Analysis of Gas Content in Oil-Filled Equipment with Low Energy Density Discharges

Oleg Shutenko and Oleksii Kulyk

Department of Electric power transmission
National Technical University Kharkiv Polytechnic Institute
Kharkiv, Ukraine
o.v.shutenko@gmail.com, kulyk.olekciy@ukr.net

Abstract: In the ageing conditions of the high-voltage oil-filled equipment stock, increasing the diagnostics reliability of its condition is an urgent and practically significant task. One possible way to solve this problem is to modify diagnostic criteria used to recognize the type of equipment defects, especially for those cases when the use of known methods does not allow establishing the correct diagnosis. In the article, the gas percentage and values of gas ratios for 184 units of equipment with electrical discharges of low energy density are analysed. It is shown that for 144 units out of 184, the values of these criteria differ significantly from the values regulated in the current standards for recognition of low energy density discharges. Nomograms (graphic areas) for 8 types of defects that are not regulated in any of the current standards are given. The comparative analysis of recognition reliability of the analysed defects with the use of known standards and methods is carried out. The given in work values of percentage and relations of gases, and also graphic areas (nomograms) of defects are the advanced diagnostic scheme which use allows to increase accuracy of defect type recognition by results of the dissolved gases analysis. This, in turn, significantly increases the operational reliability of oil-filled equipment.

Keywords: dissolved gas analysis (DGA); oil-filled equipment; electrical discharges; gas ratio; graphic areas; Duval triangle; ETRA square

1. Introduction

Electrical discharges are a process of transfer in isolation under the influence of an electric field charged particles that are formed because of ionization processes, which leads to a complete or partial breakdown of the insulation gaps. When exposed to electrical discharges, the destruction of insulation occurs due to shock ionization of hydrocarbon molecules by electrons. Discharges are also accompanied by heat release, which can be very small in the case of partial discharges (PD) or large enough in the formation of an arc discharge.

The most commonly used method for diagnosing defects, including electrical discharges with varying degrees of intensity, in oil-filled equipment (OFE) is the dissolved gas analysis (DGA). It is known [1-7] that any thermal or electrical process in insulation causes its destruction, which leads to the gases formation that dissolve in transformer oil. Depending on the energy released, each defect type has its own gases spectrum, which actually allows recognizing the type of the predicted defect. It is believed that in the event of electrical discharges, the gases with the maximum content are mainly hydrogen (H_2) and acetylene (C_2H_2), and the accompanying gases with an arbitrary content are methane (CH_4) and ethylene (C_2H_4). As a rule, electrical discharges develop in a short period time and their untimely recognition can lead to serious accidents. In this case, internal short circuits accompany emergency damage, which leads to significant economic damage associated with the need to replace the power transformer. In this regard, early detection and identification of electrical discharges is an urgent task.

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2. Criteria analysis used to identify the defect type according to the DGA results

Some standards [1-3] classify electrical discharges into discharges with low and high energy density. Discharges with low energy density (LED) include intense spark and creeping discharges, oil breakdown between solid materials and a number of others. It should be noted that in such standards as IEEE StandARCd C57.104-2008 [4], CIGRE SC-15 [5], as well as Dornenburg [6] and Rogers [7] such classification is absent. In Table 1, gas ratio values are given, which according to [1-3] correspond to LED discharges.

Table 1. Gas ratio values regulated by current standards for identification of low energy density discharges

Standard	Gas ratios		
	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
IEC 60599 [1]	>1	0.1-0.5	>1.0
SOU-N EE 46.501:2006 (Ukraine) [2]	>1	0.1-0.5	>1.0
RD 153.34.0–46.302–00 (Russia) [4]	>1	0.1-0.5	>1<3

As can be seen from the table, the gas content in equipment with LED discharges is characterized by an increased content of C_2H_4 with respect to C_2H_6 ($1<C_2H_4/C_2H_6$) and C_2H_2 with respect to C_2H_4 ($C_2H_2/C_2H_4>1$). In addition to the three gases ratio shown in Table 1, other gases ratios are regulated by different standards for recognition of defect type. For example, the Dornenburg method uses C_2H_2/CH_4 ratios (if the ratio is less than 0.3, PD are predicted, if greater than 0.3, arc discharges) and C_2H_6/C_2H_2 ratios (if the ratio is greater than 0.4, PD are predicted, if less than 0.4, arc discharges). The CIGRE SC-15 method uses the ratio C_2H_2/C_2H_6. If the value of this ratio is greater than one, the digits are predicted. It should be noted that the values of these ratios for LED discharges in [4-7] are not regulated.

Gas ratio values are also used in some graphical recognition methods. For example, in the ETRA square, developed by the Electric Technology Research Association (Japan) [8]. The method provides for the use of three gases ratio C_2H_2, C_2H_4 and C_2H_6 and a diagnostic graph to determine the nature of the defect. According to [8], the defect area, which corresponds to LED discharges, is restricted by the following gas ratios: $0.01 \le C_2H_4/C_2H_6 \le 10$ and $1 \le C_2H_2/C_2H_6 \le 10$.

In addition to the gas ratio criterion, the gases percentage in the oil sample is used to recognize defect type predicted by the DGA results. This criterion is used in Duval triangles and pentagons [9, 10, 11] and in the key gas method [12]. Using the Duval triangle allows determines the defect type by the percentage of three gases - CH_4, C_2H_4 and C_2H_2. According to the Duval method [9, 10, 11], low energy discharges are characterized by an area on the triangle limited to 13% acetylene and 23% ethylene. The key gas method [12] lacks a characteristic percentage of gases that would correspond to LED discharges.

Another criterion that is used to recognize a defect type from DGA results is the ratio of gases to gas with the maximum concentration. This criterion is implemented in the nomogram method, which was first proposed by Japanese researchers [13]. To recognize the type of defect using the nomogram method, the gas with the maximum concentration is first determined and the values of the ratio of each gas to the gas with the highest concentration are calculated. Next, the defect nomogram is constructed. The obtained ratio values were deposited on the ordinate axis, and the gases were placed on the abscissa axis in the following order: H_2, CH_4, C_2H_6, C_2H_4, and C_2H_2. A line connects the resulting points. The resulting graph is compared with the reference nomograms and the one where the maximum coincidence is achieved is selected. This nomogram determines the type of defect. As an example, Fig. 1 shows the reference nomogram regulated in [2, 3] for LED discharges. A further development of the nomogram method is the method of graphic areas [14]. This method allows consider the variability of images built for different pieces of equipment in which the same defect is detected. In this case, the defect type is determined not by visual comparison of the constructed and the reference images, but because of the minimum diagnostic distance between the operational and the reference image included in the reference area.

