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IMPROVEMENT OF METHODS FOR DETECTING INTERNAL DEFECTS IN A HIGH-VOLTAGE OIL-FILLED COUPLING CAPACITOR

Abstract. This article focuses on improving techniques for detecting internal defects in the high voltage oil-filled coupling capacitor (HVOFCC). The purpose of the article is to improve the results of technical diagnostics of HVOFCC to control its technical condition based on analyzes of samples of mineral condenser oil (MCO) from this HVOFCC. The following methods were used: gas chromatography (GCh) in determining the concentrations of the components H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2, H_2O in the volume of the operational MCO; determining the dependence solubility of air and H_2 in MCO on temperature; diagnosing HVOFCC using the Rogers method; descriptions when clarifying the mechanisms of processes occurring in HVOFCC based on the results of diagnosis after its opening. The concentrations of components (H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2, H_2O) in MCO samples from HVOFCC type CMP-166/$\sqrt{3}$-0.014 were determined. The dependences of the solubility of air and H_2 in MCO on temperature (in the temperature range of 255...373 K), as well as the solubility of gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in this MCO at a temperature of 20 °C were found using the GCh method. Calculated concentrations of gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in the air above the MCO surface in a sealed HVOFCC with internal defects. The Rogers method was used to diagnose HVOFCC based on the results of analysis of MCO samples by the GCh method. It is shown that the emergence and development of the internal defect "Flashover without Power Follow Through" in HVOFCC is facilitated by defects that have arisen during its manufacture and operation, namely, degradation of the MCO; destruction of the membrane boxes of the expander, penetration of MCO into it, penetration of air from the expander into the volume of MCO; the emergence and accumulation of combustible fire hazardous gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO in the air volume above the MCO surface. The results obtained make it possible to increase the reliability of the results of diagnosing the technical condition of HVOFCC with cellulose solid electrical insulation based on the results of GCh analyzes of MCO samples during life tests or before repair. When conducting further research (after opening the HVOFCC during life tests or before its repair), MCO should be sampled to determine its physicochemical, thermophysical and electrophysical properties and the contents of diagnostic components in it (H_2; CH_4; C_2H_4; C_2H_6; C_2H_2; CO; CO_2; H_2S; H_2O; antioxidant additives; furan compounds).

Keywords: diagnosing, condenser oil, coupling capacitor, gas chromatography, Rogers method.

Introduction and Problem Statement

High-voltage oil-filled coupling capacitors (HVOFCC) in porcelain cases are designed to provide high-frequency coupling at frequencies from 36–750 kHz in power lines with a rated voltage of 35–500 kV

