

UDC 004.9:621.319.48:621.311

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IMPROVEMENT OF METHODS FOR DIAGNOSING AN OIL-FILLED HIGH-VOLTAGE COUPLING CAPACITOR

С.В. Зайцев, В.В. Чиченін, С.А. Суцїнська, В.М. Тіхенко, П.Н. Миронюк. Удосконалення методів діагностування оливнонаповненого високовольтного конденсатора зв'язку. У системах забезпечення високочастотного електричного зв'язку використовуються оливнонаповнені високовольтні конденсатори, до показників надійності яких висуваються високі вимоги. Стаття присвячена удосконаленню процедур діагностування оливнонаповненого високовольтного конденсатора зв'язку шляхом використання методів газохроматографічного визначення вмісту розчинених діагностичних газів у мінеральних конденсаторних оліях. Метою роботи є підвищення достовірності результатів технічного діагностування електричного конденсатора зв'язку типу СМА-166V3-14УХЛ1 для контролю його технічного стану, визначення місця та причин відмови, прогнозування технічного стану та з'ясування можливості проведення технічного обслуговування та ремонту. Виконано дослідження: електричних характеристик та характеристик теплового поля конденсатора зв'язку; властивостей конденсаторної оливи після розбирання конденсатора. Визначено наступні параметри: для конденсатора зв'язку – тангенс кута діелектричних втрат, електрична ємність та її зміни, електричний опір; для конденсаторної оливи – напруга електричного пробою, тангенс кута діелектричних втрат, температура спалаху в закритому тиглі, щільність, вміст вологи, кислотне число, наявність механічних домішок, розчинність водню, вміст розчинених діагностичних газів, антиокислювальної присадки і фуранових сполук. Отримані результати дозволяють підвищити достовірність результатів діагностування технічного стану оливнонаповнених електричних конденсаторів у зв'язку з використанням традиційних та додаткових методів діагностування високовольтного електротехнічного обладнання, заповненого мінеральними оливами.

Ключові слова: діагностування, конденсаторна олива, конденсатор зв'язку, газова хроматографія

S. Zaitsev, V. Chichenin, S. Sushchinskaya, V. Tikhenko, P. Mironyuk. Improvement of methods for diagnosing an oil-filled high-voltage coupling capacitor. Oil-filled high-voltage capacitors are used in high-frequency electrical communication systems, the reliability of which is highly demanding. The article is devoted to the improvement of procedures for diagnosing an oil-filled high-voltage coupling capacitor by using methods of gas chromatographic determination of the content of dissolved diagnostic gases in mineral condenser oils. The aim of the work is to increase the reliability of the technical diagnostics results of electric capacitor communication type SMA-166V3-14UHL1 to monitor its technical condition, determine the location and causes of failure, predict technical condition and clarify the possibility of maintenance and repair. The following studies were performed: electrical characteristics and thermal field characteristics of the communication capacitor; properties of condenser oil after disassembly of the condenser. The following parameters are determined: for the coupling capacitor - the tangent of the dielectric loss angle, electric capacitance and its changes, electrical resistance; for condenser oil - electric breakdown voltage, dielectric loss tangent, flash point in a closed crucible, density, moisture content, acid number, presence of mechanical impurities, hydrogen solubility, dissolved diagnostic gases content, antioxidant additive and furan compounds. The obtained results allow to increase the reliability of the results of diagnosing the technical condition of oil-filled electric capacitors in connection with the use of traditional and additional methods of diagnosing high-voltage electrical equipment filled with mineral oils.

Keywords: diagnosing, condenser oil, coupling capacitor, gas chromatography

Introduction

When operating high-voltage power lines, equipping them with devices of high-frequency relay protection and emergency automation, it is necessary to ensure reliable electrical communication between units of energy systems [1]. This is necessary for the transmission of telemechanics signals, emergency automation and relay protection, emergency shutdown of high-voltage circuit breakers, automated systems for commercial electricity metering and other data. To do this, high-voltage oil-filled coupling capacitors (HVOFCC) are used, which transmit high-frequency electrical signals through electrical communication channels, or are used to connect communication equipment to high-voltage power lines and lightning protection cables. HVOFCCs are designed to provide high-

DOI: 10.15276/opu.1.65.2022.14

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frequency electrical communications at frequencies of 24...1500 kHz in power lines with a rated voltage of 35...750 kV. High requirements are imposed on the reliability indicators of such capacitors. The average service life is 25 years, and the probability of failure-free operation is 0.9 [1]. Currently, obsolete design HVOFCCs continue to operate in the power systems of Ukraine. Damage to such HVOFCCs leads not only to the shutdown of high-voltage power lines, but also poses a threat to the safety of maintenance personnel. Therefore, the application and improvement of methods for diagnosing the technical condition of HVOFCC is an urgent problem.

