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ANALYSIS OF FACTORS INFLUENCING THE INTENSITY OF TRANSFORMER OIL AGEING IN LONG-TERM OPERATION

The results of the analysis of influence of operational factors and peculiarities of transformer design on intensity of oxidative reactions of transformer oils in the tanks of 110 kV high-voltage power transformers are presented. As a result of two-way analysis of variance it was found that with increasing operating time there is a statistically significant increase in the value of the organic acid content in the oil. At the same time the rate of increase in the organic acids content in the transformer oil, operated under different conditions, significantly differs, which indicates a significant influence of operating conditions on the intensity of oxidative reactions. The results of two-way analysis of variance also show that the effects of changes in factor levels are not additive, that is, the effect of a change in the level of influence of one factor leads to a change in the effect of the level of influence of another. In other words, the process of oil oxidation is cumulative and a certain level of organic acids in the oil can be achieved either over a longer period of operation, but with relatively 'light' operating conditions, or over a shorter period of time, but with more 'heavy' operating conditions. In order to determine the factors most affecting the intensity of oxidative reactions, an analysis of the quality of filled oil, operating time, the influence of the region, the influence of the type and nominal characteristics of transformers on 6 data sets with identical rates of oxidative reactions was carried out. The results of the analysis show that the intensity of oxidation reactions is strongly influenced by the operating time, the transformer loading factors, the consumer composition (region of Ukraine) as well as the type and quality of oils. At the same time, factors such as rated capacity, type of transformer, number of windings, and the value of rated voltage on the medium and low voltage windings do not influence the intensity of oxidation of oils. The results obtained allow the correction of the maximum permissible values of oil acidity, taking into account the factors affecting the intensity of oxidation of oils.

Keywords: high-voltage transformers, transformer oil, ageing intensity, acidity, two-way analysis of variance, operating time, transformer loading, oil quality, Ukraine region, rated capacity, transformer type, number of windings.

С. Г. ПОНОМАРЕНКО

АНАЛІЗ ФАКТОРІВ, ЩО ВПЛИВАЮТЬ НА ІНТЕНСИВНІСТЬ СТАРІННЯ ТРАНСФОРМАТОРНИХ МАСЕЛ В УМОВАХ ТРИВАЛОЇ ЕКСПЛУАТАЦІЇ

Наведено результати аналізу впливу експлуатаційних факторів і особливостей конструктивного виконання трансформаторів на інтенсивність окислювальних реакцій трансформаторних масел у баках високовольтних силових трансформаторів напругою 110 кВ. За результатами двофакторного дисперсійного аналізу встановлено, що з ростом тривалості експлуатації має місце статистично значуще зростання значення вмісту в маслі органічних кислот. При цьому швидкість збільшення вмісту органічних кислот в маслі трансформаторів, що експлуатуються в різних умовах, істотно відрізняється, що свідчить про значний вплив умов експлуатації на інтенсивність окислювальних реакцій. Також за результатами двофакторного дисперсійного аналізу встановлено, що ефекти зміни рівнів факторів не є адитивними, тобто ефект від зміни рівня впливу одного фактора приводить до зміни ефекту від рівня впливу іншого. Іншими словами, процес окислення масел носить кумулятивний характер при цьому певний рівень вмісту в маслі органічних кислот може бути досягнутий або за більш тривалий період експлуатації, але з відносно «легкими» умовами експлуатації, або за більш короткий проміжок часу, але з більше «важкими» умовами експлуатації. Для визначення факторів, які найбільше впливають на інтенсивність окислювальних реакцій був виконаний аналіз якості масла, що заливається, тривалості експлуатації, впливу регіону та впливу типу і номінальних характеристик трансформаторів по 6 масивам даних з ідентичною швидкістю окислювальних реакцій. За результатами аналізу встановлено, що на інтенсивність окислювальних реакцій найбільший вплив мають тривалість експлуатації, значення коефіцієнтів завантаження трансформаторів, склад споживачів (регіон України), а також сорт і якість масел. У той же час такі фактори як-от номінальна потужність, тип трансформатора, кількість обмоток і значення номінальної напруги на обмотках середньої і низької напруги не впливають на інтенсивність окислення масел. Отримані результати дозволяють виконати коригування гранично-допустимих значень кислотності масел з урахуванням факторів, що впливають на інтенсивність окислення масел.