at alternating current with a frequency of 50 or 60 Hz [1, 2]. They must be operated at an ambient temperature of – 60 °C to + 45 °C [3]. Currently, HVOFCCs of obsolete designs, continue to be in operation in the energy systems of Ukraine [4]. HVOFCC damage is often accompanied by an explosion and poses a danger to the operating personnel of the power plant [5]. Therefore, it is necessary to ensure their reliable operation, maintenance and repair [3, 6]. In this regard, the application and improvement of methods for diagnosing the technical condition of HVOFCC, including the results of monitoring the properties of mineral capacitor oil (MCO), is an urgent problem when performing life tests or repairs with the opening of these HVOFCCs [7]. The gas chromatography (GCh) method can be used to determine the content of dissolved gases in the samples of capacitor oil from HVOFCC for its diagnosis [8], [9]. The paper [7] describes the experience of using GCh methods for determining the content of dissolved gases in electrical insulating oils in the process of manufacturing HVOFCC, life tests, and when performing repair work. The application of methods of chromatographic (GCh) analyzes of dissolved diagnostic gases in HVOFCC during their manufacture, as well as during repair work, is described in the article [8]. In [10], the result of the analysis of modern methods and tools for diagnosing power cosine electrical capacitors with paper-oil electrical insulation is presented. The need to control the properties of electrical insulating oils during their operation is noted. The results of this work can be applied to the diagnosis of HVOFCC using the GCh method to determine the concentrations of dissolved gases in MCO. References [3, 11] show HVOFCC circuits with basic elements and with a dielectric made of capacitor paper impregnated with MCO. These schemes can be used to clarify the mechanisms of processes that occur in HVOFCC based on the results of diagnosis after its removal from operation and opening. The reasons for the deterioration of the insulating properties and reliability indicators of HVOFCC type CMP–166/$\sqrt{3}$–14UKHL1 during its operation were studied in [1]. It is noted that the main causes of failures can be: moisture ingress through the sealing rubber rings between the upper flange and the body; poor-quality impregnation of electrical insulation between layers with capacitor oil; the presence of individual solid particles between the layers of electrical insulation; aging of solid electrical insulation in contact with capacitor oil; deterioration in the quality of condenser oil. This can lead to the formation of gases in the paper-oil electrical insulation and in the volume of the MCO. The works [12, 13] investigated: the reasons for the formation of apparent charges of partial discharges in sectioned capacitors; consequences of degradation of electrically insulating liquids under the action of partial discharges, heat and ultrasonic fields; the relationship between the quantitative indicators of the electrical partial discharges that have arisen in HVOFCC and the qualitative composition of the resulting gases that dissolve in MCO. The works [14–18] describe GCh methods for determining the content of dissolved gases in electrically insulating liquids. Methods for diagnosing oil-filled electrical equipment based on the results of GCh analyzes of samples of electrical insulating oils and free gases are described in [19]. The works [20, 21] describe the Rogers method for diagnosing oil-filled electrical equipment based on the results of GCh analyzes of samples of electrical insulating oils and free gases. This method: is based on the use of concentration ratios of dissolved gases $R_1 = CH_4/H_2$, $R_2 = C_2H_6/CH_4$, $R_3 = C_2H_4/C_2H_6$, $R_4 = C_2H_2/C_2H_4$ in mineral insulating oil, assigning a code number to the corresponding calculated result of the concentration ratio, determining the type defect in high-voltage oil-filled electrical equipment, depending on the combination of code numbers. The Rogers method can be applied to diagnose HVOFCC from the results of GCh analyzes of MCO samples. At present, the application and improvement of methods for diagnosing the technical condition of HVOFCC based on the results of GCh analyzes of MCO samples is an urgent problem when performing life tests or repairs with the opening of these coupling capacitors.

The aim of the work is to improve the methods for detecting internal defects in HVOFCC during its technical diagnostics to assess performance and determine the possibility of performing maintenance and repair, taking into account the properties of MCO samples from this HVOFCC.

Main Material Presentation

Research objectives: 1) Visual inspection of the internal elements of HVOFCC type CMP-166/$\sqrt{3}$-0.014. 2) Determination by GCh methods of concentrations of *i*-th dissolved components (H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2, H_2O) in MCO samples from HVOFCC. 3) Determination of the dependence of the

solubility of air, H_2 in MCO on temperature in the temperature range of 255...373 K, as well as the solubility of gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in this MCO at a temperature of 20 °C using the GCh method. 4) Calculation of the concentrations of *i*-th gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in the air above the MCO surface in a sealed HVOFCC with internal defects. 5) Application of the well-known Rogers method for diagnosing HVOFCC based on the results of analyzes of samples of mineral electrical insulating oils by the GCh method, based on the use of numerical codes when detecting internal defects for diagnosing the investigated HVOFCC. 6) Clarification of the mechanisms of processes occurring in HVOFCC type CMP-166/√3-0.014 based on the results of diagnosis after opening the HVOFCC. The object of research is the methods for detecting internal defects in HVOFCC when controlling the properties of MCO samples from this HVOFCC. The subject of research is HVOFCC type CMP-166/√3-0.014 and samples of operational MCO from it.

Materials and methods. When studying the electrical [22, 23] and thermal [24] characteristics of HVOFCC, measuring and testing equipment were used: megaohmmeter EC0202/2Г; AC electric bridge CA7100-2; thermal imager "Kryonik". The gas chromatograph "Krystal-2000M" was used to determine the content of C_i dissolved in MCO and gases H_2, CH_4, C_2H_6, C_2H_4; C_2H_2, CO, CO_2 – with the use of a methanator, a thermal conductivity detector (TCD), a flame ionization detector, and the values of the distribution coefficients K_i for each dissolved gas in the equilibrium system "MCO – dissolved gas – gaseous extractant (argon)" [17, 25, 26, 27].

The ranges of measured concentrations and measurement errors in determining the content of dissolved gases in MCO are given in Table 1 [17].