Analysis of recent research and publications

The results of the study of the reasons for the deterioration of the insulating properties and reliability indicators of HVOFCC type CMP-166V3-14УХЛ1 are given in [1]. It is noted that the main causes of failures can be the following: moisture ingress through the sealing rubber rings between the upper flange and the body; poor-quality impregnation of film electrical insulation between layers with capacitor oil; the presence of individual solid particles and rare brown spots (tint) between the layers of electrical insulation; aging of film electrical insulation in contact with capacitor oil; deterioration in the quality of condenser oil.

It is noted that the main diagnostic parameter that determines the electrical insulation defect for a given batch of HVOFCC is the increase in electrical capacitance, which is caused by electrical breakdown of a part of the series-connected sections. The paper [3] discusses a diagnostic model of the processes of changing the technical state of the HVOFCC voltage class 330 kV, built on the basis of a study of the electrical parameters and parameters of the temperature field during operation. The reasons for the deterioration of the insulation characteristics of such HVOFCCs that have not worked out their passport life, and changes in the values of diagnostic parameters when using different diagnostic methods, are investigated. In [4], the features of the flow of violations in the high voltage electrical network, as well as thermal imaging control of HVOFCC and high-frequency barriers, are considered; the number of controlled points of this electrical equipment; diagnostics of electric capacitors with a voltage of 35 kV in production shops with a description of the transient process in the event of a defect, as well as design features of HVOFCC with a voltage of 110...220 kV. Based on the calculations, a method of thermal imaging control was formed with the recommended deadlines for eliminating these defects. The effect of capacitor oil properties on HVOFCC reliability has not been considered. Typical internal defects that occur during the operation of HVOFCC are given in [5]. It is noted that in the event of a defect associated with the release of air from the damaged bellows inside the HVOFCC with the simultaneous accumulation of gaseous H_2 generated under the influence of electric discharges in the form of bubbles in it, it is possible to form a saturated solution of H_2 in oil and free gaseous H_2 above the oil surface with the appearance of an electric arc. In this case, in the closed internal volume of the HVOFCC, a sharp increase in pressure to an unacceptable level is possible, which can lead to an explosion. At this point in time, continuous pressure monitoring in HVOFCC during operation is not provided. In [6], the experience of using the methods of chromatographic (GCh) analyzes of dissolved diagnostic gases in HVOFCC during their manufacture, as well as during repair work, is summarized. The possible formation of an electrically conductive deposit in the oil and its deposition on the inner surfaces of the lower part of the porcelain lid was noted at an increased electric field strength and (or) an increased oil temperature. This process can lead to electrical flashing of the HVOFCC insulation along the inside surface of the porcelain cap. Sedimentation increases the dielectric loss tangent of the oil. The formation of wax in oil can also occur due to the development of ionization processes in paper-oil insulation. It was noted in [7] that for HVOFCC oil quality indicators are not monitored during operation, during acceptance tests and during the overhaul period. At the same time, when performing repair work related to the opening of the HVOFCC, monitoring the quality indicators of the drained and refilled oil ensures further reliable operation of the HVOFCC. The paper [8] presents an analysis of modern methods and tools for diagnosing power cosine electrical capacitors with paper-oil electrical insulation. New methods and information-measuring systems built on their basis for diagnosing electrical capacitors are described. The need to control the properties of oils during their operation is noted. The results of this work can be applied to the diagnosis of HVOFCC. The paper [9] describes

the experience of using GCh methods to determine the content of dissolved diagnostic gases in oils during the manufacture of HVOFCC, as well as during repair work. The relationship between the quantitative indicators of the electrical partial discharges that have arisen in HVOFCC and the quantitative and qualitative composition of the resulting gases that dissolve in the capacitor oil is shown in [10]. To calculate the concentrations of dissolved diagnostic gases, the values of the Ostwald solubility coefficients B_i used for the corresponding i -th diagnostic gases dissolved in mineral transformer oils were used. It is shown that to perform calculations, it is preferable to use the values of the distribution coefficients K_i for the corresponding i -th diagnostic gases in mineral electrically insulating oils in equilibrium systems "mineral oil – i -th dissolved gas – gaseous extractant" instead of the Ostwald solubility coefficients B_i . This is because the values of the coefficients B_i differ from the values of the distribution coefficients K_i for the corresponding dissolved i -th diagnostic gases in mineral electrical insulating oils.

The purpose of this article is to increase the reliability of the results of diagnosing HVOFCC type CMP-166V3-0.014 to monitor its technical condition, determine the location and causes of failure (malfunction), as well as predict maintenance and repair.