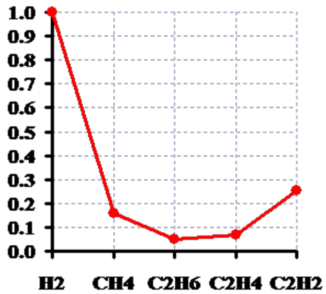

Figure 1. Reference nomogram of low energy density discharges

The analysis of open literature sources showed that the criteria described above are used not only in the existing standards, but also in a number of author's methods. Thus, in [15-17] fuzzy inference models are developed for defect type recognition, in which gas ratio values are used as input parameters. In [18-20] it is proposed to use neural networks for recognition of defect type. In [21] a Bayesian network is proposed to interpret the DGA results. In [22] it is proposed to perform defect type recognition using Association rules, but gas ratios from IEC 60599 [1] are used for recognition. In [23 and 24] the vector relevance method was used to diagnose the equipment state. In [25] a hybrid method of recognition using the key gas method and gas ratios from standards [1, 4 and 6] is proposed. In [26] an intelligent expert system has been developed for defect type recognition, but it also uses the values of gas ratios regulated in [6] and [7]. In [27] an expert system for assessing the state of power transformers has been developed. The paper presents a new fuzzy logic interpretive approach for dissolved gas analysis of transformer oil based on the dissolved gases. The fuzzy logic model for detecting various incipient transformer faults given in [28] uses gas ratio values from the Rogers, Dornenburg and IEC methods. In [29] a fuzzy model has been developed to assess the transformer condition, taking into account multifactorial effects on the complex of diagnostic features, which allows optimizing the process of transformer operation.

However, any diagnostic system can only recognize defect type it is trained to recognize, otherwise it will either be misdiagnosed or fail to recognize. At the authors' disposal, there are DGA results of equipment, in which LED discharges are detected. For these results, the values of the criteria used to recognize defect type differ considerably from the values that are regulated by current standards. As will be shown below, in some cases, these differences have led to misdiagnosis, resulting in equipment damage. In this regard, the research purpose is to increase recognition accuracy of LED discharges based on the gas content analysis in the OFE.

3. Research procedure

The initial data were analysed DGA results for 184 pieces of high-voltage OFE with known diagnoses, namely LED discharges. Input data were obtained by the authors because of cooperation with 15 energy companies of Ukraine, for the period from 2008 to 2018. Oil samples were taken from existing equipment (mainly power transformers) and sent to certified laboratories, where the concentrations of gases dissolved in oil were determined. For this purpose, chromatographs, which is special devices for separation and analysis of substance mixtures, were used. The chromatograph consists of a sample entry system, a chromatographic column, a detector, a registration and temperature control system, and devices for receiving the separated components. The chromatograph works as follows. The carrier gas is continuously fed from the cylinder to the chromatographic column via pressure and flow regulators at variable or constant speed. The column is placed in a thermostat and filled with sorbent. The temperature is kept constant and up to 500°C. The transformer oil under analysis is injected with a syringe. The column divides the multi-component mixture into several binary mixtures, which include both carrier gas and one of the analysed components. Depending on how the components of the binary mixtures are sorbable, the mixtures arrive at the detector in a certain order. The result of the detection records the change in concentration of the components at the output. The processes occurring in the detector are converted to an electrical signal and then recorded as a chromatogram. In carrying out these tests were used chromatographs with the detection limit of gases not exceeding the following values: for hydrogen - 0.0005% rpm, for methane, ethylene, ethane - 0.0001% rpm, for acetylene - 0.00005% rpm. Then the analysis of the obtained values was carried out. To level the differences in the values of the three criteria used for defect recognition, defect groups with similar o criteria values were first formed. For this by analogy with [30, 31] at the first stage of the research, the gas ratio values pairs recommended in [1-7] were calculated. To reduce the error, the calculation was performed only if the concentration of gases constituting this ratio exceeded the values corresponding to the "limit of occurrence of gases in the oil." These values depend on both the chromatograph sensitivity and the measurement technique and according to [2] are H_2=50, CH_4=C_2H_6=C_2H_4=15 and C_2H_2=3 μl/l. If the calculated ratio values were outside the values range that are regulated by current standards for this defect, the DGA results were transferred to another array. Further, the percentage of hydrocarbon gases and hydrogen was calculated for each piece of equipment [30-32]. The calculated values were compared with each other and transferred to another array in case of a difference in percentage. Then nomograms of defects were built for each piece of equipment [13]. The constructed nomograms were compared with each other and transferred to another array in case of visual differences in DGA results. As a result, 9 arrays with identical gas ratio values, similar gas content and nomograms were formed. The gas percentage values for the obtained arrays, indicating defect type and the sample values volume are given in Table 2. In Table 3 the gas ratio values are shown.

Table 2. Percentages of gases content with low energy density discharges

No.	Fault type, sample value	Gases content, %				
		H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
1	Low energy discharges. N=17	40-86	8-31	0.1-23	0.01-8	0.7-32
2	Low energy discharges. N=5	33-48	32-45	5-22	0.3-3	0.5-13
3	Low energy discharges. N=16	40-65	4-17	8.5-25	1.0-10	10-38
4	Low energy discharges. N=12	5-37	1.2-16	10-32	2-22	25-60
5	Low energy discharges. N=7	55-83	2.5-6.5	1.0-10	1.5-11	10-30
6	Low energy discharges. N=81	44-90	1-8	0-5	0.1-22	5.5-44
7	Low energy discharges. N=3	25-45	1-4	0.2-15	4-15	35-55
8	Low energy discharges. N=33	33-75	5-27	1-16	1.8-17	5-36
9	Low energy discharges. N=10	10-36	4-25	4-14	5-22	33-67

To account the nomograms coordinate values drift, graphical areas were constructed for each array with homogeneous criteria values [14]. In addition to the graphic areas method, diagnostics was performed for each selected data set using the gas ratio values recommended in IEC 60599 [1], the Duval triangle [9] and the ETRA square [8], which made it possible to analyse the capabilities of these methods in the recognition of LED discharges. Besides, in the process of analysis the diagnoses for the analysed equipment were compared with the diagnoses set in open literature sources for the equipment with similar gas content.

Table 3. Gas ratio values with low energy density discharges

No.	Gases ratio					
	CH_4/H_2	C_2H_6/CH_4	C_2H_4/C_2H_6	C_2H_2/CH_4	C_2H_2/C_2H_6	C_2H_2/C_2H_4
1	0.1-0.71	0.02-0.87	0.12-0.88	0.03-1.4	0.141-4.14	1.05-4.47
2	0.92-0.98	0.14-0.63	0.06-0.23	0.014-0.39	0.1-0.63	1.1-9.9
3	0.11-0.39	0.88-2.22	0.11-0.66	0.99-5.90	0.47-4.13	1.8-35.6
4	0.78-0.922	2.0-6.14	0.49-1.0	2.4-11.6	1.04-4.65	1.33-8.5
5	0.05-0.08	0.29-1.47	1.0-1.26	1.9-2.87	1.9-8.2	1.8-6.7
6	0.014-0.099	0.007-1.03	3.4-35.6	0.09-30.5	5.88-180.6	1.361-11.7
7	0.05-0.086	0.01-0.08	2.75-15.2	12.9-44	3.2-161	2.8-10.6
8	0.12-0.543	0.107-0.90	1.0-1.88	0.39-4.1	1.0-7.29	1.0-4.92
9	0.353-0.854	0.194-1.45	1.0-1.765	1.48-4.032	2.77-10.6	1.78-4.33