Ключові слова: високовольтні трансформатори, трансформаторне масло, інтенсивність старіння, кислотне число, двофакторний дисперсійний аналіз, тривалість експлуатації, завантаження трансформаторів, якість масла, регіон України, номінальна потужність, тип трансформатора, кількість обмоток.

С. Г. ПОНОМАРЕНКО

АНАЛИЗ ФАКТОРОВ ВЛИЯЮЩИХ НА ИНТЕНСИВНОСТЬ СТАРЕНИЯ ТРАНСФОРМАТОРНЫХ МАСЕЛ В УСЛОВИЯХ ДЛИТЕЛЬНОЙ ЭКСПЛУАТАЦИИ

Приведены результаты анализа влияния эксплуатационных факторов и особенностей конструктивного исполнения трансформаторов на интенсивность окислительных реакций трансформаторных масел в баках высоковольтных силовых трансформаторов напряжением 110 кВ. По результатам двухфакторного дисперсионного анализа установлено, что с ростом продолжительности эксплуатации имеет место статистически значимый рост значения содержания в масле органических кислот. При этом скорость увеличения содержания органических кислот в масле трансформаторов, эксплуатирующихся в различных условиях, существенно отличается, что свидетельствует о значимом влиянии условий эксплуатации на интенсивность окислительных реакций. Также по результатам двухфакторного дисперсионного анализа установлено, что эффекты изменения уровней факторов не являются аддитивными, то есть эффект от изменения уровня воздействия одного фактора приводит к изменению эффекта от уровня воздействия другого. Иными словами, процесс окисления масел носит кумулятивный характер при этом определенный уровень содержания в масле органических кислот может быть достигнут либо за более продолжительный период эксплуатации, но с относительно «легкими» условиями эксплуатации, либо за более короткий промежуток времени, но с большее «тяжелыми» условиями эксплуатации. Для определения факторов, наиболее влияющих на интенсивность окислительных реакций был выполнен анализ качества заливаемого масла, длительности эксплуатации, влияние региона, влияние типа и номинальных характеристик трансформаторов по 6 массивам данных с идентичной скоростью окислительных реакций. По результатам анализа установлено, что на интенсивность окислительных реакций наибольшее влияние оказывают продолжительность эксплуатации, значение коэффициентов загрузки трансформаторов, состав потребителей (регион Украины), а также сорт и качество масел. В тоже время такие факторы как номинальная мощность, тип трансформатора, количество обмоток и значения номинального напряжения на обмотках среднего и низкого напряжения не влияют на интенсивность окисления масел. Полученные результаты позволяют выполнить корректировку предельно-допустимых значений кислотности масел с учетом факторов, влияющих на интенсивность окисления масел.

Ключевые слова: высоковольтные трансформаторы, трансформаторное масло, интенсивность старения, кислотное число, двухфакторный дисперсионный анализ, продолжительность эксплуатации, загрузка трансформаторов, качество масла, регион Украины, номинальная мощность, тип трансформатора, количество обмоток.

Introduction. The operational reliability of high-voltage power transformers, as one of the most critical and costly elements of electrical networks, is determined by the reliability of its individual components: windings, magnetic core, high-voltage bushings, on-load tap changers, cooling system, etc. Transformer oil is one of the most important elements in the insulation of high-voltage transformers, which largely ensures their uninterrupted operation. The ageing of transformer oils during operation leads to deterioration of their insulating properties due to changes in their chemical structure. It is obvious that the intensity of oil ageing in different transformers will be different and is determined by the influence of a number of different factors, starting from operating modes of electrical networks and ending with the design of transformers. Improvement of diagnostic methods of transformer oils is fundamentally impossible without taking into account the regularities of transformer oil ageing in terms of long-term operation and analysis of the influence of operational factors on the speed of oil ageing. In this regard, the study of transformer oil ageing processes under conditions of real operating conditions during long-term operation is an urgent and important task. In this paper the results of analysis of factors influencing the intensity of oil ageing under conditions of long-term operation are given.