Presentation of the main material

Objects of research: oil-filled electrical coupling capacitor of the CMP-166 V3-0.014 type, filled with mineral capacitor oil; samples of mineral condenser oil. Investigated electrical and thermal characteristics of HVOFCC: dielectric loss tangent $\text{tg}\delta_{\text{ks}}$ %, electrical insulation [11, 12]; electric capacitance C_{ks} μF [11, 12]; electrical resistance R_{izm} MOhm, insulation [11, 12]; temperature t_f , °C, of the upper or lower elements of phase B [13]. The investigated characteristics of oil samples from HVOFCC: electrical breakdown voltage (breakdown voltage) U kV [14]; flash point of oil vapor in a closed crucible t_{vsp} °C [14]; acid number AN, mg KOH per 1 g of capacitor oil [14]; dielectric loss tangent $\text{tg}\delta_{\text{km}}$ % [15]; the presence of mechanical impurities [14]; density ρ g/cm³ [14]; moisture content W g/t [15]; content of C_i % of volumetric, dissolved diagnostic gases H₂, CH₄, C₂H₆, C₂H₄, C₂H₂, CO, CO₂, O₂, N₂ [16]; the content of the antioxidant additive "Ionol" [17]; the content of diagnostic furan compounds [18, 19]. When studying the electrical and thermal characteristics of HVOFCC, measuring and testing equipment was used: megohmmeter ЭС0202/2Г; AC electric bridge CA7100-2; thermal imager "Cryonic". Gas chromatograph "Crystal-2000M" was used to determine: the content of C_i dissolved in oil i -th diagnostic gases (H₂, CH₄, C₂H₆, C₂H₄; C₂H₂, CO, CO₂, O₂, N₂, air); the content of the antioxidant additive "Ionol" and furan compounds in the oil; values of distribution coefficients K_i for each of these diagnostic gases in the equilibrium system "condenser oil - dissolved diagnostic gas – gaseous extractant (argon)". The moisture content W in the oil was determined by the GCh method using an «JIXM-80» gas chromatograph. When studying the solubility of gaseous hydrogen in oil depending on temperature (at temperatures $t_1 = 20$ °C, $t_2 = 5$ °C, $t_3 = -18$ °C), hydrogen solutions in oil were obtained by saturating it with gaseous H₂ under static conditions at given temperatures within 8 hours according to the known method [16].

For oil, when determining such indicators as electrical breakdown voltage U , flash point of oil vapor in a closed crucible t_{vs} , acid number AN, dielectric loss tangent $\text{tg}\delta_{\text{m}}$, the presence of mechanical impurities, density ρ , and calculating the errors of their measurements, normalized methods were used [14]. When determining the magnitude of the electrical breakdown voltage U : the average relative square error of the results of determining the breakdown voltage of oil during successive electrical breakdowns in one portion is no more than $\pm 2.5\%$ relative; the coefficient of variation should not exceed 20% relative. When determining the value of the tangent of the dielectric loss angle $\text{tg}\delta_{\text{km}}$: measurement of the tangent of the dielectric loss angle from 0.0001 to 1.0 – with an error of no more than $\pm(0.05\text{tg}\delta_{\text{km}}+0.0002)$; the discrepancy between the results of two determinations should not exceed when measuring the tangent of the dielectric loss angle of the liquid – 15% of the value of the larger result $+0.0002$. When determining the flash point of oil vapor in a closed crucible t_{vs} : the arithmetic mean of at least two consecutive determinations is taken as the test result; two results of the determinations are recognized as reliable at $P = 0.95$, if the discrepancies between them (convergence) do not exceed 5 °C at t_{vs} above 104 °C. When determining the value of the acid number AN: the test result is

taken as the arithmetic mean of the results of two parallel determinations; the results of two parallel determinations should not differ by more than 6% relative. When determining the indicator “presence of mechanical impurities”: the arithmetic mean of the results of two consecutive determinations is taken as the test result; the mass fraction of mechanical impurities of 0.005% or less is assessed as their absence; with a content of mechanical impurities up to 0.001% mass, inclusive, repeatability $r=0.0025\%$ mass. The ranges of measured concentrations and errors of measurement results when determining the content of dissolved diagnostic gases in oil by the GCh method are shown in Table 1 [16].

Table 1

Total relative measurement error of diagnostic gases in oil

Range of measured concentrations, % vol.	Total relative error measurement results, % relative
< 0.0001	> 50
0.001...0.005	≤ 50
0.005...0.05	≤ 20
> 0.05	≤ 10
< 0.1 (for O ₂ , N ₂)	> 50
0.1...12.0 (for O ₂ , N ₂)	≤ 10

The discussion of the results

During the operation of the electric coupling capacitor CMP-166V3-0.014 (phase B), the characteristics of the thermal field in the infrared (IR) radiation region were determined (Fig. 1).

The temperature rise of the upper element Δt with respect to the temperature of the lower element was determined by the formula [13]:

$$\Delta t = t_v - t_n, \quad (1)$$

where t_v – maximum temperature of the upper element of phase B of the condenser, °C;

t_n – maximum temperature of the lower element of phase B of the condenser, °C,

subject to $t_v > t_n$.

