

IMPROVING THE EFFICIENCY OF ASSESSING THE TECHNICAL CONDITION OF ELECTRICAL EQUIPMENT

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Abstract

In recent years, the understanding of the efficiency of technical diagnostics of electrical equipment has increased significantly. The main reasons for this are, in particular: more than half of the equipment in operation has exhausted its estimated service life; the rate of aging of the equipment exceeds the rate of its renewal; due to limited funds for technical maintenance, as well as due to the transition to repairs based on technical condition. High quality and timely diagnostics improve the objectivity of assessing the technical condition of high-voltage electrical equipment. All this allows planning and timely execution of necessary maintenance and repair operations, which makes the operation of electrical equipment more reliable, extends its service life, saves money, and reduces the risk of damage. A method for assessing the moment of occurrence of a change in the growth of concentration of gases dissolved in oil has been developed, allowing to establish the presence of a developing transformer defect, the main gases, the probable type of defect and the nature of its manifestation. A method and algorithm for predicting the time of occurrence of a faulty state of power transformers based on the data of chromatographic analysis of gases dissolved in transformer oil are proposed. A method developed to assess the moment of occurrence of changes in the concentration of dissolved gases in oil, which makes it possible to establish the presence of a developing transformer defect, the main gases, and the likely type of defect and the nature of its manifestation. A method and algorithm for predicting the time of occurrence of a faulty state of power transformers based on chromatographic analysis of gases dissolved in transformer oil are proposed. The recommended algorithm will make it possible to increase the objectivity of comparing the same type of indicators of gases dissolved in oil at the initial stage of wear change.

Keywords: Transformer, diagnostics, technical condition, chromatographic analysis, defect, time of occurrence, intensity, duration

I. Introduction

One of the factors influencing the development of events in the energy sector is the growing share of equipment whose service life exceeds the standard [7]. The increase in the volume of industrial production leads to an increase in energy consumption, and, consequently, to an increase in the number of negative external influences (overloads, overvoltage, etc.) [10]. Together with equipment wear, this contributes to a certain increase in the number of accidents and equipment failures. In these conditions, increasing the efficiency of diagnostics of the state of electrical equipment involves

the development of new approaches and methods for assessing the technical condition of equipment, and the development of a diagnostic system. The diagnostic system is assumed in the form of a clear technical strategy for identifying defects in electrical equipment and predicting their development. A significant contribution to the improvement of the system for analyzing the results of measuring diagnostic indicators was made by studies [9], focused on the use of expert systems.

The technology for assessing the condition of oil-filled electrical equipment involves the use of any information about the object at any stage of its life cycle. In this case, the following results are used to assess the condition of transformers: periodic and extraordinary inspections; thermal imaging control; verification of the transformation ratio; verification of the winding connection group, etc. At the same time, when assessing the condition, information is analyzed, which is entered based on the results of the following types of tests: chromatographic analysis of oil; measurement of insulation parameters under operating voltage; physical and chemical analysis of oil, etc. [1]

An important result is the issuance of recommendations based on the analysis of the equipment condition, which can be grouped into two groups:

- diagnostic, which are aimed at clarifying the type of defect and are associated with new tests;
- current, which are designed to reduce the negative impact of possible defects, i.e., to ensure the operational condition of the equipment or prevent an accident.

This approach is aimed at assessing the condition of not only the control object, but also the control subject, i.e., training of operational and repair personnel. The main focus is on three areas: ensuring the appropriate level of training of operational, repair and engineering and technical personnel; providing of personnel with regulatory and technical documentation; organizing maintenance, monitoring and assessment of the equipment condition, planning and conducting repair and technical maintenance. The solution to these problems is based on the application of an algorithm for monitoring the significance of features and their varieties [2].

II. Estimate the time of occurrence of a defect and the duration of its development

One of the main tasks of diagnostics of the technical condition of power system equipment is to estimate the time of occurrence of a defect and the duration of its development to the level at which the probability of damage is sufficiently high. The absence of this information leads to the fact that the frequency and volume of equipment tests are regulated as deterministic values, i.e., values that do not depend on the technical condition of the equipment. To a certain extent, the solution to the issue of the timing of testing and repair is achieved by assessing the residual service life before failure of operability (ΔT_s^*).