4. Analysis of gases content in the equipment with low energy density discharges

The gas content peculiarity from group No. 1 is the relatively low content of C_2H_4 in relation to C_2H_6. Despite this, in some works, for example [22], defects with such a gas content are identified as high energy density electric discharges. It should be noted that, despite the relatively low value of the ratio C_2H_4/C_2H_6, when opening the transformer with similar DGA results, as a rule, traces of discharges, insulation damage, the presence of surface discharges on the barriers and on the windings are detected. In the bushing of the 220 kV oil circuit breaker, with such gas content, deposits of X-wax were detected. Fig. 2 (a) shows the diagnostic results with gas ratios recommended by IEC 60599 [1]. As can be seen from the figure, due to the low content of C_2H_4, the value of the ratio $C_2H_4/C_2H_6<1$, which corresponds to PD. At the same time, the values of the ratios $CH_4/H_2=0.1\text{-}1$ and $C_2H_2/C_2H_4>1$, which corresponds to low energy electric discharges. As a result, the points corresponding to the gas ratio values from the group of defects No. 1 do not fall into any of the diagnosis areas. That is, it was not possible to determine the type of defect using IEC 60599 standard. Fig. 2 (b) shows the diagnostic results of equipment from defect group No. 1 with use of the Duval triangle [9]. As can be seen from the figure, according to the Duval method, the gas content corresponds to both LED discharges and discharges accompanied by overheating, as well as PD. According to the authors, this difference in diagnoses is due to both the non-consideration of H_2 and C_2H_6 in the Duval method, and the differences in the content of CH_4 and C_2H_4 in the oil of the analysed equipment. At the same time, diagnostics from this group of defects using ETRA square [8] showed the presence of electrical discharges with LED (Fig. 2 (c)). Fig. 2 (d) shows the graphical area, built on the DGA results of equipment with such defects (solid line indicates the centre of the area, which coincides with the nomogram of the defect, dotted lines are the lower and upper border of the defect area). Comparing the obtained nomogram with the gas percentage values from Table 2 it is easy to see that the defect nomogram actually reflects the gas percentage normalized in relation to the gas with the maximum content. As can be seen from the figure, for the analysed defect type, the gas with the maximum content is H_2 (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis, are equal to one). The second gas with respect to the H_2 content is CH_4, and then comes C_2H_2. The content of C_2H_6 and C_2H_4 with respect to H_2 is much lower than for other gases.

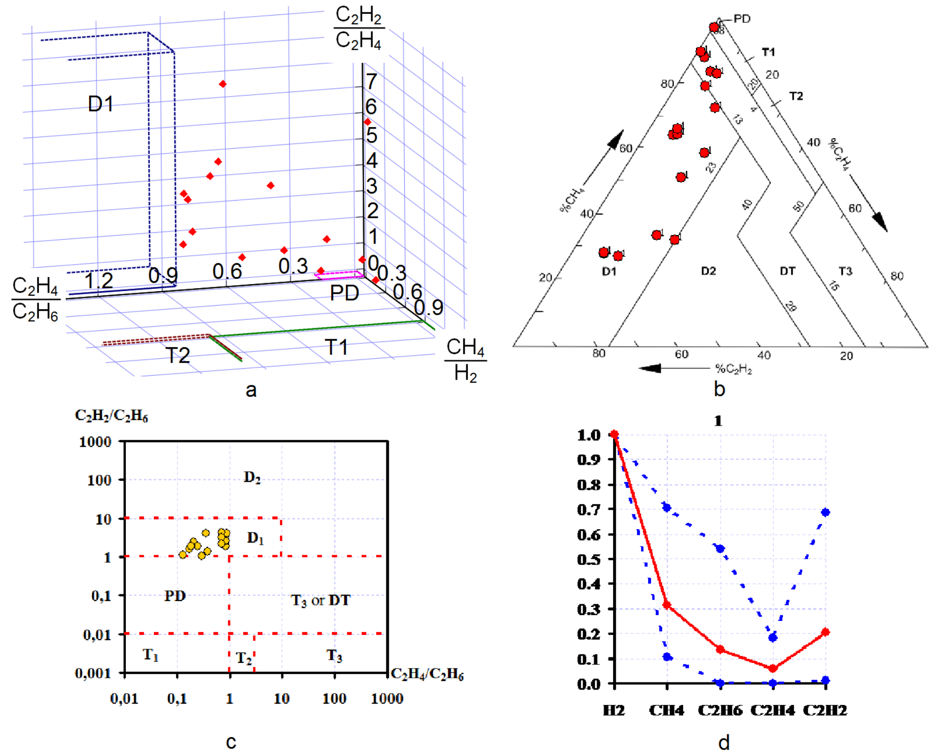

Figure 2. Diagnostic results from defect group No. 1 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

In equipment from group No. 2, there is a higher CH_4 content relative to H_2 ($CH_4/H_2>0.9$). The content of C_2H_6 is higher than C_2H_4 ($C_2H_4/C_2H_6<1$) and the content of C_2H_2 is higher than C_2H_4 ($C_2H_2/C_2H_4>1$). As shown in [33], such defects are accompanied by accidental damage to the equipment. For example, the cause of emergency damage to the transformer voltage of 125 kV, hydroelectric station "Nelson river", Northern Canada [33], was damage to the insulation between the coils and the coil insulation.

This transformer was manufactured in 1977 and operated at 75% capacity. The damage occurred in August 1998, and the gas content and gas ratio values corresponded to defect group No. 2. In the works [22 and 34] for equipment with similar gas ratio values, the diagnosis "electrical discharges with high energy density" was made. The diagnostic results from the group of defects No. 2 using IEC 60599 [1] are shown in Fig. 3 (a). As can be seen from the figure, the points corresponding to the gas ratio values do not fall into any of the diagnosis areas. This is due to both the low content of C_2H_4 ($C_2H_4/C_2H_6<1$) and the high content of CH_4 ($CH_4/H_2>0.9$). Thus, the use of gas ratio values regulated in [1] in relation to the DGA results o from group No. 2 does not allow to establish a diagnosis, that is, the rejection of recognition. Fig. 3 (b) shows diagnostic results from the group of defects No. 2 with the use of Duval triangle [9]. As can be seen from the figure, according to the Duval method, the gas content corresponds to both LED discharges and discharges accompanied by overheating and PD. However, the use of the ETRA square [8] (Fig. 3 (c)) showed the presence of PD in the OFE. This diagnosis is due to the relatively low content of C_2H_4 relative to C_2H_6. The graphical area constructed from the DGA results of equipment with defects No. 2 is shown in Fig. 3 (d). As in the previous case, the gas with the maximum content is H_2 (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis, is equal to one). The difference of the received nomogram is higher content of CH_4 and C_2H_6 in relation to H_2. The content of C_2H_4 to H_2 is extremely low. Comparing the resulting nomogram with the reference nomogram characteristic of LED discharges (Fig. 1 (a)), and with reference nomograms, which are regulated in [2-3] for different defect types, it was found that the nomogram on Fig. 3 (d) does not match any of the regulated nomograms.