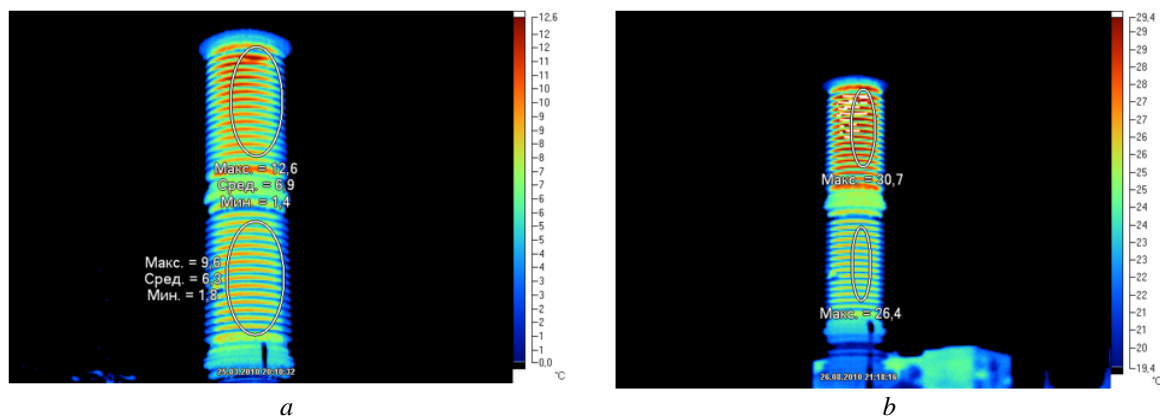


Fig. 1. Thermograms for HVOFCC type CMP-166V3-0.014 (phase B): *a* – temperature rise of the upper element $\Delta t = 3$ °C in relation to the temperature of the lower element; *b* – temperature rise of the upper element $\Delta t = 4.3$ °C in relation to the temperature of the lower element (after 5 months of operation)

Table 2 shows the results of determining the characteristics of the thermal field in the IR radiation region for the upper element of the phase.

Notes: Δt °C is the temperature rise of the upper element relative to the temperature of the lower element (formula (1)); τ is the time interval, in months, between two subsequent measurements of the Δt indicator; $\gamma(\Delta t)\%$ relative is the relative rate of change in temperature rise values Δt °C, of the upper element in relation to the temperature of the lower element of phase B for HVOFCC (formula (2));

$\Delta\gamma$ % relative per month is the relative rate of change of the indicator $\gamma(\Delta t)$ over a period of time τ between two subsequent measurements of the values of the Δt value (formula (3)).

Table 2

The results of thermal imaging control of the electric coupling capacitor

Control period	Δt °C	$\gamma(\Delta t)$ % rel.	$\Delta\gamma$ % rel. per month
First control.	1.5	–	–
$\tau = 11.5$ months	3.0	100	8.7
$\tau = 5$ months	4.3	43.3	8.7
$\tau = 1.7$ month	5.0	16.3	9.6

The value of $\gamma(\Delta t)$ is calculated by the formula:

$$\gamma(\Delta t) = (\Delta t_2 - \Delta t_1) \cdot 100 / \Delta t_1, \quad (2)$$

where Δt_1 – temperature rise of the upper element in relation to the temperature of the lower element, °C, at the first measurement;

Δt_2 is the temperature rise of the upper element in relation to the temperature of the lower element, °C, during the subsequent measurement.

In mathematical form, the dependence of $\Delta\gamma$ on τ has the form:

$$\Delta\gamma = \gamma(\Delta t) / \tau, \quad (3)$$

where τ – time interval between two measurements of temperature rises Δt_1 and Δt_2 .

The value of $\Delta\gamma$ characterizes the rate of defect development associated with an increase in the temperature difference of the upper element relative to the temperature of the lower element of phase B for HVOFCC. From Table 2 it follows that the value of $\Delta\gamma$ tends to increase during the operation of HVOFCC, which characterizes the stable development of internal defects in it. When performing a thermal imaging survey of HVOFCC type CMP-166V3-0.014, it was revealed that the temperature of the upper element of phase B exceeded the temperature of the lower element of phase B by 5 °C.

This exceeds the norms $\Delta t_n = 3$ °C established in [13]. Due to regulatory requirements [13], HVOFCC was withdrawn from service for additional studies. In accordance with the recommendations [13, 20], HVOFCC assumes defects of the type “General increase in the dielectric loss tangent of electrical insulation” or “Local increase in the dielectric loss tangent of electrical insulation or electrical breakdown of individual sections”. On fig. Figure 2 shows the nature of the dependence of the indicators $\Delta\gamma$ on the time intervals τ of measuring the temperature rises Δt of the upper element in relation to the temperature of the lower element of phase B.