Table 1

Total relative error of measurements of gas concentrations in MCO

RMC, % vol.	TRE, % relative	RMC, % vol.	TRE, % relative	RMC, % vol.	TRE, % relative	RMC, % vol.	TRE, % relative
< 0.0001	> 50	0.001–0.005	≤ 50	0.005–0.05	≤ 20	> 0.05	≤ 10

Notes: RMC – range of measured concentrations, % by volume; TRE – total relative error of the measurement results, % relative.

To determine the concentration of the *i*-th gas dissolved in MCO, the calculation formula [9], [28] used for the equilibrium system "liquid – gas dissolved in liquid – gaseous extractant" was used:

$$C_{i,m} = C_{i,g}\left(K_i + \frac{V_g}{V_m}\right),$$ (1)

where $C_{i,m}$ is the concentration of the *i*-th gas dissolved in MCO, % vol.; $C_{i,g}$ is the concentration of the *i*-th gas in the volume of the gaseous extractant above the MCO surface, % vol.; K_i is the distribution coefficient for the *i*-th gas dissolved in MCO, in the systems "MCO – dissolved *i*-th gas – gaseous extractant" at a temperature of 20 °C; V_m is a given volume of MCO in equilibrium with a given volume of gaseous extractant above the surface of MCO, % vol.; V_g is the given volume of the gaseous extractant above the surface of the MCO, which is in equilibrium with the given volume of the MCO, % vol.

Numerical values of the distribution coefficients K_i for *i*-th dissolved gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in the studied MCO in the systems "MCO – dissolved *i*-th gas – gaseous extractant (argon)", as well as the values of solubilities X_i for these *i*-th dissolved gases, obtained at a temperature of 20 °C experimentally according to the methods described in [9], [17], [28].

The LKhM-80 gas chromatograph with TCD and the introduction of a sample of the analyzed MCO into the evaporator of the chromatograph was used to determine the water content *W* in MCO according to

the methods recommended in [29], [30]. When determining the water content W in MCO [30]: the determination threshold is 2 g/t; the error values of the measurement results are given in Table 2.

<div align="right">*Table 2*</div>

Error values of the results of measurements of H_2O contents in MCO

W, g/t	2	5	10	20	25	30	50	60	80
Δ_i, g/t	0.79	1.9	3.4	5.7	6.3	6.6	7.2	7.3	7.4
ε_i, % relative	39.5	36.9	34.2	28.3	25.1	22.0	14.3	12.0	9.2

Notes: W – content of H_2O, g/t; Δ_i – absolute error, g/t; ε_i – relative error, % relative.

When studying the solubility of gaseous air, H_2 in MCO, the corresponding solutions of air, H_2 in MCO were obtained by saturating it with gaseous H_2 under static conditions at given temperatures for 8 hours according to the methods [9], [17].

Applied equipment: a) low-temperature dry-air thermostat TSV-02: temperature control range from – 20 °C to + 10 °C; instability of maintaining the set temperature ± 1 °C; b) Thermoton-01M thermostat: temperature control modes from 20 °C to 100 °C, temperature setting error no more than ± 0.1 °C, temperature maintenance error no more than ± 0.02 °C; c) oven FED-53 (E2): temperature control range from 20 °C to 300 °C; temperature fluctuation is not more than ± 0.3 °C at temperatures up to 150 °C.

When determining the content of dissolved gases H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 in the air above the surface of the sample of operational MCO from HVOFCC, a glass syringe with a volume of 200 cm^3 was used. In this syringe, the volume of MCO $V_{oil} = 200$ cm^3, the volume of equilibrium air $V_{air} = 10$ cm^3, the ratio $n = V_{air} / V_{oil} = 0.05$.

Results and Discussion

According to the results of electrical and thermal imaging tests of HVOFCC: a) the temperature of the upper element of phase B_{up} for HVOFCC exceeded the temperature of the lower element of phase B_{doun} by $\Delta t = 4.3$ °C, which exceeds the normalized value $\Delta t_n = 3$ °C [24], [31], [32]; b) electrical capacitance after manufacture under factory test conditions $C_{cr, i} = 0.0138$ µF, electrical capacitance during operation $C_{cr} = 0.0147$ µF, normalized value of electrical capacitance during operation $C_{cr, n} < 0.0140$ µF. At the same time, the maximum relative deviation of the electrical capacitance value for HVOFCC from the results of factory tests is $\Delta C = 6.5$ % relative upwards at an allowable rate of not more than $\Delta C_n = 5$ % relative; c) the value of the indicator $tg\delta_{ks}$ ("dielectric loss tangent, %, electrical insulation") of electrical insulation for HVOFCC after manufacturing under factory test conditions is $tg\delta_{ks,i} = 0.3$ %, the value of this indicator during operation is $tg\delta_{cr} = 0.74$ % and approaches the boundary value $tg\delta_{cr,n} = 0.8$ %; d) the results of the thermal imaging test indicate the presence of internal defects such as "general increase in $tg\delta_{cr}$", or "local increase in $tg\delta_{cr}$", or "electrical breakdown of individual HVOFCC sections" [24], [32]; f) the studied HVOFCC does not meet the requirements of the established norms [24] and was withdrawn from work for additional studies.