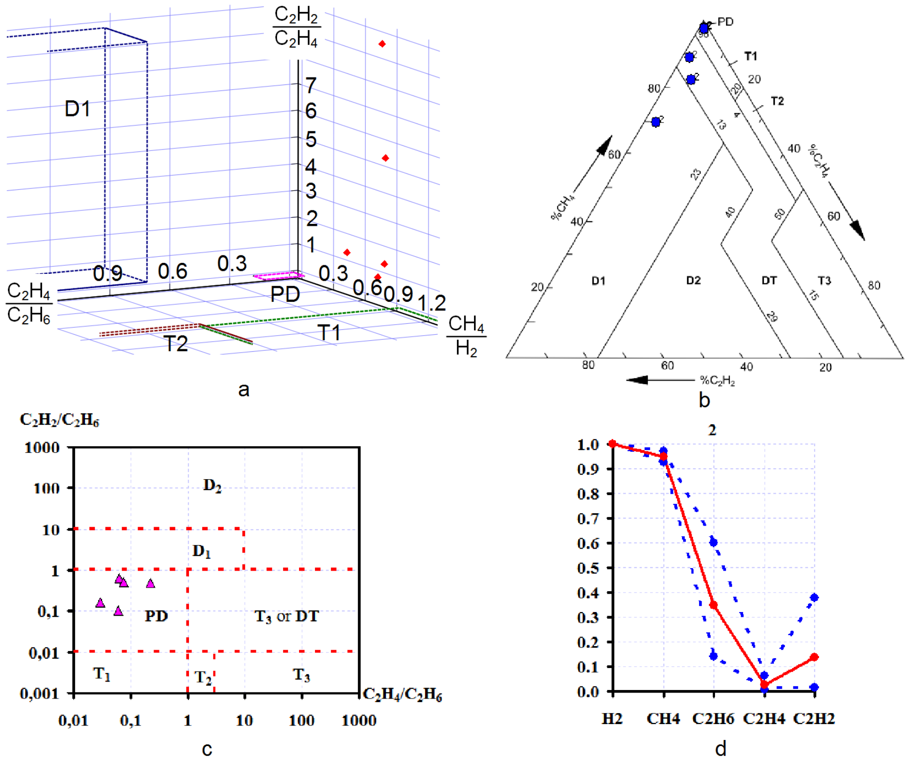

Figure 3. Diagnostic results from defect group No. 2 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

In the OFE of group No. 3, the gas with the highest content is H_2, and the second gas with the highest content is C_2H_6, which according to the current standards is not typical for LED discharges. As can be seen from Table 3 for such equipment, the ratio values ($C_2H_4/C_2H_6<1$), which is typical for PD, the values of the remaining ratios correspond to low energy discharges. By results of opening in the transformer voltage of 110/35/6kV, with such content of gases damages of isolation, presence of surface discharges on barriers on a winding of a high voltage are revealed [33]. In work [35] for the equipment with the similar content of gases the diagnosis "low energy discharges ", and in [36] "high energy discharges" was made. Fig. 4 (a) shows diagnostic results of this equipment using the criteria regulated by IEC 60599 [1]. As in previous cases, the low values of the C_2H_4/C_2H_6 ratio did not allow to establish a diagnosis using gas ratio value regulated in [1]. Fig. 4 (b) shows diagnostic results from defect group No. 3 with the use of the Duval triangle [9]. As can be seen from the figure, for this group of defects, the use of the Duval method made it possible to establish the diagnosis – low energy discharges. Diagnostics of the o OFE DGA results from the defect group No. 3 using the ETRA square [8] (Fig. 4 (c)) showed the presence of both LED and PD. Fig. 4 (d) shows the graphical area, built on the DGA results with these defects. As can be seen from the figure, upon development of this defect in the equipment the gas with the maximum content is H_2, and the second gas in relation to H_2 is C_2H_2. Such content is typical for arc discharges. However, as can be seen from the figure, in the analysed transformers there is a higher content of C_2H_6 in relation to H_2, compared to the equipment with arc discharges. The comparison of the obtained nomogram with the reference nomograms regulated for the recognition of different defect types revealed no coincidence.

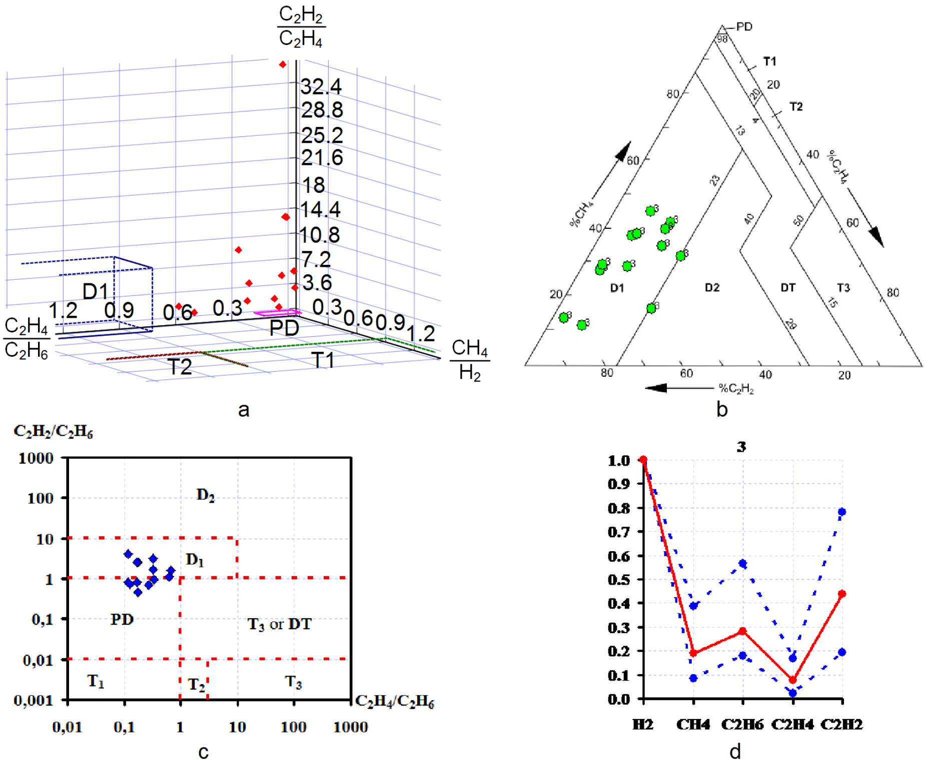

Figure 4. Diagnostic results from defect group No. 3 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

The gases content from the group of defects No. 4 is similar to the gas content from the group No. 3. However, the gas with the maximum content for the equipment from group No. 4 is C_2H_2, and the second gas content is C_2H_6. As shown in [33] when opening a 500 kV transformer, traces of discharges and burnout of insulation were found with a similar gas content. In work [9] the close gases content that is caused by a spark between springs of contacts OLTC is resulted. According to the data given in [36], in a transformer with a capacity of 66 kVA and a voltage of 11 kV with the same gas content, high energy discharges were detected on 02.05.2010. The low value of the ratio C_2H_4/C_2H_6 with the relatively high content of CH_4 ($CH_4/H_2>0.5$) did not allow to establish a diagnosis for this group of defects using the IEC 60599 standard [1] (Fig. 5 (a)). Even despite the fact that acetylene is the gas with the maximum content for this defect and the values of the ratio C_2H_2/C_2H_4 significantly exceed 1. Fig. 5 (b) shows diagnostic results of this equipment with the use of the Duval triangle [9]. As can be seen from Fig. 5 (b), LED and high energy density discharges were diagnosed by the Duval method for the OFE in this group. At the same time, high energy discharges were diagnosed for the OFE with a relatively high content of C_2H_2 [37, 38]. As can be seen from Fig. 5 (c), diagnostics of DGA results from defect group No. 4 using the ETRA square [8] for all analysed values allowed establishing the diagnosis of low energy discharges. Graphic area and defect nomogram shown in the Fig. 5(d) is almost the same as the graphical area and the defect nomogram shown in Fig. 4 (d). The difference is that in the analysed nomogram, the gas with the maximum content is acetylene (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis, is equal to one). The ratio of other gases concentrations to the concentration of C_2H_2 is at the same level as for defect No. 4. Comparison of the resulting nomogram (Fig. 5 (d)) with reference nomograms, regulated for the recognition of different defect types, did not allow establishing the type of defect using this method.