Based on Fig. 2 extrapolation of the results $\Delta\gamma$, % relative per month, for a period of time in 1 month from the start date of measurement to the end date (after 13 months) is performed. The obtained results of extrapolation show that after 1 month of operation of HVOFCC, there would be an increase in the value of Δt to a value of 5.9 °C, the value of $\gamma(\Delta t)$ to a value of 17% relative, the value of $\Delta\gamma$ to a value of 17% relative per month. This means that the value of the indicator $\gamma(\Delta t) = 9.6\%$ relative per month will increase by about 1.8 times, i.e. up to the value $\gamma(\Delta t) = 17\%$ relative per month, at the end date. Assuming that the indicator $\gamma(\Delta t)$, relative % per month, is proportional to the relative rate of increase in the concentrations of dissolved diagnostic gases in oil during the continuous development of defects inside the HVOFCC, it is possible to estimate the concentrations of diagnostic gases in the oil volume for a given period of time for the development of an internal defect in the HVOFCC, associated with the generation of diagnostic gases in the capacitor oil. Based on the data in Table. 2, Fig. 2 and formulas (1), (2) and (3) it can be assumed that the degree of danger of the development of internal defects in the investigated capacitor

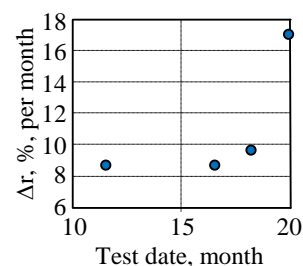


Fig. 2. The nature of the dependence of indicators $\Delta\gamma$ on the time intervals τ of measurements of temperature rises Δt of the upper element in relation to the temperature of the lower element of phase B

can be established by the relative rate $\Delta\gamma$, % relative per month, changes in the indicator $\gamma(\Delta t)$ over the time interval τ between two subsequent measurements of the values Δt (Table 3): if $\Delta\gamma \geq 8\%$ relative per month, then in a 2-element HVOFCC one can assume the presence of internal developing defects, even if the Δt value is lower than the normalized value $\Delta t_n = 3^\circ\text{C}$ [13]. In this case, it is advisable to subject the HVOFCC to thermal imaging control at intervals, for example, once a year. An example of in-service HVOFCC electrical test results are shown in Table 3.

Table 3

Coupling Capacitor Electrical Test Results

Period	Reason	Indicators *			
		$\text{tg}\delta_{\text{ks}}$, %	C_{ks} , μF	ΔC , % rel.	R_{izm} , $\text{M}\Omega$
normalized value of the indicator		0.8	< 0.014	< 5	> 100
In the manufacture	Factory testing	< 0.3	0.0138	–	–
After 12 years	Exploitation	0.5	0.0143	3.6	10000
After 15 months	Exploitation	0.74	0.0147	6.5	7000

* $\text{tg}\delta_{\text{ks}}$ – dielectric loss angle tangent, %; C_{ks} – electric capacitance, μF ; ΔC – relative deviation of the value of the electrical capacitance of the coupling capacitor from the results of factory tests, relative%; R_{izm} is the electrical resistance between the electrical leads, $\text{M}\Omega$

According to the results of electrical tests, HVOFCC does not meet the requirements of the standards [21]: the maximum relative deviation of the electrical capacitance value of HVOFCC from the results of factory tests is 6.5% relative upwards, with an allowable norm of not more than 5% relative; the value of $\text{tg}\delta_{\text{ks}}$ of electrical insulation approaches the limit value of 0.8%. In accordance with the requirements of [21], this HVOFCC was withdrawn from work for additional studies. Measurements were made of the electrophysical, thermophysical, physicochemical characteristics of the oil after opening the HVOFCC. The presence of carbon particles in the oil and on the internal surfaces of the HVOFCC has been found.

Table 4 shows the main physical and chemical properties of the oil according to the requirements of regulatory documents [21, 22] and obtained as a result of research after opening HVOFCC.

Table 4*Basic physical and chemical properties of capacitor oil*

№	Characteristic	Norm for impregnation and fill	Result tests	
1	Breakdown voltage, U kV,	> 50	55.6	
2	Moisture content, W g/t,	–	12.2	
3	Flash point in a closed crucible, t_{vsp} $^\circ\text{C}$	> 150	131	
4	Dielectric loss tangent, $\text{tg}\delta_{\text{km}}$ % at temperature	20 $^\circ\text{C}$	–	0.18
		50 $^\circ\text{C}$	–	0.42
		70 $^\circ\text{C}$	–	1.25
		90 $^\circ\text{C}$	–	2.02
		100 $^\circ\text{C}$	< 0.005	2.5 *
5	Mechanical impurities	absence	presence	
6	Acid number, AN, mg KOH per 1 g of capacitor oil	< 0.02	0.005	
7	Density, ρ at 20 $^\circ\text{C}$ g/cm^3	0.860...0.865	0.865	

* The value of the indicator $\text{tg}\delta_{\text{km}}$ was obtained by graphical extrapolation of the measurement results according to Fig. 3

It follows from Table 4 that:

a) the condenser oil does not meet the standardized values in terms of t_{vsp} , $\text{tg}\delta_{\text{km}}$, “mechanical impurities” in comparison with the requirements for filling with HVOFCC oil during its manufacture or repair;

b) low values of W and AN values for condenser oil presumably indicate the absence of atmospheric air penetration into the HVOFCC volume during its operation.