1. Results of visual inspection of internal HVOFCC components. On Fig. 1 shows the structural diagram of a CMP-166/$\sqrt{3}$-0.014 type HVOFCC with its main elements and with an MCO-impregnated capacitor paper dielectric. The internal volume of the studied HVOFCC is filled with MCO [3, 11]. The investigated HVOFCC has the following design features. The top cover has two openings for vacuuming and topping up MCO. Both holes are hermetically sealed with plugs and soldered. The body is made of porcelain. Cold-resistant rubber gaskets are used for sealing.

The inner part consists of several packages connected in parallel-series. Each package consists of a large number of sections connected in series, consisting of MCO-impregnated capacitor paper (Fig. 2, *a*).

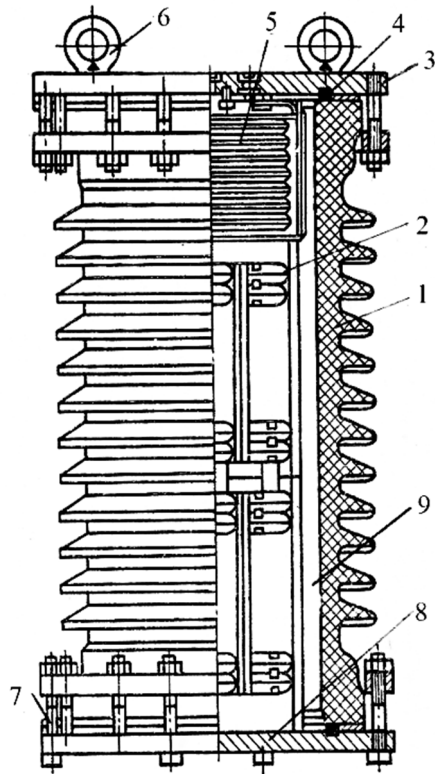On Fig. 2 shows some of the results of a visual inspection of the HVOFCC internals.

Fig. 1. Scheme of HVOFCC type CMP-166/√3-0.014:
1 – porcelain tire; 2 – extractable part; 3 – top cover;
4 – sealing ring; 5 – expander; 6 – cargo screw:
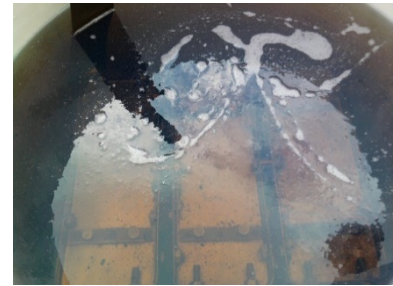7 – contact bolt;
8 – bottom cover; 9 – MCO

a　　　　　　　　*b*　　　　　　　　*c*

d　　　　　　　　*e*　　　　　　　　*f*

Fig. 2. The results of visual inspection of the internal elements of HVOFCC type CMP-166/√3-0.014:
a – package sections; b – break of flexible electrical connection; c – the process of separating gas bubbles from
the MCO; d – settled carbon particles on membrane boxes; e – rupture of the seam of the connection
of the upper and lower plates of the membrane boxes; f – deposits in the form of particles of carbon
and products of corrosion (rust) of the metal

To create pressure compensation of the MCO inside the HVOFCC when the ambient temperature changes, expanders are used, consisting of a set of membrane boxes located above the package. Metal

expanders are installed over the HVOFCC retrievable part and come into contact with the MCO. During the operation of the HVOFCC, an overpressure of the MCO is established, above atmospheric pressure. Inside the hermetic expander there is air at a slight overpressure [3, 11].