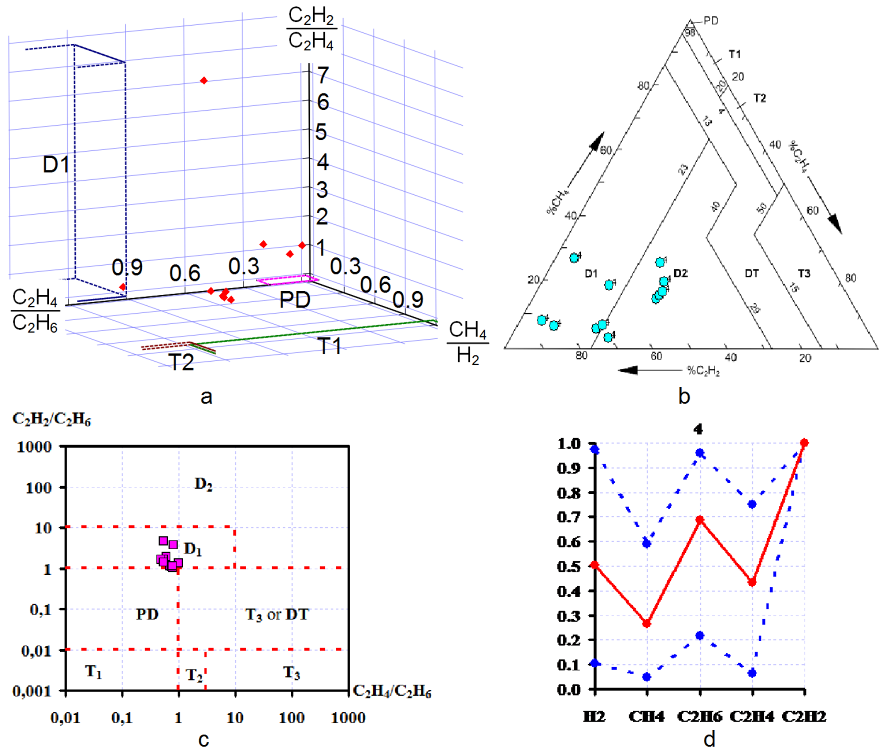

Figure 5. Diagnostic results from defect group No. 4 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

A feature of the gas content from group No. 5 is the low content of CH_4 ($CH_4/H_2<0.1$), which is typical for PD, and the values of the ratios $C_2H_2/C_2H_4>1$ and $C_2H_4/C_2H_6>1$, which is typical for LED discharges. Such gas ratio values did not allow recognizing the defect type using IEC 60599 [1], which is illustrated in Fig. 6 (a). In [36] the defect with similar gas ratio values was identified as high energy discharges, and in [39] as an arc in oil. In [40] for the OFE with the same gas content "Low corona" was diagnosed. Fig. 6 (b) shows diagnostic results from the group of defects No. 5 with the use of the Duval triangle [9]. As can be seen from the figure for this group of defects, despite the low CH4 content, the use of the Duval method made it possible to establish the diagnosis of low and high energy discharges. The diagnostic results for the analysed data using the ETRA square [8] are shown in Fig. 6 (c). As can be seen from the figure for 7 pieces of equipment from the group of defects No. 5, LED discharges was diagnosed using the ETRA method. Fig. 6 (d) shows the graphical area, built on the DGA results with these defects. For this defect, the gas with maximum content is H_2. The highest content in relation to H_2 is observed for C_2H_2. The content of C_2H_6 and C_2H_4 is approximately the same in relation to H_2, and the lowest content in relation to the gas with the maximum concentration is CH_4.

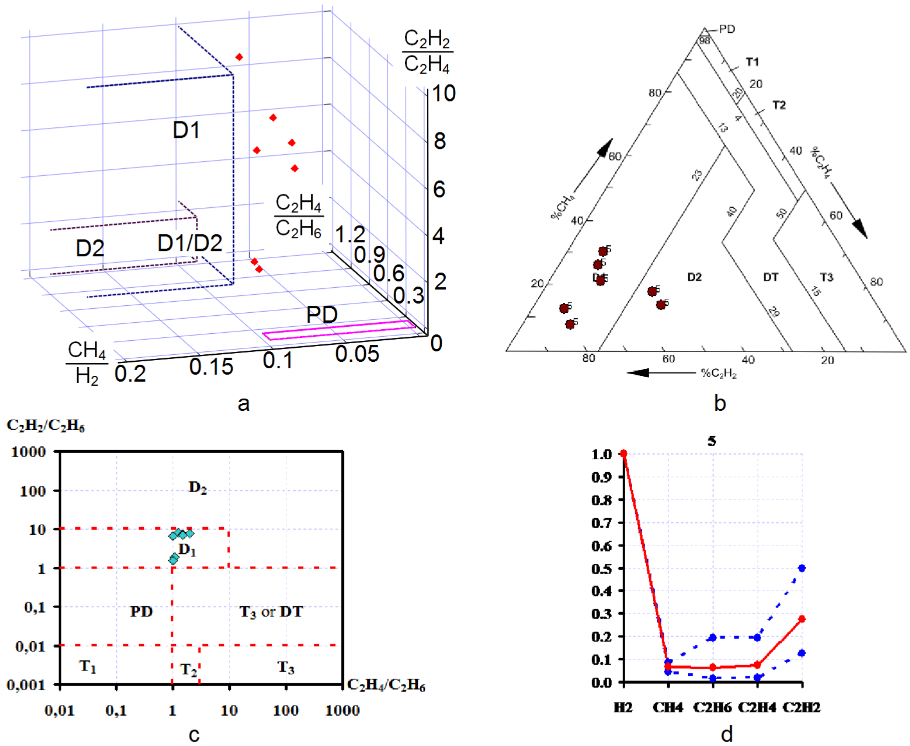

Figure 6. Diagnostic results from defect group No. 5 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

The equipment from group No. 6 also has a low CH_4 content ($CH_4/H_2<0.1$), which is typical for PD. At the same time the values of the ratios $C_2H_2/C_2H_4>1$ and $C_2H_4/C_2H_6>2$, which is typical for high energy discharges. Consequently, the use of gas ratios regulated in [1] for the DGA results from defect group No. 6 did not allow recognizing the defect type (Fig. 7 (a)). At the same time, different sources for equipment that had such a gas content, different diagnoses were established. For example, in [9] diagnose of "Severe coking" were established, [40] – "Low energy arcing and corona", in [41] – "Partial discharge" and in [42] – "High energy discharge". Fig. 7 (b) shows diagnostic results of this OFE with the use of the Duval triangle [9]. As can be seen from the figure, with the help of the Duval triangle for the analysed equipment, such diagnoses as low and high energy discharges and discharges that are accompanied by overheating were established. Diagnostics of the results using the ETRA square [8] (Fig. 7 (c)) showed the presence of discharges with both low and high energy density. In this case, the diagnosis of "high energy density discharges" was made for equipment in which the values of the ratio $C_2H_4/C_2H_6>10$. The graphical area built on the DGA results from group No. 6 is shown in Fig. 7 (d).

As in the previous cases, solid line indicates the area centre, which coincides with the nomogram of the defect. Dotted lines indicates the lower and upper border of the defect area. This nomogram is visually similar to the one shown in the Fig. 6 (d). The difference is the higher content of C_2H_4 in relation to H_2.