From Fig. 3 it follows that in the studied temperature range from 20 °C to 100 °C, the values of $tg\delta_{km}$ % increase with increasing temperature, which corresponds to a similar character of the dependence for mineral transformer oils [23]. The results of determining the content of the additive “Ionol” in the oil showed that its content is 0.15% by weight.

This indicates that the Ionol additive in the oil has not exhausted its resource, which is characterized by a minimum concentration of 0.1% by weight in mineral electrical insulating oils [14, 22]. The results of determining the content of furan compounds in capacitor oil showed their absence – their concentrations did not exceed the established normalized values of the determination thresholds of 0.00002 wt % for mineral electrical insulating oils [18, 24]. This indicates that the cellulose electrical insulation in HVOFCC did not undergo deep degradation [25, 26, 27, 28]. Determination of the concentrations of diagnostic gases in mineral capacitor oil was carried out after opening the HVOFCC (Table 5).

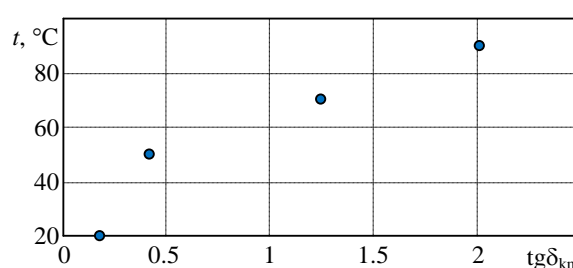


Fig. 3. Interdependence between the values of $tg\delta_{km}$ %, and the temperature t °C of condenser oil

Table 5

The results of calculating the concentrations of dissolved diagnostic gases in the investigated condenser oil at a temperature of 20 °C

Parameter	H ₂	CH ₄	C ₂ H ₄	C ₂ H ₆	C ₂ H ₂	CO	CO ₂	O ₂	N ₂	Air
B_i	0.05	0.43	1.70	2.4	1.20	0.12	1.08	0.17	0.09	–
R_i	0.06	0.45	1.82	2.89	1.21	0.16	1.17	0.17	0.09	–
K_i	0.06	0.43	1.70	2.60	1.24	0.15	1.07	0.16	0.10	0,101
$C_i(K_i)$, % volume	3.43	0.93	0.25	0.30	0.28	0.24	0.14	0.47	2.9	O ₂ +N ₂ = 3.37
$X_i(K_i)$, % volume	6	43	170	260	124	15	107	16	10	10.1

Notes: 1. B_i – values of Ostwald solubility coefficients for dissolved i -th diagnostic gases in electrically insulating mineral oils [16]; 2. R_i are the values of distribution coefficients for i -th dissolved diagnostic gases in the systems “electrical insulating oil – dissolved i -th diagnostic gas – gaseous extractant (argon)” at a temperature of 20 °C [15]; 3. K_i – values of distribution coefficients for i -th dissolved diagnostic gases in the system “condenser oil – dissolved i -th diagnostic gas – gaseous extractant (argon)”, calculated according to the method [16]; 4. $C_i(K_i)$ – concentration values, % vol., for i -th dissolved diagnostic gases in the studied mineral condenser oil, calculated according to the method [15] using the values of distribution coefficients K_i ; 5. $X_i(K_i)$ – values of solubility, % by volume, for i -th dissolved diagnostic gases H₂; CH₄; C₂H₆; C₂H₄; C₂H₂; CO, O₂, N₂, air, in the investigated condenser oil, calculated from the corresponding values of the distribution coefficients K_i at a temperature of 20 °C.

From Table 5 it follows that:

A. for the dissolved diagnostic gases H₂, CH₄, C₂H₂, CO₂, O₂, N₂, the values of the coefficients B_i , R_i , K_i , are close for their solutions in mineral electrical insulating oils, except for the dissolved diagnostic gases C₂H₄, C₂H₆, CO in the studied condenser oil. This indicates the need for experimental determination of the values of the distribution coefficient K_i for all diagnostic gases dissolved in oil samples taken from HVOFCC, for example, according to the method [16].

B. For dissolved diagnostic gases H₂, CH₄, C₂H₂, C₂H₄, C₂H₆, CO, CO₂, O₂, N₂, air, their concentrations $C_i(K_i)$, % by volume, in the studied oil do not exceed the corresponding solubility values $X_i(K_i)$, % volumetric, at a temperature of 20 °C.

C. The concentration of H₂ diagnostic gas dissolved in oil ($C_i(K_i) = 3.43\%$ vol), measured at a temperature of 20 °C, is commensurate with the calculated value of its solubility at a temperature of 20 °C ($X_i(K_i) = 6\%$ vol).

This means that the content of dissolved H₂ gas in the oil is close to its solubility, and with a further increase in temperature with the development of an internal defect while continuing to generate

H₂ in the oil volume, HVOFCC may be damaged and its tightness will be violated, since H₂ will not be able to be absorbed in the oil volume, but will be in a free state, creating an excess pressure of H₂ gas inside the housing. In this case, continuously formed H₂ bubbles in the oil volume will lead to an increase in the processes of partial electric discharges in the oil volume, which in turn is a source of generation of H₂ and other gases in the oil.