After removing the investigated HVOFCC from work and opening it, a visual inspection of the internal elements was carried out, which made it possible to determine its real state and identify a number of internal defects. There was no leakage of MCO from the HVOFCC volume to the environment. When drilling the sealed plug of the top cover, a certain amount of gas under pressure was released into the atmosphere from the internal cavity. When lifting the top cover, one flexible metal electrical connection was bolted to the cover, and the second was broken off at a distance of 0.2 m from the fixing bolt on the cover (Fig. 2, *b*). After opening the HVOFCC and lifting the top cover, intensive release of gas bubbles from the MCO was observed (Fig. 2, c) with the formation of foam on the surface of the MCO. The MCO level is 0.05 m lower than the upper sealing cover and does not come into contact with this cover, which is a defect (according to regulatory requirements, the height of the air layer above the MCO surface in HVOFCC $h_{air} = 0.05$ m; and the height of the MCO layer $h_m = 0.95$ m). Traces of decomposition of solid electrical insulation in the form of suspended carbon particles and settled carbon particles on capacitor paper (Fig. 2, *a*), the lower sealing cover and membrane boxes (Fig. 2, *d*) were found in the MCO volume. Inside the cavity of the five membrane boxes of the expander, there is MCO, which got inside through the ruptures in the seam of the connection of the upper and lower plates of the membrane boxes (Fig. 2 e). Traces of deposits in the form of carbon particles and metal corrosion (rust) products were found on the outer surfaces of metal membrane boxes (Fig. 2, *f*). Two clamp bolts were missing from the top terminal box of the packages.

2. Determination by GCh methods of concentrations of *i*-th dissolved components in samples of MCO from HVOFCC.

Table 3 shows the results of the GCh determination of the concentrations of the *i*-th dissolved components (H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2) in MCO samples from HVOFCC.

Table 3

The results of determining the concentrations of i-th dissolved components in MCO samples from HVOFCC by GCh methods

Parameter	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2
$C_i(K_i)$, % vol.	3.43	0.93	0.24	0.14	0.25	0.30	0.28
K_i	0.06	0.43	0.15	1.07	1.70	2.60	1.24
$C_{i,air}(K_i)$	31.20	1.94	1.20	0.13	0.14	0.11	0.22
$C_{i,air}$	30.80	1.87	1.11	0.12	0.13	0,10	0.21
$\Delta C_{i,air}$	- 1.3	- 3.6	- 7.5	- 7.7	- 7.1	- 9.1	- 4.6
CLFP	4–75	5–15	12.5–74	–	2.7–36	3–12.4	2.5–100
X_i	6	38	12	110	260	250	350

*Notes: $C_i(K_i)$, % vol. – concentration values, % by volume, for *i*-th dissolved gases in the studied MCO; K_i – values of distribution coefficients for *i*-th dissolved diagnostic gases in the investigated MCO in the system "MCO – dissolved *i*-th gas – gaseous extractant (argon)"; $C_{i,air}(K_i)$ is the calculated value of the concentration of the *i*-th gas in the volume of gaseous air above the MCO surface, % by volume; $C_{i,air}$ is the measured value of the concentration of the *i*-th gas in the volume of gaseous air above the MCO surface, % vol; $\Delta C_{i,air}$ – relative difference between the values $C_{i,air}(K_i)$ and $C_{i,air}$, % relative; CLFP is the concentration limit of flame propagation, % vol [33]; X_i – values of solubilities for *i*-th dissolved gases in the investigated MCO, % vol.*

From Table 3 it follows that for the dissolved gases H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2, air, their concentrations $C_i(K_i)$, % by volume, in the studied MCO do not exceed the corresponding values of solubilities X_i, % by volume, at a temperature of 20 °C. At the same time, the value of the concentration of H_2 gas dissolved in MCO $C_i(K_i) = 3.43$ % by volume, measured at a temperature of 20 °C, is comparable to the value of its solubility $X_i = 6$ % by volume at this temperature. In addition, the values of solubilities X_i for

i-th dissolved gases in the investigated MCO (Table 3) are close to the corresponding values given in [34] for mineral transformer oil.

3. Determination of the temperature dependence of the solubility of air and hydrogen in MCO.

Using the GCh method [17], the dependence of the solubility of air (X_{air}), hydrogen (X_h) in MCO on temperature in the temperature range – 18...+ 100 °C (255–373 K) was investigated (Table 4).