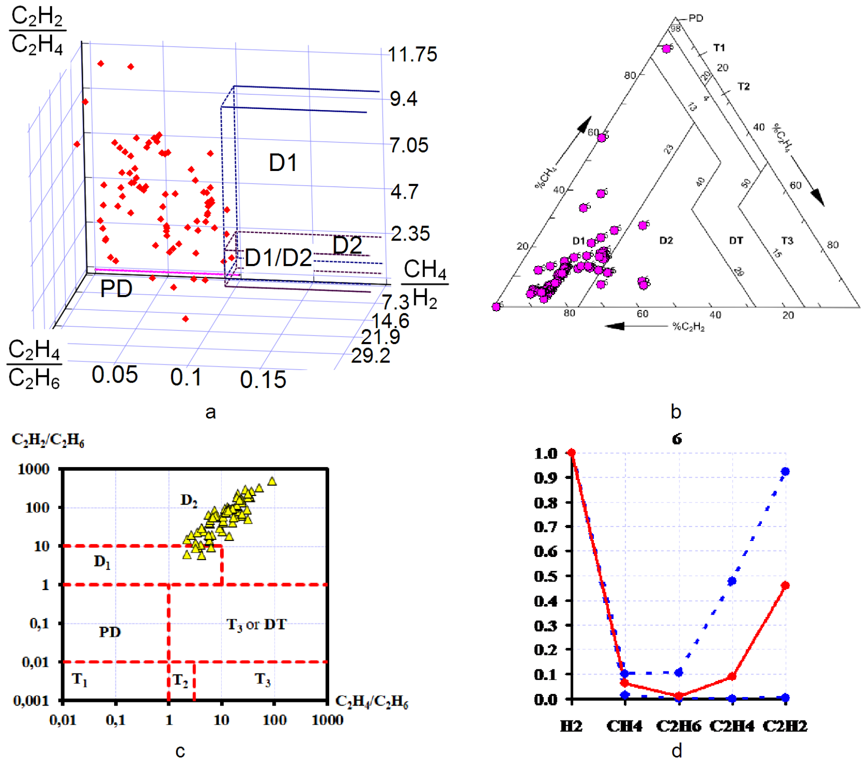

Figure 7. Diagnostic results from defect group No. 6 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

As can be seen from Table 3, the gas ratio values for equipment from group No. 7 are similar to the gas ratio values for defect group No. 6. However, as can be seen from Table 2, in the OFE from group No. 7, the gas with the maximum content is C_2H_2. In [40] such defects are identified as "Low energy arcing", and in [42] as "High energy discharge". Fig. 8 (a) shows the diagnostics results from the group of defects No. 7 using IEC 60599 [1]. As can be seen from the figure, due to the low values of the CH_4/H_2 ratio, the points reflecting gas ratio values did not fall into any of the diagnosis areas. Fig. 8 (b) shows diagnostic results from defect group No. 7 with the use of the Duval triangle [9]. As can be seen from the figure, the use of the Duval method, allowed establishing the diagnosis of low energy discharges. The diagnostic results with the use of the ETRA square [8] are shown in Fig. 8 (c). As can be seen from the figure diagnoses made with the help of the ETRA square almost completely coincide with the diagnoses made by the method of Duval. Fig. 8 (d) shows the graphical area, built on the OFE DGA results with these defects. The graphical area and defect nomogram shown in Fig. 8 (d) are almost the same as the graphical area and defect nomogram shown in the Fig. 7 (d). The difference is that in the analysed nomogram, the gas with the maximum content is acetylene (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis, is equal to one). The ratio of other gases concentrations to the concentration of C_2H_2 is approximately at the same level as for defect No. 6. Comparative analysis of the operational nomogram with reference nomograms, which are regulated in [2, 3] for the recognition of different defect types, did not allow to determine the defect type.

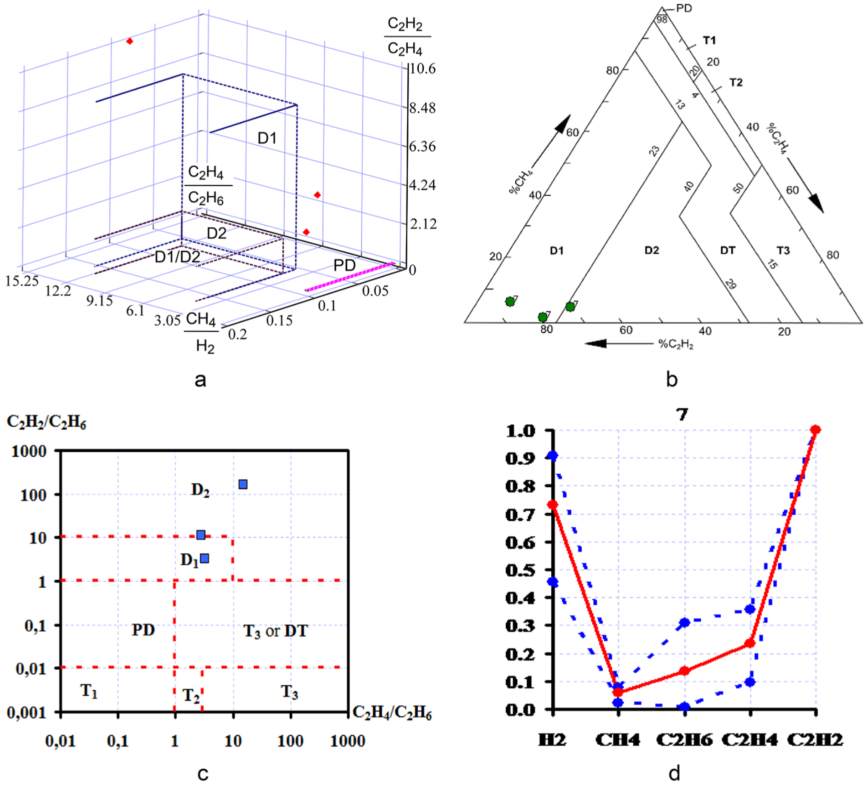

Figure 8. Diagnostic results from defect group No. 7 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

The difference in the gas content from groups' No. 8 and No. 9 is that in equipment from group No. 8 the gas with the maximum content is H_2, and in equipment from group No. 9 is C_2H_2. At the same time, the gas ratio values for this equipment (Table 3), almost completely match with the values regulated by most standards for low energy discharges. As shown by the analysis of literary sources [9, 32, 36-38 and 42] recognition of such defects is not difficult. The exception is a few pieces of equipment for which the ratio $CH_4/H_2>0.5$. As a consequence, in Fig. 9 (a) and 10 (a), the points corresponding to the gas ratio values for the OFE with the values of the CH_4/H_2 ratio>0.5 go beyond the diagnoses regulated by the IEC 60599 [1]. Diagnostic results of these groups with the use of the Duval triangle [9] are shown in Fig. 9 (b) and 10 (b), respectively.