The assessment of this value in accordance with [3] is carried out according the formula:

$$\Delta T_s(t_k) = \min[\Delta T_{S,1}(t_k); \Delta T_{S,2}(t_k); \dots \dots \dots; \Delta T_{S,m}(t_k)] \quad (1)$$

$$\Delta T_{S,j}^*(t_k) = \frac{1 - I_{z_j}(t_k)}{\sigma[I_{z_j}(t_k)]} \quad (2)$$

where: t_k - date of control test; m - number of indicators characterizing the technical condition of the equipment; $I_{z_j}(t_k)$ is the amount of wear of the j -th material at the moment t_k . It is calculated by the formula:

$$I_{z_j}(t_k) = \frac{P_j(t_k) - P_{j,INI}}{P_{j,PER} - P_{j,INI}} \quad (3)$$

where $j=1,m$; $P_j(t_k)$ - quantitative assessment of the j -th parameter at the time t_k ;
 $P_{j,INI}$ and $P_{j,PER}$ - initial and maximum permissible values of the j -th parameter; $\vartheta[Iz(t_k)]$ - rate of change of the value of the j -th parameter at the moment t_k .

Calculated by the formula:

$$\vartheta[Iz_j(t_k)] = \frac{Iz_j(t_k) - Iz_j(t_{k-1})}{(Iz_{j,PER} - Iz_{j,INI})(t_k - t_{k-1})} \quad (4)$$

where: t_{k-1} - moment of the previous test.

The question of the time of occurrence of a defect remains open largely, because there is no clear quantitative interpretation of the concept of "defect." Consider the physical essence of the process of defect development. It is known, that during the operation of equipment, there is a monotonous deterioration of the electrical, electromagnetic, thermal, mechanical and other properties of structural elements. The patterns of change in this process are quite complex, include continuous and discrete components, and are determined by many operational factors.

At a certain stage of wear, "weak links" of materials begin to appear. These "weak links" are usually called local defects. They are manifested in the fact, that the rate of wear of the material increases significantly [4]. The number of defects and their types depend on the service life of the equipment (T_s) and, undoubtedly, increase as the T_s grows. This is confirmed by the experience of inspecting equipment that has been shut down for major repairs.

Thus, by the time of occurrence of a defect we will understand the moment of time, starting from which the rate of wear of the equipment increases.

We will consider the practical implementation of this approach using the example of changes in the technical condition of power transformers [5,6].

As an important part of electrical networks, transformers are manufactured in accordance with high standards of accuracy and quality and are designed for a long service life. Since the average life of such transformers in many countries is from 30 to 40 years, the probability of failure is constantly increasing. This situation is aggravated by the growing tendency of operating transformers in modes close to the limit. As the relative number of power transformers whose service life exceeds the estimated one increases, the urgency of the problem of refining the assessment of their technical condition, refining the fleet of faulty transformers, assessing the volume of scheduled repairs, and the feasibility of replacement also increases.

In order to optimize the strategy of repair and maintenance, it is necessary to be able to assess the condition of the transformer fleet. The purpose of the strategic assessment of the technical condition of the transformer fleet is to detect and prevent failures of the most vulnerable units in order to organize their priority maintenance, repair and replacement planning. At the same time, the aging of the power transformer fleet, the analysis of damage and operating experience, and the accumulated experience in analyzing the technical condition of transformers indicate the need to improve methods and algorithms aimed at developing and improving the system for assessing the technical condition and diagnostic methods of power transformers to ensure and improve their operational reliability.

III. Effective methods for assessing the wear of power transformers

Currently, one of the most effective methods for assessing and predicting wear changes in power transformers, without taking them out of operation, is the method of chromatographic analysis of dissolved gases in transformer oil (CADG) [1].

It should be emphasized, that the accumulated long-term experience of using CADG to assess the condition of power transformers has made a significant contribution to ensuring the reliability of their operation. It confirmed the effectiveness of using the developed set of features, that have high diagnostic value, which make it possible to determine the type and nature of detected defects at an early stage of development for make decisions on the further operation of power transformers or the need to take them out for repair.

A characteristic feature of the CADG data processing methodology used is the multi-criteria nature of the decision on the presence, type and nature of the developing damage to transformers.

The criteria are based on the results of measuring the concentration of individual gases $(C_i)_n$, where n - the number of analyzed gases, calculating the concentration of the sum of combustible gases C_Σ and the ratio of the concentrations of individual gases $(C_i/C_j)_m$, where m - the number of calculated ratios.

Along with comparison with maximum permissible (boundary) values of gas concentrations $(C_{i,PER})_n$, criteria based on comparison of the rate of change of $[\vartheta(C_i)]_n$ with permissible values are widely used. Exceeding, at least one of the measured values of $\{C_i\}_n$ the corresponding permissible values $(C_{i,PER})_n$ or the rate of their change of 10% vol., indicates the possibility of a defect and the need to identify the causes of these excesses.