To evaluate the nature of the change in the solubility of H₂ in oil, the solubility of $X_i(K_i)$, % by volume, H₂ at temperatures $t_1 = 20$ °C, $t_2 = 5$ °C, $t_3 = -18$ °C was studied in it. The results of measurements for H₂ solubilities were obtained: $X_i(K_i) = 6\%$ by volume at $t_1 = 20$ °C; $X_i(K_i) = 4.4\%$ by volume at $t_2 = 5$ °C; $X_i(K_i) = 3.2\%$ by volume at $t_3 = -18$ °C. From these results it follows that in the studied temperature range from 20 °C to -18 °C for the studied oil, the solubility of gaseous H₂ in it decreases with decreasing temperature. A similar nature of the temperature dependence of the solubility of gases CO, O₂, N₂ in transformer oil was noted in [23]. It can be assumed that for the studied HVOFCC, which have internal defects of an electrical nature, the simultaneous action of two factors - the continuous generation of H₂ in the oil and a decrease in the ambient temperature, can lead to the formation of H₂ bubbles in the oil and the release of gaseous H₂ from the oil volume into the gas phase above it. This increases the likelihood of electrical breakdowns in the liquid phase of the oil and in the gas phase above it with the formation of an electric arc; increased pressure inside the HVOFCC with possible explosive destruction of its body.

In the work, the types of defects in the upper element of phase B for HVOFCC type CMP-166V3-0.014 were determined, based on the results of GCh analysis of the oil, taking into account the recommendations [29, 30]. Determination of the presence of a defect by the "Tabular method". Based on the data in Table 5 and in accordance with the recommendations [29], the expected type of defect in the upper element of phase B for HVOFCC type CMP-166V3-0.014 was determined using the concentration ratios of dissolved diagnostic gases: $C_2H_2/C_2H_4 = 1.12$; $CH_4/H_2 = 0.27$; $C_2H_4/C_2H_6 = 0.83$. Tentatively, we can assume the presence of a defect of the type "Electric discharges of low energy" [29]. In addition, it is assumed that in the defect zone: at a value of $CO_2/CO = 0.58$, the temperature is above 250 °C; at a value of $O_2/N_2 = 0.16$, high-intensity oxidative processes occur [29]. According to the results of GCh analysis of oil from the upper element of phase B, the presence of defects was determined by graphical methods (Fig. 4) in accordance with the recommendations of the regulatory document [29].

Fig. 4, *a* shows the result of determining the presence of a supposed defect using the "Graphic image" method [29]. The main dissolved diagnostic gas is H₂ (the dissolved diagnostic gas with the highest concentration in oil). Supposed defect of the type "Partial electric discharges" [29]. Fig. 4, *b* shows the result of determining the presence of a suspected defect by the ETRA method. The concentration ratios C_2H_2/C_2H_6 and C_2H_4/C_2H_6 were used. Supposed defect of the type "Partial electric discharges" [29]. Fig. 4, *c* shows the result of determining the presence of an alleged defect using the Duval Triangle method. For this, the following values were calculated: the sum of the concentration of dissolved gases $S = (CH_4 + C_2H_4 + C_2H_2) = 1.46\%$ by volume; % $CH_4 = 100 A/S = 63.7\%$ relative; % $C_2H_4 = 100 B/S = 17.1\%$ relative; % $C_2H_2 = 100 C/S = 19.2\%$ relative, where A is the concentration of CH₄, % by volume, B is the concentration of C₂H₄, % by volume, C is the concentration of C₂H₂, % by volume. The technique for constructing the Duval Triangle using the calculated values of S, A, B, C is described in [29]. Assumed defect of the type "Partial electric discharges of low energy (sparking)" [29].

Based on the results of the GCh analysis of the oil, it was found that a sufficiently high concentration of the dissolved diagnostic gas C₂H₂ (Table 4) $C_i(K_i) = 0.28\%$ by volume, as well as the presence of carbon particles in the oil and on the internal surfaces of the HVOFCC, indicates the formation of an electrical arcs in the volume of oil. At the same time, the presence of the "Electric arc in oil" defect based on the results of using such diagnostic methods as "Table method" and "Graphic methods" (Fig. 4) does not indicate the process of formation of an electric arc in the oil volume.