As can be seen from the figures for almost all pieces of equipment, the Duval method allowed establishing the diagnosis of low energy discharges. Fig. 9 (c) and 10 (c) show diagnostic results using the ETRA square [8]. It can be seen from the figures that the use of the ETRA square for the DGA results, according to which groups of defects No. 8 and No. 9 for all oil samples without exception were formed, allowed to establish the diagnosis of low energy discharges. The graphics areas plotted from the DGA results are shown in Fig. 9 (d) and 10 (d). As can be seen from the Fig. 9 (d), for the analysed defect type the gas with the maximum content is H_2 (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis is equal to one). The second gas in relation to the H_2 content is CH_4, and then comes C_2H_2. The content of C_2H_6 and C_2H_4 in relation to H_2 is approximately the same. The defect nomogram shown in Fig. 9 (d) is identical to the reference nomogram shown in Fig. 1

(a), which makes it possible to make a correct diagnosis. The graphical area and the defect nomogram shown in Fig. 10(d) are almost the same as the graphical area and the defect nomogram shown in Fig. 9(d). The difference is that in the analysed nomogram, the gas with the maximum content is acetylene (the ratio values of the given gas to the gas with the maximum content, plotted on the ordinate axis, is equal to one). The ratio of other gases concentrations to the concentration of C_2H_2 is approximately at the same level as for defect No. 8. At the same time, there are coincidences between the defect nomogram shown in Fig. 10 (d), and reference nomograms, which are regulated in [2, 3], for the recognition of different defect types were not revealed.

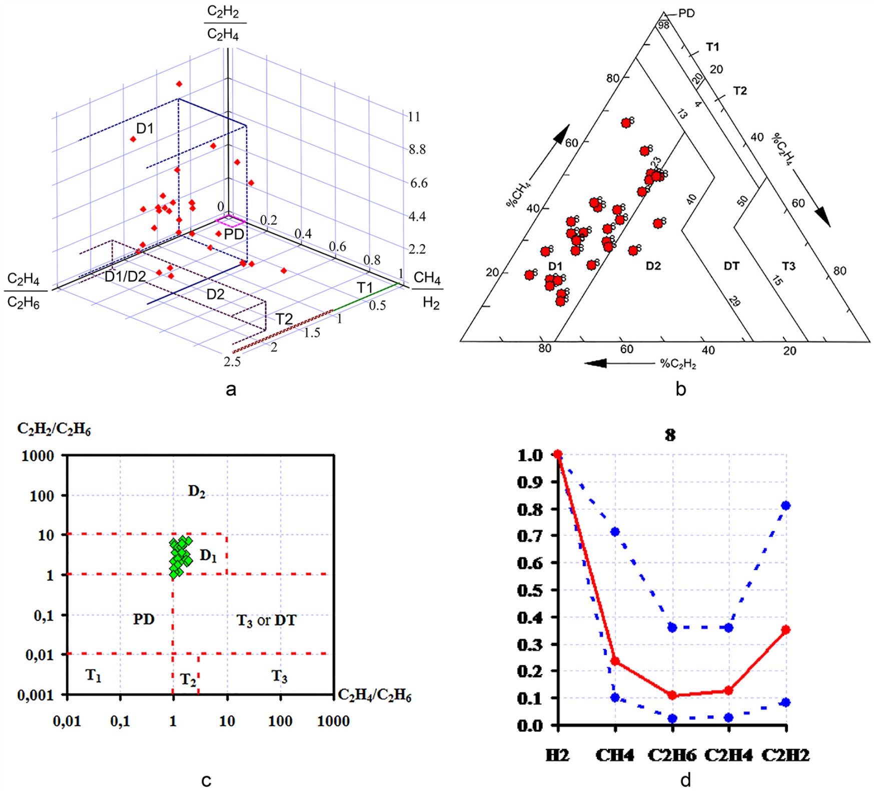

Figure 9. Diagnostic results from defect group No. 8 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

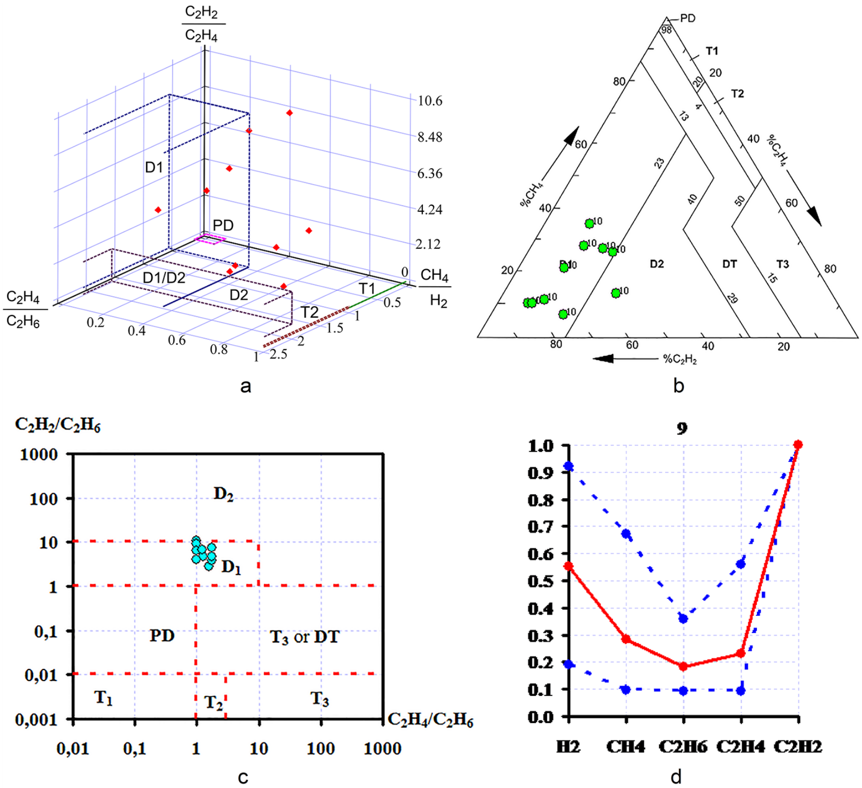

Figure 10. Diagnostic results from defect group No. 9 using IEC 60599 (a), Duval triangle (b), ETRA square (c), nomogram and graphic area method (d)

The given results show that from 184 units of the analysed OFE with LED discharges, the values of gas percentage and gas ratios coincide for the values regulated by the current standards, only for 43 units (defect groups No. 8 and No. 9). For 141 units of equipment the values of these criteria differ significantly from the regulated ones. From 9 constructed defect nomograms coincidence with the reference ones was found only for one nomogram (defect No. 8), which allows to make a correct diagnosis for 33 units out of 184.

5. Estimation of the recognition reliability of LED discharges according to DGA results, using criteria regulated by the current standards

To assess the recognition reliability of the analysed defects using the criteria regulated in the current standards and methods, a comparative analysis of diagnoses established by the results of the equipment disassembly (given in Table 2), with the diagnoses made by the most well-known standards, was made. For this purpose, the statistics of correct and incorrect diagnoses for each unit of equipment has been calculated. The number of partially correct diagnoses was also determined (the defect type was determined correctly, but its intensity or the nature of the defect - thermal, electrical, combined - was erroneously assessed). In addition, the statistics of recognition rejections were calculated (means that there are cases when the analysed method does not allow making a diagnosis). The results of the analysis are given in Table 4.