Publication analysis. At present, the kinetics of oil ageing is sufficiently well studied and described in the literature. In [1-3] it was found that the oxidation of transformer oils occurs by a chain mechanism. The main ageing factor is the interaction of free air oxygen with hydrocarbons contained in the oils. Operating oil temperature, electric field strength, moisture, as well as some structural materials are factors that accelerate the aging process. It should be noted that research into the ageing process of oils is continuing now. For example, in [4] an experimental study was carried out to assess the correlation between water content and insulating characteristics of oils, in particular breakdown voltage, resistivity and dielectric dissipation factor. An experimental study of new and reclaimed in-service transformer oil was carried out in [5]. A comparative study found that the reclaimed transformer oil in service is unstable and more susceptible to thermal aging processes than the new one. It has been demonstrated in [6] that annual oil sampling may not be sufficient to monitor moisture content, which can lead to misdiagnosis. A liquid quality index (LQI), which is determined by moisture content analysis, has been proposed to assess the condition of transformer oils. In [7] statistical data on the effect of oil-impregnated paper wear on transformer oil is presented. The correlation between the indicators of interfacial tension (IFT), acidity and colour with the conditions of ageing of transformer paper was revealed. In [8] the results of an analysis of the influence of transformer load-dependent operating temperature on the intensity of oil ageing are given. It was found that an increase in transformer load from 10 to 50% leads to a 3.5 times increase in organic acids after 25 years of operation. In [9] a linear regression method is applied to analyse the characteristics of transformer oils with an operating time of up to 30 years and a loading rate of 9-80%. It is shown that the oil in transformers with a higher load factor wears out faster, especially the increase in acidity and colour change. Regression and classification models based on machine learning are used in [10] to test the correlation between transformer oil IFT values and other oil test results, namely breakdown voltage, acidity, colour, dissipation factor and moisture content. Experimental results show that both acidity and colour have the highest correlation with IFT. In [11], a multiple linear regression model was proposed to estimate the degree of oil ageing from a set of diagnostic indicators. In [12] the trajectory method was used to assess the condition of transformer oils. However, despite a sufficient amount of research, the influence of operating conditions and design features of transformers are not sufficiently covered, which is the reason for this paper.

Research purpose. In this article, the influence of operating factors on the intensity of transformer oil ageing is evaluated by analysing the results of in-service inspection.

Problem solving method. The results of periodic tests of transformer oils condition for 249 transformers of 110 kV from 6 regions of Ukraine were used as the initial data for the analysis. Both the results of control of physical and chemical parameters of oils and the results of chromatographic analysis of gases dissolved in oil were analysed. Totally, the results of tests on 20 indicators characterizing change of insulating properties of oils at an interval up to 50 years of operation were analysed. These results were entered into the database of information and analytical system "SIRENA" [13], in the medium of which this analysis was performed. For convenience of analysis, groups of indicators with the same drift rate were formed according to the statistical processing procedure proposed in [14, 15]. Such groups (M-1...M-6) are graphically illustrated in Fig. 1, which shows the dependences of the acidity of transformer oils on the duration of operation.

The first stage of the study tested how the rates of acid number drift differed between the 6 groups. Since it is assumed that the values of the indicators change not only over time, but also between groups, a mathematical model of cross-sectional two-way analysis of variance (ANOVA) [16] was used to test for differences in the ageing rate. In this case, the factor of operating time was placed on the rows and the factor of the group on the columns. Given the non-linear nature of oil indicators dependence on the operating time [17], the data were divided by rows, taking into account the induction and acceleration period, which are different for the analysed arrays. It is assumed that the number of observations in each cell is the same and equal to *m*.