A feature of the diagnostics of the technical condition of transformers according to CADG data is also the fact, that a significant increase in the concentration of analyzed gases often occurs on defect-free transformers. These changes are usually caused by a number of operational factors [1].

A feature of the diagnostics of the technical condition of transformers according to CADG data is also the fact, that a significant increase in the concentration of analyzed gases often occurs on defect-free transformers. These changes are usually caused by the impact of a number of operational factors [1]. The impact of these factors is quite fully revealed based on the data of the physical and chemical analysis of oil (PCAO). Therefore, it is advisable to compare the change in the CADG data with the change in the PCAO data.

In real conditions, gases are released as a result of electrical discharge or heating, aging of transformer insulation, exposure to overvoltage, through short-circuit currents, load changes and many other operational factors. An important condition for increasing the reliability of the analysis of CADG data is the improvement of the methodology for calculating the indicators characterizing the technical condition of the transformer.

Let us consider some features of CADG data processing. [8]

Operating experience shows that a noteworthy change in the concentration of dissolved gases in oil is most often manifested in exceeding the rate of change in the relative concentration of gas of the permissible value $\vartheta[\delta C(t)]_{PER}$.

Such a transformer is taken under control and after 1-2 weeks a control CADG is carried out.

The known recommendations for assessing $\vartheta[\delta C(t)]_{PER}$ are based on reducing the absolute rate of increase of the i-th gas at time t_{j+1} to the previous value (at time t_j) of the concentration of this gas and are determined by the formula:

$$\vartheta_{REL}(t_{j+1}) = \frac{C(t_{j+1}) - C(t_j)}{C(t_j) \cdot \Delta T_{j+1}} 100 (\%), \quad (5)$$

which limits the possibility of analyzing the dynamics of change $\vartheta_{REL}(t)$.

To overcome this difficulty, it is recommended to calculate the rate of change of the relative concentration of the i-th gas using the formula:

$$\vartheta[\delta C(t_{j+1})] = \frac{\delta C_i(t_{j+1}) - \delta C_i(t_j)}{\Delta T_{j+1}} = \frac{C_i(t_{j+1}) - C_i(t_j)}{C_{i,PER} \cdot \Delta T_{j+1}}, \quad (6)$$

where: $\Delta T_{j+1} = (t_{j+1} - t_j)$.

It is assumed that the upper permissible (boundary) value $\vartheta[\delta C(t)]_{PER} \leq 10\%$.

If as a result of processing the data of the control CADG it is established that the gas growth rate has increased, then while maintaining the assumption of the linear nature of the change in the relative concentration of gas in the oil of power transformers, the estimate of the moment of change in speed can be performed by solving the following equation:

$$\delta C_i(t_k) = \vartheta[\delta C_i(t_{j+1})](t_x - t_j) = \delta C_i(t_{j+3}) - \vartheta[\delta C_i(t_{j+3})](t_{j+3} - t_x) \quad (7)$$

where: $i=1,7$; $(t_x - t_j) = \Delta T_x$; $(t_{j+1} - t_j) = \Delta T_1$; $(t_{j+2} - t_{j+1}) = \Delta T_2$; $(t_{j+3} - t_{j+2}) = \Delta T_3$; $t_{j+3} - t_x = \sum_{\vartheta=1}^3 \Delta T_{\vartheta} - \Delta T_x$.
 $\vartheta[\delta C_i(t_{j+1})]$ and $\vartheta[\delta C_i(t_{j+3})]$ - the rate of change of the relative concentration of the gas at moments t_{j+1} and t_{j+3} .

Consider the indicator of the relative concentration of the i -th gas at $t_j - \delta C_i(t_j)$. Quantitatively, this indicator is determined by the formula:

$$\delta C_i(t_j) = \frac{C_i(t_j) - C_{i,INI}}{\delta C_{i,PER} - C_{i,INI}} \quad (8)$$

$C_{i,INI}$ and $C_{i,PER}$ - respectively, the initial and permissible (boundary) values of the concentration of the i -th gas;

The maximum value of the relative concentration of gases is determined by the formula:

$$\delta C_{max}(t) = \max[\delta C_1(t_1), \delta C_2(t_2), \dots, \delta C_n(t_n)] \quad (9)$$

The intensity of the process of change in wear of power transformer units is characterized by the rate of change in the increase in gas concentration in the oil. In order to compare the rates of change in gas concentration, the rate must be assessed using the formula:

$$\vartheta[\delta C_i(t_2)] = \frac{\delta C_i(t_2) - \delta C_i(t_1)}{(t_2 - t_1)} = \frac{C_i(t_2) - C_i(t_1)}{(C_{i,PER} - C_{i,INI})(t_2 - t_1)} \quad (10)$$

