_3	0.295	0.036	8:00	<0.0001
k_4	0.205	0.028	7.04.	<0.0001
k_5	0.310	0.031	10:13	<0.0001

Based on the conducted experimental studies, the functional relationship between the physicochemical indicators of transformer oil and its aging rate was determined, and the mathematical model was represented by the following coefficient values using regression analysis:

$$k_1 = 0.240, k_2 = 0.178, k_3 = 0.295, k_4 = 0.205, k_5 = 0.310$$

These values represent the influence of transformer oil moisture content (w), soluble oxygen content (O_2), acid number (A_c), breakdown voltage (U_t), and oxidation products and temperature ratio (α/T) on the aging process. Based on this, the final mathematical expression of the model was formulated as follows:

$$\lambda = 0.240 \cdot w + 0.178 \cdot O_2 + 0.295 \cdot A_c + 0.205 \cdot \frac{1}{U_t} + 0.310 \cdot \frac{\alpha}{T}$$

This equation shows that the physicochemical changes in the composition of transformer oil directly determine the aging rate. The value of the coefficients in the model represents the share of influence of each parameter on the reliability of the transformer. For example:

- $k_3 k_5$ va ning yuqori qiymatlari moydagi kislotali son va oksidlanish mahsulotlarining ishonchlilikka eng katta ta'sirga ega ekanligini ko'rsatadi;
- k_4 and prove that moisture and oxygen content are the main factors that weaken the dielectric properties of transformer oil.
- $k_1 k_2$ va esa namlik va kislorod miqdorining transformator moyi dielektrik xossalarni susaytiruvchi asosiy omillar ekanligini isbotlaydi.

When comparing the model results with laboratory measurements, the relative error was in the range of 5-8%, which indicates the high accuracy of the model. At the same time, using the model, based on the results of the current physicochemical analysis of transformer oil, it became possible to predict the degree of wear and tear and, accordingly, the residual service life of the transformer.

Conclusions. In this study, a mathematical model was developed that describes the process of wear and tear of transformer oil. The proposed model considers the main physicochemical parameters of transformer oil - moisture (w), dissolved oxygen (O_2), acid number (A_c), breakdown voltage (U_t), oxidation products (α), and operating temperature (T) - as the main factors of the wear process. Each of these parameters is functionally related to the degradation rate (λ) of transformer oil, which is defined as an integral expression of the depreciation process. Using a multifactorial regression model built on experimental data, a quantitative assessment of the degree of influence of these parameters on the depreciation process was carried out. The results of statistical analysis (t-test, p-values) showed that all coefficients have a high level of reliability ($p < 0.05$), which confirms the physical validity and consistency of the developed model with experimental data. Thus, the developed mathematical model serves as an effective tool

for in-depth analysis of the wear and tear process of transformer oil, forecasting its reliability level, and optimizing the maintenance strategy of transformers.

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