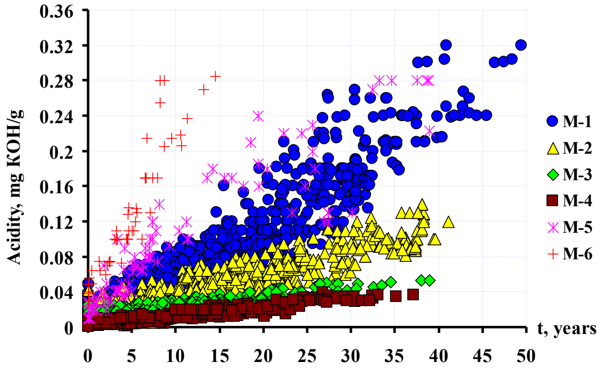

Figure 1 – Dependence of the acidity on operating time for 6 groups of transformers with the same ageing rate

If the effects of changes in factor levels are additive, that is, the difference in mathematical expectations between any two levels of one factor is the same for any levels of the other, then a variance-components model can be represented as a linear equation [16]:

$$y_{ijr} = \mu + p_i + \gamma_j + \varepsilon_{ijr}, \tag{1}$$

where y_{ijr} is the value of the oil quality indicator;

μ is the overall mean;

p_i is the average deviation relative to μ for the *i*-th level of the first factor;

γ_j is the average deviation relative to μ for the j- th level of the second factor;

ε_{ijr} is a residual random variable;

i is the level of the first factor;

j is the level of the second factor; the order of occurrence of one of the m_{ij} observations for the combination of the *i*-th level of the first factor with the *j*-th level of the second factor.

If the effects are non-additive, it is necessary to introduce a component into the model (1) that characterises the interaction between the factors. Then equation (1) will take the form:

$$y_{ijr} = \mu + p_i + \gamma_j + (\rho\gamma)_{ij}, \tag{2}$$

where $(\rho\gamma)_{ij}$ is the component describing the interaction between the factors.

The expression for the total squariance for model (2) is:

$$\sum_{i=1}^{n}\sum_{j=1}^{k}\sum_{r=1}^{m}(\bar{y}_{ij}-\bar{y})^2 = k\cdot m\cdot\sum_{i=1}^{n}\left(\bar{y}_i-\bar{y}\right)^2 +$$

$$+n\cdot m\cdot\sum_{j=1}^{k}\left(\bar{y}_i-\bar{y}\right)^2 +$$

$$+m\cdot\sum_{i=1}^{n}\sum_{j=1}^{k}\left(\bar{y}_{ij}-\bar{y}_i-\bar{y}_j+\bar{y}\right)^2 \tag{3}$$

Whence total squariance is:

$$Q_{\text{total}} = Q_A + Q_B + Q_{AB} + Q_\varepsilon, \tag{4}$$

where $Q_A = k\cdot m\cdot\sum_{i=1}^{n}\left(\bar{y}_i-\bar{y}\right)^2$ is the sum of squared deviations, describing the scatter of the mean across rows relative to the overall mean;

$Q_B = n\cdot m\cdot\sum_{j=1}^{k}\left(\bar{y}_i-\bar{y}\right)^2$ is the squariance between columns, characterising the scatter of the mean across columns;

$Q_{AB} = m\cdot\sum_{i=1}^{n}\sum_{j=1}^{k}\left(\bar{y}_{ij}-\bar{y}_i-\bar{y}_j+\bar{y}\right)^2$ is the sum of squared deviations characterising the mutual influence effect;

$Q_\varepsilon = \sum_{i=1}^{n}\sum_{j=1}^{k}\sum_{r=1}^{m}(\bar{y}_{ijr}-\bar{y})^2$ is the sum of squared deviations within a series, describing the scatter of individual observations in the series relative to the series mean, due to the influence of random variables alone.

The hypothesis of the significance of the influence of factors and their interactions was tested using Fisher's test. To do this, first the mean square estimates were found – total (5), interlinear (6), between-column (7), interactions (8) and residual (9).