In this case, the greatest rate of change in gas concentration will be equal to:

$$\vartheta[\delta C(t)]_{max} = \max\{\vartheta[\delta C_1(t)], \vartheta[\delta C_2(t)], \dots, \vartheta[\delta C_n(t)]\} \quad (11)$$

The $\delta C_{max}(t)$ and $\vartheta[\delta C(t)]_{max}$ indicators are certainly important, but each of them separately is not informative enough. Therefore, it is advisable to identify the main gases by comparing the residual time $\{\Delta T_i(t_k)\}_n$, at the time t_k , after which the value of $\delta C(t)$ will be equal to one, according to the formula:

$$\Delta T_i(t_k) = \frac{[1 - \delta C_i(t_k)]}{\vartheta[\delta C_i(t_k)]} \quad (12)$$

where $i=1,n$

The value of $\Delta T_i(t_k)$ is, in essence, an estimate of the time until the next control of gas concentration in the oil of power transformers. Therefore, the subsequent CADG should be carried out in a time, not exceeding:

$$\Delta T_{PER}(t_k) = \min\{\Delta T_1(t_k), \Delta T_2(t_k), \dots, \Delta T_n(t_k)\} \quad (13)$$

The $\Delta T_{PER}(t_k)$ value is estimated at $\delta C_{\max}(t) < 1$.

If $\delta C_{\max}(t) > 1$, then should be followed the recommendations for monitoring of developing defects of transformer equipment, when changing the concentration of transformer oil gases.

As is known, the change in $\delta C(t)$ occurs not only due to developing defects in power transformers, but also as a result of the impact of a number of operational factors. Some factors lead to an increase in the concentration of dissolved gases in oil (these include: increasing the load, adding of oil, that has been in use and containing dissolved gases, etc.), while others lead to a decrease in the concentration of dissolved gases (for example, replacement of silica gel, degassing oil, etc.).

In practice, questions about the magnitude and duration of change are of considerable interest. A graphical illustration of the change process is shown in Fig. 1a and 1b.

These graphs clearly show, that the actual pattern of $\delta C(t)$ change differs significantly from the piecewise linear curve constructed using the CADG data. So, figure 1a, shows the combination of two processes of changing $\delta C(t)$. The first of them is associated with the natural aging of insulation, changes in its dielectric properties, thermal conductivity, mechanical strength.

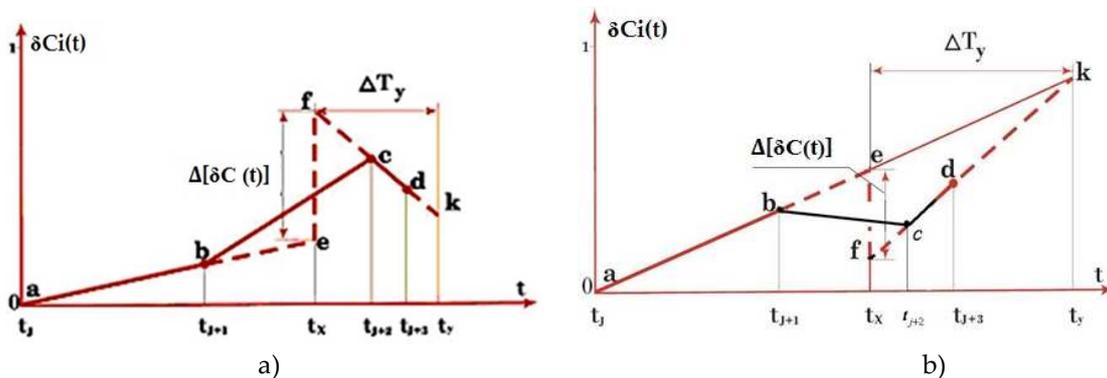


Figure. 1: Graphic illustration of changes $\delta C(t)$ under the influence of operational factors causing: a) increase $\delta C(t)$; b) decrease $\delta C(t)$.

The second process is caused by the operational factor, causing an increase in $\delta C(t)$ of transformer oil at the moment t_x . The real regularity of $\delta C(t)$ change is characterized by the *abefcd* route, and formed by CADG data is characterized by the *abcd* route.

A similar conclusion can be made based on the data in fig. 1b. In this figure, the process of monotonic (linear) change in $\delta C(t)$ is superimposed on the process of change in $\delta C(t)$ due to an effect, that causes a sharp decrease in $\delta C(t)$.