Dependence of solubility of air, H$_2$ in MCO on temperature

T, K	228*	255	273	278	283	293	303	323	373
X_{air}, % vol.	8.57	9.22	9.60	9.70	9.80	9.98	10.16	10.50	11.20
X_h, % vol.	1.81	3.20	4.40	4.78	5.17	6.0	6.89	8.86	14.79

Notes: X_{air} or X_h – the solubility of air or H$_2$, respectively, in MCO, % by volume; T is the temperature of MCO, K;
* Extrapolated temperature value of MCO, K.

From Tab. 4 it follows that the decrease in the solubility of X_{air} for air and X_h, for H$_2$ in the investigated MCO with a decrease in temperature T is similar to the known solubility of gases H$_2$, CO, CO$_2$, N$_2$, air, H$_2$O in mineral transformer oils [35], and H$_2$ in mineral turbine oil [36].

The dependences of the solubility of X_{air} (% vol.) for air or X_h (% vol.) for H$_2$ on the temperature T, K, in the investigated MCO can be expressed by the equation of the solubility of gases in a liquid with the formation of an ideal solution [37]:

$$\ln X_{air} = 2.84 \frac{156.9}{T}, \tag{2}$$

$$\ln X_h = 6.0 \frac{1233.3}{T}, \tag{3}$$

where X_{air} or X_h is the solubility of air or H$_2$, respectively, in MCO, % by volume; T is the temperature of MCO, K.

It follows from formulas (2) and (3) that the temperature T = 258.7 K (-14.3 °C) corresponds to the value of the saturated concentration X_h = 3.43 % by volume for H$_2$ in MCO.

At temperatures below – 5 °C (below 268 K), the formation of H$_2$O crystals in the form of "snowflakes" of various configurations was found in the volume of the investigated MCO. In this case, some part of the H$_2$O crystals is located: on the surface of the MCO volume; in suspension in the volume of MCO; at the bottom of the measuring cell filled with MCO. At the same time, the concentrations of H$_2$O in MCO have the following values: W_{293K} = 12.2 g/t at a temperature of 293 K (20 °C); W_{255K} = 2 g/t at a temperature of 255 K (-18 °C).

4. Calculation of the concentrations of *i*-th gases in the air above the surface of the MCO in the hermetic HVOFCC.

Taking into account Fig. 1 and formula (1), an expression was obtained for calculating the values of the concentrations of the *i*-th gas in the air above the MCO surface in a sealed HVOFCC:

$$C_{i,air} = C_{i,m} \left/ \left(K_i + \frac{h_{air}}{h_m} \right) \right., \tag{4}$$

where $C_{i,air}$ is the concentration of the *i*-th gas in the volume of gaseous air above the MCO surface, % vol; $C_{i,m}$ is the concentration of the *i*-th gas dissolved in MCO, % vol.; h_{air} = 0.05 is the height of the air layer above MCO in HVOFCC, m; h_m = 0.95 is the height of the MCO layer in HVOFCC, m.

The calculation results are presented in Table 3, from which it follows that: a) the concentrations of $C_i(K_i)$, % vol., of combustible gases CH$_4$, C$_2$H$_2$, C$_2$H$_4$, C$_2$H$_6$, CO in the air above the surface of the MCO in a sealed HVOFCC do not exceed the corresponding values of the concentration limits of flame propagation for each individual *i*-th gas in a homogeneous system "*i*-th gas – air" at a temperature of 293 K (20 °C) [33];

b) the concentration $C_i(K_i)$, % vol., of the combustible gas H_2 in the air located above the surface of the MCO in a sealed HVOFCC, is in the range of the concentration limit of flame propagation for H_2 in air (4–75 % vol.) in a homogeneous system "i-th gas – air" at a temperature of 293 K (20 °C), and this mixture is flammable [33]; c) the total value of the combustible gases concentrations in the air above the MCO surface is $\Sigma C_{i,air}$ = 34.22 % by volume; d) in a sealed HVOFCC above the MCO surface are: a flammable heterogeneous mixture in the form of a foam of MCO vapors, MCO drops, combustible gases in the air (Fig. 2, *c*); flammable homogeneous mixture in the form of combustible gases in the air; e) values $\Delta C_{i,air}$ do not exceed the established values of relative errors in determining the contents of *i*-th gases in the volume of the gas space above the MCO surface in a sealed HVOFCC in accordance with the requirements of Table 1 and the normative document [17], which is acceptable for technical calculations.