$$S_{\text{total}}^2 = \frac{Q_{\text{total}}}{n\cdot k\cdot m-1} = \sigma_\varepsilon^2 + \sigma_A^2 + \sigma_B^2 + \sigma_{AB}^2; \tag{5}$$

$$S_A^2 = \frac{Q_A}{n-1} = \sigma_\varepsilon^2 + k\cdot m\cdot\sigma_A^2 + m\cdot\sigma_{AB}^2; \tag{6}$$

$$S_B^2 = \frac{Q_B}{k-1} = \sigma_\varepsilon^2 + n\cdot m\cdot\sigma_B^2 + m\cdot\sigma_{AB}^2; \tag{7}$$

$$S_{AB}^2 = \frac{Q_{AB}}{(n-1)\cdot(k-1)} = \sigma_\varepsilon^2 + m\cdot\sigma_{AB}^2; \tag{8}$$

$$S_\varepsilon^2 = \frac{Q_\varepsilon}{n\cdot k\cdot(m-1)} = \sigma_\varepsilon^2. \tag{9}$$

The *F*-criterion values were calculated as the ratio of the corresponding mean squares to the residual mean square:

$$F_A = \frac{\sigma_A^2}{\sigma_\varepsilon^2};$$

$$F_B = \frac{\sigma_B^2}{\sigma_\varepsilon^2};$$

$$F_{AB} = \frac{\sigma_{AB}^2}{\sigma_\varepsilon^2}. \tag{10}$$

The hypothesis of no influence of a factor or interaction effect was not rejected if the calculated *F*-criterion was less than the table value, with corresponding freedom degrees values and significance level α = 0.05.

Two-way ANOVA was performed using the "DDA" software [18] integrated in the information and analytical system "SIRENA". The values of the variance decomposition totals as well as the calculated and critical *F*-criterion values obtained from the variance decomposition for the groups of acidity are shown in Table 1.

Table 1 – Two-way ANOVA results

n	**k**	**Variance decomposition totals**					**F-criterions (calculated/ critical)**		
		Q_{total}	Q_A	Q_B	Q_{AB}	$Q_{\text{res.}}$	F_A	F_B	F_{AB}
6	5	0.831	0.223	0.435	0.14	0.033	1193	2905	187.4
							2.23	2.39	1.59

For all the oil quality indicators analysed, the calculated F-criterion values are significantly higher than the table values. This means that the drift rates of the indicators differ significantly between the groups.

From this, the following conclusions can be drawn:

1. Significant exceeding of the calculated F_A criterion limit values indicates that there is a drift in the values of the oil indicators over time, which means that oil ageing processes are taking place.
2. Significant exceeding of the calculated F_B criterion limit values indicates that the drift rates of the oil values differ between the groups, which means that the transformers in the different groups have been operated under different conditions;
3. Significant exceeding of the calculated F_{AB} criterion limit values indicates that he effects of changes in factor levels are non-additive, meaning that the effect of a change in the exposure level of one factor leads to a change in the effect of the exposure level of another.

Results analysis. The different oil ageing rate between the groups of indicators is primarily due to different transformer loads [8, 9]. However, it is of interest to analyse the influence of other factors as well. Therefore, the quality of the filled oil, the operating time, the influence of the region, the influence of transformer type and rated characteristics on the oil ageing rate were analysed. Table 2 shows the main characteristics of transformers, which are included in the groups M-1 to M-6 for the acidity of transformer oils. The analysis of the data in Table 2 allows drawing a number of conclusions about the significance of the influence of the following factors on the oil ageing rate.

The following types of transformers are abbreviated in the Table 2:

- TDN is the three-phase transformer with Oil Natural Air Forced (ONAF) cooling and on-load tap-changer (OLTC);
- TMN is the three-phase transformer with Oil Natural Air Natural (ONAN) cooling and (OLTC);
- TDNG is the lightning proof three-phase transformer with ONAF cooling and OLTC;
- TRDN is the three-phase split-winding transformer with ONAF cooling and OLTC;
- TDTN is the three-phase three-winding transformer with ONAF cooling and OLTC;
- TDTNG is the lightning proof three-phase three-winding transformer with ONAF cooling and OLTC;

Table 2 – Characteristics of groups of transformers with the same acidity drift rate