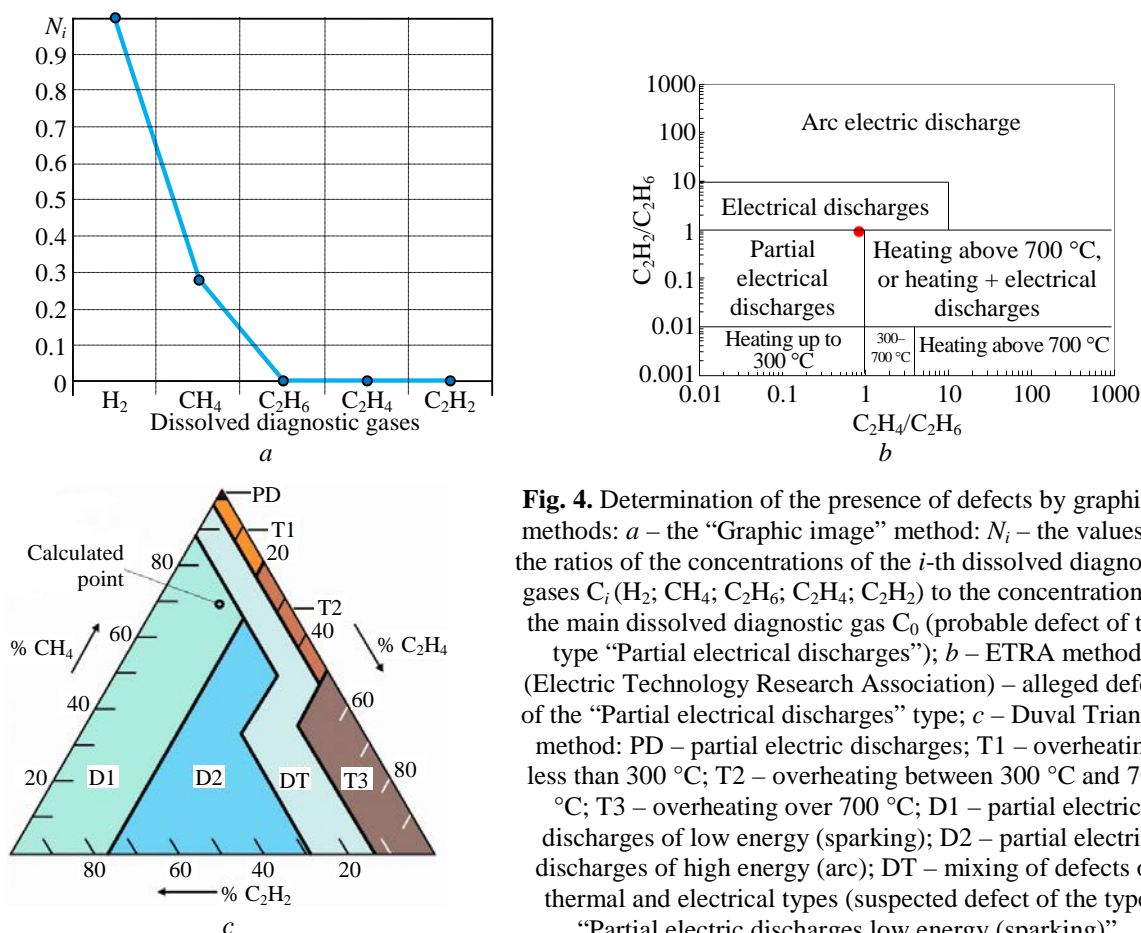


Fig. 4. Determination of the presence of defects by graphical methods: *a* – the “Graphic image” method: N_i – the values of the ratios of the concentrations of the i -th dissolved diagnostic gases C_i (H_2 ; CH_4 ; C_2H_6 ; C_2H_4 ; C_2H_2) to the concentration of the main dissolved diagnostic gas C_0 (probable defect of the type “Partial electrical discharges”); *b* – ETRA method (Electric Technology Research Association) – alleged defect of the “Partial electrical discharges” type; *c* – Duval Triangle method: PD – partial electric discharges; T1 – overheating less than 300 °C; T2 – overheating between 300 °C and 700 °C; T3 – overheating over 700 °C; D1 – partial electric discharges of low energy (sparking); D2 – partial electric discharges of high energy (arc); DT – mixing of defects of thermal and electrical types (suspected defect of the type “Partial electric discharges low energy (sparking)”) ”

Conclusions

The results of studies of HVOFCC type CMP-166V3-0.014 showed that in order to increase the reliability of the results of diagnosing high-voltage oil-filled capacitors, the following can be recommended:

- in order to accumulate statistical data when opening the coupling capacitor for repair, determine the presence of a “partial electric discharges” defect and take samples of the capacitor oil to determine the properties of the oil and the content of dissolved diagnostic gases;
- control the pressure inside the coupling condenser using strain gauge pressure sensors with remote data transmission using modern microprocessor measuring equipment; similarly, it is possible to control the temperature inside the coupling capacitor using temperature sensors;
- to determine an internal defect of the “partial electric discharges” type, it is possible to use the methods of acoustic and (or) electric detection of partial electric discharges;
- determination of the content of dissolved diagnostic gases in the condenser oil during the operation of an oil-filled condenser can be performed continuously or periodically using an automatic chromatograph equipped with diffusion sensors;
- for diagnosing HVOFCC using GCh methods for analyzing samples of mineral capacitor oil, to use modern methods for diagnosing high-voltage electrical equipment filled with mineral transformer oils.

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Received January 23, 2022

Accepted March 18, 2022