5. Application of the Rogers method for diagnosing HVOFCC type CMP-166/√3-0.014.

The Rogers method is based on the use of concentration ratios of dissolved gases R_1 = CH_4/H_2, R_2 = C_2H_6/CH_4, R_3 = C_2H_4/C_2H_6, R_4 = C_2H_2/C_2H_4, in mineral insulating oil, assigning a code number for the corresponding calculated result of the concentration ratio, determining the type defect in high-voltage oil-filled electrical equipment, depending on the set of code numbers according to the method proposed in [20], [21]. For the results shown in Table 4: R_1 = CH_4/H_2 = 0.27 and 0.1<R_1<1 (code "0"); R_2 = C_2H_6/CH_4 = 0.32 and R_2 < 1 (code "0"); R_3 = C_2H_4/C_2H_6 = 0.83 and R_3 < 1 (code "0"); R_4 = C_2H_2/C_2H_4 = 1.12 and 0.5 < R_4 < 3 (code "1"). In accordance with the recommendations [20], [21], HVOFCC assumes the presence of an internal defect – "a creeping electric discharge on the surface of a solid dielectric without electrical overlap" (Flashover without Power Follow Through). As a result of this defect, carbon particles are formed on the surface of the paper electrical insulation, which was confirmed by opening the investigated HVOFCC (Fig. 2, *a*).

6. Clarification of the mechanisms of processes occurring in HVOFCC based on the results of diagnosis after its opening.

A) Presence in the volume of capacitor oil (Table 3; Fig. 2, *d*; Fig. 2, *f*): a) dissolved gas H_2 – indicates a defect that characterizes "partial electrical discharges"; c) dissolved gas C_2H_2 – indicates defects that characterize: "partial electrical discharges of high energy"; "electric arc discharge"; local heating of MCO to temperatures from 750 °C and above; c) particulate carbon – indicates defects characterizing: "partial electrical discharges of high energy"; "electric arc discharge"; local heating of MCO to temperatures from 500 °C and above [38], [39].

B) The concentration of H_2 gas dissolved in MCO $C_i(K_i)$ = 3.43 % vol., measured at a temperature of 20 °C, is commensurate with the calculated value of its solubility ($X_i(K_i)$) = 6 % vol.) at a temperature of 20 °C (Table 3). This means that the content of the dissolved gas H_2 in MCO is close to its solubility, and with a further increase in temperature with the development of an internal defect with the simultaneous continuation of H_2 generation in the MCO volume, HVOFCC may be damaged with a violation of its tightness, since H_2 will not be able to be absorbed in the MCO volume, but will be in a free state, creating an overpressure of H_2 gas inside the HVOFCC housing. In this case, the continuously formed H_2 bubbles in the MCO volume will lead to an increase in the processes of partial electric discharges in the MCO volume, which, in turn, is again a source of generation of H_2 and other gases in the MCO [40].

C) It can be assumed that: 1) if there is an internal defect in the HVOFCC associated with the continuous release of H_2, when the ambient temperature reaches T = 258.7 K (-14.3 °C), and, accordingly, the MCO temperature, and its further decrease in winter period of the year, during the operation of the HVOFCC, H_2 gas will be continuously released from the MCO. The H_2 bubbles will float to the surface of the MCO and accumulate above it. During the destruction of the bellows in HVOFCC filled with compressed air, air bubbles passing through the MCO layer also float to its surface. As a result, a fire hazardous concentration of H_2 will form in the air in the "hydrogen – air" system above the MCO surface. In addition, during the movement of H_2 bubbles and air through the MCO layer, under the action of an electric field inside the HVOFCC, the processes of formation of partial electric discharges in the MCO volume will intensify. This will cause deterioration of electrophysical parameters for MCO, such as breakdown voltage,

electrical resistance, dielectric loss tangent [34, 40]; 2) for HVOFCCs with internal defects of an electrical nature, the simultaneous action of two factors – the continuous generation of H_2 in the MCO and a decrease in the ambient temperature, can lead to the formation of H_2 bubbles in the MCO and the release of gaseous H_2 from the MCO volume into the gas phase above it. This increases the likelihood of occurrence of: electrical breakdowns in the liquid phase of the MCO 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.

D) It can be assumed that when the MCO temperature drops below 273 K (0 °C), the formation of H_2O crystals can: occur from the dissolved and bound forms of H_2O located in the MCO volume; occur in the volume of paper-oil insulation HVOFCC; affect the formation of electrical breakdown both in the volume of the MCO and in the volume of the HVOFCC oil-paper insulation during its operation under the influence of an electric field [34]. Water in the MCO, presumably, can come from: paper electrical insulation of the plates of the HVOFCC capacitor sections; during diffusion of H_2O vapor from atmospheric air through a layer of rubber gaskets between HVOFCC flanges; during diffusion of liquid H_2O in rainy weather through a layer of rubber gaskets between HVOFCC flanges [41].