Array characteristics	Data array					
	M-1	**M-2**	**M-3**	**M-4**	**M-5**	**M-6**
Indicator value at time of oil filling, mg KOH/g						
Maximum	0.049	0.043	0.027	0.009	0.028	0.049
Average	0.020	0.019	0.018	0.004	0.017	0.040
Minimum	0.010	0.003	0.010	0.001	0.010	0.030
Average time for the indicator to reach the limit value, years	18.41	30.76	–	–	7.33	4.49
Distribution of transformers by service life, %						
up to 10 years	0	0	15	6	0	0
10 to 20 years	21	35	52	63	25	0
20 to 30 years	31	35	30	31	50	0
30 to 40 years	35	27	3	0	0	33
over 40 years	13	3	0	0	25	67
Distribution of transformers by region, %						
Donetsk	23	16	3	6	25	33
Crimea	0	5	9	19	0	0
Lugansk	49	24	3	44	75	67
Poltava	5	8	0	6	0	0
Sumy	8	5	0	25	0	0
Kharkiv	15	42	85	0	0	0
Distribution of transformers by rated capacity, %						
10 MBA	0	0	0	6	0	0
16 MBA	2	8	3	13	0	0
20 MBA	6	8	0	0	0	0
25 MBA	33	22	58	31	0	0
32 MBA	33	16	6	25	25	0
40 MBA	22	46	33	19	25	67
63 MBA	4	0	0	6	50	33
Distribution of transformers by type, %						
TDN	6	2	3	6	0	0
TMN	0	0	0	6	0	0
TDNG	22	6	3	6	50	0
TRDN	24	39	27	25	0	33
TDTN	44	39	61	44	50	33
TDTNG	4	10	6	13	0	34
Foreign-made	0	4	0	0	0	0
Distribution of transformers by rated voltage, %						
110/6 kV	27	29	21	38	0	33
110/10 kV	8	20	12	6	0	0
110/10/6 kV	4	4	21	0	0	0
110/35/6 kV	43	41	40	25	75	34
110/35/10 kV	18	6	6	31	25	33

Influence of the quality of the filled oil. As can be seen from Table 2, the values of the acidity at the time of filling the transformer tank fluctuate within a fairly wide range. The lowest values of the acidity are found in the M-4 group. This group also has the lowest oxidation rate (Fig. 1). The maximum values of the acidity were observed in group M-6 (maximum oxidation rate). For the other groups of transformers the acidity at the time of filling has intermediate values. The influence of oil quality on the ageing rate can be explained by the increase in the number of free radicals in the oil with the worst quality (in this case with an increased value of the acidity), which leads to an increased intensity of oxidation reactions.

Influence of the operating time. The acidity groups with the highest oxidation rates (M-1, M-5 and M-6) mainly consist of transformers with more than 30 years of operating time, while the groups with the lowest oxidation rates (M-3 and M-4) contain the highest percentage of transformers with up to 20 years of operating time. On the one hand, this shows the influence of transformer load on the oxidation intensity (because oil temperature will largely depend on load losses and transformer load before 1990 was much higher than after 1990). On the other hand, operating time is also an important factor, as insulation ageing also occurs at low temperatures, but with less intensity (the effects of changing factor levels are not additive).

Influence of the region. When analysing the distribution of transformers from different regions of Ukraine into groups, one cannot but notice that the groups with the highest ageing intensity (M-1, M-5 and M-6) consist mainly of transformers in operation in Donetsk and Luhansk regions. This is most likely due to the predominance of industrial consumers in the load of these transformers, and hence the harsher temperature conditions of their operation.

Influence of the rated capacity. As would be expected, the rated capacity of transformers has no influence on the oil ageing intensity. The relevant factor is not the rated capacity of the transformers, but how many percent of the rated capacity the transformer in question has been loaded over the entire service interval. This fact is clearly illustrated in Fig. 2, which shows the dependence of the acidity on the operating time for transformers with a rated capacity of 25 MVA (curve 1) and 40 MVA (curve 2) of the same rated voltage, installed in different substations in the Kharkiv region.