To calculate the value of $\delta C(t)$ as a result of some operational impact, we use the equations of straight lines passing through points a and b, c and d. If we denote the value of the relative concentration of gases dissolved in oil before the impact at moment t_x of some operational factor by $\delta C(t_x)$:

$$\delta C(T_x) = V[\delta C(t_{j+1})]t_x \quad (14)$$

and is graphically illustrated by a straight-line segment, connecting points t_x and e .

After exposure to this factor, the relative concentration of gases dissolved in transformer oil, almost instantly changes and is equal to:

$$\delta C(t_x) = V[\delta C(t_{j+3})](t_x - t_{j+2}) + \delta C(t_{j+2}) \quad (15)$$

and is graphically represented by a straight-line segment, connecting points t_x and f .

In accordance with fig. 1, the value of the operational factor effect is displayed by the line segment fe , which for fig. 1a is calculated as the difference between the segments txf and txe by the formula:

$$\Delta_1[\delta C(t_x)] = V[\delta C(t_{j+3})](t_x - t_{j+2}) + \delta C(t_{j+2}) - V[\delta C(t_{j+1})]t_x \quad (16)$$

and for fig.1b it is calculated as the difference between the segments txe and txf by the formula:

$$\Delta_2[\delta C(t_x)] = V[\delta C(t_{j+1})]t_x - \delta C(t_{j+2}) - V[\delta C(t_{j+3})](t_x - t_{j+2}) \quad (17)$$

Thus:

$$\Delta[\delta C(t_x)] = \Delta_1[\delta C(t_x)] = -\Delta_2[\delta C(t_x)] \quad (18)$$

The completion of the change in the value $\delta C(t)$, caused by the impact of the operational factor, occurs at the moment of time t_y , which, based on equations (12) and (13), is calculated using the formula:

$$t_y = \frac{\delta C(t_{j+2}) - V[\delta C(t_{j+3})]t_{j+2}}{V[\delta C(t_{j+1})] - V[\delta C(t_{j+3})]} \quad (19)$$

and the duration of the change in the relative concentration of gases in the transformer oil of a defect-free transformer is calculated using the formula:

$$\Delta T_y = t_y - t_x \quad (20)$$

Analysis of the graphs in fig. 1 shows, that the occurrence of a sudden change (increase or decrease) in $\delta C(t)$ due to the impact of operational factors leads to a decrease in the $V[\delta C(t)]$ speed on the interval (with an increase in $\delta C(t)$), or an increase in the speed on the interval (with a decrease in $\delta C(t)$), and can be considered as a diagnostic sign of the causes of the change in $\delta C(t)$. Note that in the presence of defects in the power transformer, the rate of change in $\delta C(t)$ satisfies the condition:

$$V[\delta C(t_j)] \leq V[\delta C(t_{j+1})] \leq V[\delta C(t_{j+2})], \quad (21)$$

where: $t_j < t_{j+1} < t_{j+2}$.

The $\Delta T_{PER}(t_k)$ value is estimated if $\delta C_{max}(t) < 1$.

If $\delta C_{max}(t) > 1$, then the appropriate recommendations for diagnosing developing defects in transformer equipment based on the results of chromatographic analysis of dissolved gases in transformer oil should be followed.

Operating experience shows that the nature of wear of power transformers can often be determined from the ratio of gas concentrations, namely from the ratio

$$\frac{C_2H_2}{C_2H_4}, \frac{CH_4}{H_2} \text{ and } \frac{C_2H_4}{C_2H_6}.$$

Considering the fact, that the ratio of absolute values of gases noted above is not sufficiently objective, an increase in the information content of physically explainable ratios can be achieved by switching to ratios of corresponding $\delta C_i(t)$ estimates.

Conclusions

1. The technical condition of power transformers depends to a large extent on the operating factors influencing them. The recommended formulas for calculating the time of defect occurrence (ΔT_x), intensity $\Delta[\delta(t)]$ and duration (ΔT_y) of the impact of many operating factors and their varieties on the change in the concentration of dissolved gases according to the CADG data allow increasing the objectivity of the analysis of the technical condition of power transformers.
2. Proposed a method for calculating the indicators, which characterize the concentration of gases dissolved in transformer oil. The main gases are most objectively determined by the parameter characterizing the time interval before the next CADG is carried out. A gas should be considered the main, if this time interval is the smallest for it;
3. The proposed method of estimating the permissible (boundary) values of concentrations of gases dissolved in transformer oil by a variety of operational factors and their varieties allows ensuring the objectivity of the calculation of these indicators.
4. There is a dependence of the reliability of the presence of defects in power transformers on operational factors. This determines the need to use automated CADG data processing systems as a subsystem for intellectual analysis of the technical condition of transformers, systematizing and summarizing information about operating conditions, failures, tests and planned repairs.

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