E) It is known that in the process of generation of impurities in electrically insulating liquids, including in MCO, with the development of internal defects of electrical and thermal nature in HVOFCC, in the resulting heterogeneous systems "impurity in MCO – MCO" from two contacting phases, that phase is charged with a positive electric charge, which has the greater value of the permittivity of these contiguous phases (Ken's rule) [37].

In Table 5 shows the values of the permittivity ε for impurities H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2, air, H_2O(liquid), H_2O(ice), H_2O vapor) present in the investigated MCO.

Table 5

Values of permittivity ε for impurities in MCO

Impurity	ε	Impurity	ε
H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2,	1.00007–1.0014 at T = 293 K [42]	H_2O_{liquid}	80.4 at T = 293 K [44]
Air	1.0006 at T = 293 K [42]	H_2O_{ice}	3.25 [45]
H_2O_{steam}	1.0075 at T = 373 K [43]	MCO	2.3 at T = 293 K [46]

Notes: H_2O_{steam} – vaporous phase of H_2O; H_2O_{liquid} – liquid phase of H_2O; H_2O_{ice} is the solid phase of H_2O.

From Table 5 it follows that: a) bubbles H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2, H_2O vapor, air in the MCO volume will have a negative electric charge; c) impurities H_2O (liquid), H_2O (ice) will have a positive electric charge. The formation and presence of solid carbon particles in the bulk of the MCO change its electrical conductivity, reducing the value of the electric breakdown voltage [34]. When carbon particles are formed, characterized by a phase interface at the "solid carbon – MCO" interface, the surface energy is converted into: Gibbs energy, heat, mechanical energy, chemical energy, electrical energy [37]. This leads to the formation of electric charges on the surface of the carbon particles. The exponent ε for carbon particles may depend on its allotropic modifications. So, some particles of coal formed in mineral transformer oil can be electrically conductive [34], and carbon particles in the form of soot can have a value of ε = 4 [47]. Under the influence of an electric field in the volume of the MCO, these electrically charged impurities will separate and move in the volume of the MCO to electrodes that have the opposite electric charge for the corresponding impurity [34]. This will change the electrical conductivity of the MCO, reducing the value of the electrical breakdown voltage [34]. Such an electrical flow can cause the decomposition of MCO by electrolysis with the formation of gaseous products, for example, H_2, CH_4, C_2H_4, C_2H_6, C_2H_2, CO, CO_2 [48]. In addition, under the influence of partial electric discharges, acoustic shock waves arise in the MCO, which in turn leads

to the appearance of the effect of cavitation, degradation of the MCO with the formation of gas bubbles, and the occurrence of sonochemical reactions [49].

Conclusions

At the initial stage of research on HVOFCC type CMP-166/√3-0.01, after its removal from operation and opening, internal defects were identified and classified. The GCh methods determined the values of the concentrations of the *i*-th components in the MCO samples from HVOFCC. The presence in the volume of MCO: a) dissolved gas H_2 – indicates an internal defect such as "partial electrical discharges"; b) dissolved gas C_2H_2 – indicates internal defects that characterize: "partial electrical discharges of high energy" and "electric arc discharge". The dependences of the solubility X_i (% vol.) for air or H_2 in the studied MCO on temperature are determined and expressed as equations. It has been established that the concentration of $C_i(K_i)$, % vol., of the *i*-th combustible gas in the air located above the surface of the MCO in a homogeneous system "*i*-th gas – air" at a temperature of 293 K (20 °C): a) does not exceed the corresponding values of the concentration limits of flame propagation for each individual *i*-th gas CH_4, C_2H_2, C_2H_4, C_2H_6, CO; c) is in the range of the concentration limit of flame propagation for H_2 in air (4–75 % by volume) and this mixture is flammable. The Rogers method of diagnosing HVOFCC was applied to detect internal defects in it according to the results of analyzes of MCO samples using the GCh method and the ratios of concentrations of dissolved gases in capacitor oil. The results of the conducted studies can be used to control the technical condition, determine the location and causes of faults, and predict the technical condition of coupling capacitors.

Acknowledgments

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