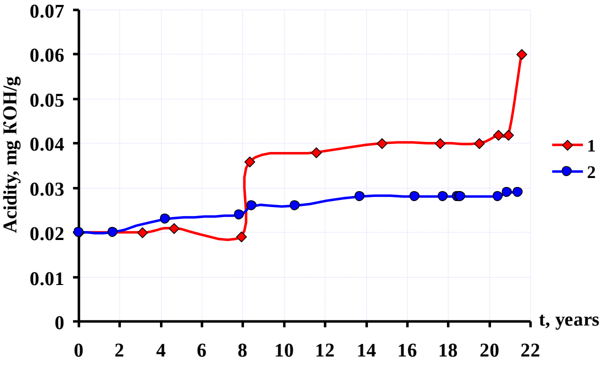

Figure 2 – Dependence of the acidity on the operating time for 2 transformers of different rated capacity and the same rated voltage, installed in different substations in the Kharkiv region

As can be seen from the figure, the oil ageing rate of the transformer indicated by curve 1 is higher than that of the transformer indicated by curve 2, despite the fact that the latter has a higher rated capacity. This is due to the fact that the average load of the first transformer was 35.2 % and that of the second transformer was 16.2 %.

Influence of transformer types and rated voltages. By analysing the data in Table 2. it is easy to see that neither the transformer type, nor the voltages of the medium and low voltage windings have a significant influence on the oil ageing rate. As in the case of transformer rated capacity, a decisive factor in the intensity of oil ageing is the transformer load. Transformers of the same type, with the same voltage on the medium and low voltage sides, have different ageing rates at different loading factors (Fig. 3). Thus, two transformers of the same type, with 40 MVA and 110/35/6 kV, installed in the neighbourhood of the same substation, have an average load of 39 % and 11 %, which results in different oxidation rates at the same types and rated voltages of these transformers. At the same time, the oil ageing rate for transformers of different types, but with the same load, is almost identical (Fig. 4). The loads of 2 transformers of different types, installed in the neighbourhood of the same substation, are approximately the same – 52 % and 54 % respectively, which results in approximately the same ageing rate for the different types of transformers.

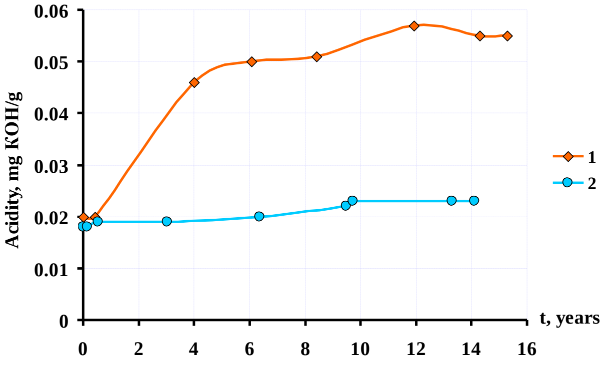

Рисунок 3 – Dependence of the acidity on the operating time for 2 transformers of the same types installed in the neighbourhood of the same substation

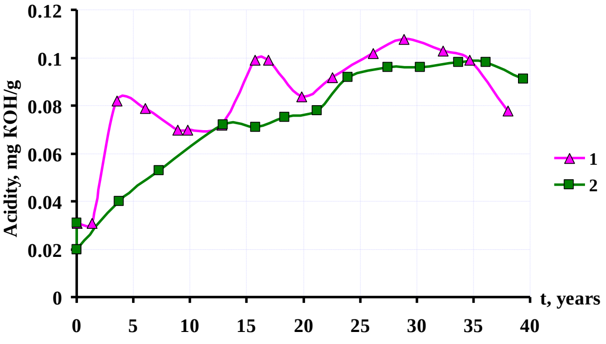

Figure 4 – Dependence of the acidity on the operating time for 2 transformers of different types installed in the neighbourhood of the same substation

Conclusions. Under long-term operating conditions the ageing of transformer oils in the tanks of power high-voltage transformers proceeds with different speeds. As a result the drift rate of quality indicators of transformer oils significantly differs. The main factors influencing the intensity of oil ageing are transformer loading, operating time and oil quality. The rated power, type and rated voltages on medium and low voltage transformer windings have been found to have no significant influence on the intensity of oxidation reactions. The results obtained allow the correction of the maximum permissible values of oil acidity, taking into account the factors affecting the intensity of oxidation of oils.

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