Table 4. Results of a comparative analysis of the recognition reliability of LED discharges using the most well-known standards

Defect Group	IEEE StandARCd C57.104-2008 [4]		IEC 60599 [1]		SOU-N EE 46.501:2006 (Ukraine) [2]		RD 153.34.0-46.302-00 (Russia) [3]		Dornenburg ratio method [6]	
	1	2	1	2	1	2	1	2	1	2
1	-	-	5.9	-	5.9	23.5	5.9	17.6	-	-
	-	100	-	94.1	-	70.6	52.9	23.5	17.6	82.4
2	-	-	-	-	-	60	-	80	-	-
	-	100	-	100	-	40	-	20	-	100
3	-	-	-	-	-	18.8	-	-	-	-
	-	100	-	100	-	81.3	50	50	18.8	81.3
4	-	-	-	-	-	8.3	8.3	50	-	-
	-	100	-	100	8.3	83.3	41.7	-	8.3	91.7
5	-	-	-	-	-	-	-	-	-	-
	-	100	-	100	-	100	42.9	57.1	-	100
6	-	-	-	-	-	-	-	-	-	-
	-	100	6.2	93.8	-	100	55.6	44.4	1.2	98.8
7	-	-	-	-	-	-	-	-	-	-
	-	100	-	100	-	100	33.3	66.7	-	100
8	-	-	33.3	-	42.4	-	48.5	-	-	-
	3.0	97.0	3.0	63.6	-	57.6	-	51.5	21.2	78.8
9	-	-	10	-	-	10	40	-	-	-
	-	100	-	90	-	90	-	60	30	70
Σ	**-**	**-**	**7.1**	**-**	**8.2**	**6.5**	**12.0**	**7.1**	**-**	**-**
	0.5	**99.5**	**3.3**	**89.7**	**0.5**	**84.8**	**38.6**	**42.4**	**9.8**	**90.2**

Defect Group	Roger's ratio method [7]		Duval triangle [9]		Nomogram method [12]		ETRA square [8]	
	1	2	1	2	1	2	1	2
1	-	11.8	64.7	35.3	100	-	64.7	35.3
	5.9	82.4	-	-	-	-	64.7	-
2	-	60	20	80	-	-	-	100
	-	40	-	-	-	100	-	-
3	-	-	81.3	-	-	-	62.5	37.5
	-	100	18.8	-	-	100	-	-
4	-	-	50	-	-	-	-	-
	16.7	83.3	50	-	-	100	100	-
5	-	-	71.4	-	-	-	100	-
	-	100	28.6	-	-	100	-	-
6	-	-	90.1	1.2	-	-	6.2	-
	-	100	8.6	-	-	100	93.8	-
7	-	-	66.7	-	-	-	33.3	-
	-	100	33.3	-	-	100	66.7	-
8	-	-	84.8	-	100	-	93.9	6.1
	21.2	78.8	15.2	-	-	100	-	-
9	-	-	90	-	-	-	90	-
	-	100	10	-	-	100	10	-
Σ	**-**	**2.7**	**80.4**	**6.0**	**27.2**	**-**	**50.5**	**-**
	5.4	**91.8**	**13.6**	**-**	**-**	**72.8**	**49.5**	**-**

The column numerator No. 1 shows the percentage of correct diagnoses made for the given defect group using the analysed standard. The denominator shows the percentage of partially correct diagnoses. The numerator for column No. 2 shows the percentage of incorrect diagnoses, and the denominator shows the percentage of recognition rejections.

As can be seen from Table 4, the maximum recognition reliability of all compared methods is ensured by using graphical recognition methods, namely Duval triangle (80.4% correct and 13.6% partially correct diagnoses) and ETRA square (50.5% correct and 49.5% partially correct diagnoses). From the results, it follows that the use of the ETRA square in more than 50% of all cases allows make the correct diagnosis. However, the ETRA method uses the gas ratio values to determine defect type, as well as in the standards [1-7]. The latter circumstance clearly demonstrates that defect type recognition reliability is determined not only by the criteria used (gas ratios, gas percentages, gas ratios to gas with the maximum content), but also by the values of the criteria that determine the defect areas boundaries, and the number of recognized defects. Comparing the results of equipment diagnostics by Duval and ETRA methods it is easy to see that for the same DGA results (for example, a group of defects No. 1, No. 3, No. 4 and No. 5) these methods establish different diagnoses. At the same time, the use of these methods ensures that there are no cases of recognition refusal. The nomogram method provides 100% recognition probability only for those defects, for which the reference nomograms are regulated. In this connection, the graphic areas and defect nomograms shown in Fig. 2-10 (d) allow to significantly expand the possibilities of this method. It is of fundamental importance that the gas ratio values for defects having similar graphic areas (for example, defects No. 1, No. 5, No. 6 and No. 8) may differ significantly. At the same time, the graphical areas constructed on the basis of DGA results with similar gas ratio values may also differ (for example, defects No. 1 and No. 3), which clearly illustrates the need to unify the interpretation methods of DGA results. To solve this problem, it is proposed to use all three criteria analysed in the work.

The lowest reliability of recognition is provided by standards and methods based on the use of gas ratio values. So for defects No. 1-7 gas ratio values simultaneously correspond to different defect types (for example, partial and low energy discharges No. 1-5 or partial and high energy density discharges No. 6-7). This circumstance did not allow recognizing fault type for the OFE from this group of defects No. 1-7, using the gas ratio values regulated by existing standards. The rejection of recognition, according to the authors, is the most difficult case, because it can lead to missed defect. The highest number of recognition rejections were detected using the values of gas ratios, regulated by the IEEE StandARCd C57.104 2008 (99.5%), as well as the Rogers (91.8%) and Dornenburg (90.2%) methods. This is caused by the absence in these standards of regulated values of gas ratios for most analysed defects. In this regard, the gas ratio values obtained by the authors and given in Table 3 will help to offset this defect. The authors hope that the results presented in this article will prevent accidental damage to high-voltage OFE due to the timely detection and defects recognition described in this article.

6. Conclusion

The article analysed the values of diagnostic criteria used to identify the defect type of high-voltage oil-filled equipment, in which discharges with low energy density were detected. As a result, it was established that out of 184 units of the analysed equipment with low energy density discharges, the values of gas percentage and gas ratios coincide with the values regulated by the current standards, only for 43 units (group of defects No. 8 and No. 9). For 141 units of equipment the values of these criteria differ significantly from the regulated ones. From 9 constructed defect nomograms coincidence with the reference nomograms has been revealed only for one (No. 8), which allows making the correct diagnosis for 33 out of 184 units of equipment.

The comparative analysis of the recognition reliability of the analysed defects using the known standards and methods has shown that the greatest recognition reliability for the analysed defects is provided by the graphic methods of Duval triangle and ETRA square. However, at the same time, for the same DGA results, these methods establish different diagnoses. Standards and methods that use values of gas ratios provide the lowest recognition reliability. There are also significant differences in defect type estimation using different diagnostic criteria (for instance, gas ratios and defect nomograms), which clearly illustrates the need to unify methods of DGA results interpretation.

To solve this problem, it is proposed to use all three criteria analysed in the work, namely, gas percentage, gas ratio and defect nomograms. The values of gas percentage in Table 2 and values of gas ratio in Table 3, as well as the built defect nomograms, can be considered as an improved diagnostic scheme that allows levelling out the revealed differences and reliably recognizing the defect type using three criteria simultaneously. The authors hope that the results presented in this paper will help to prevent accidental damages of high-voltage equipment by timely detection and recognition of defects described in this article.

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Oleg Shutenko graduated from the Electric Power Engineering Department of the Kharkiv Polytechnic Institute in 1994 with a degree in electrical insulation, capacitor and cable engineering. In 2010 he defended his dissertation for the degree of Candidate of Technical Sciences in the specialty 05.09.13 - technique of strong electrical and magnetic fields. The theme of his dissertation work: "Improvement of power high-voltage transformers diagnostics based on the analysis of patterns of long-term oil aging". The main area of scientific research is diagnostics of insulation condition of high-voltage equipment. Currently works as an associate professor of the Department of "Electric Power Transmission", NTU "KhPI". Has 131 scientific publications, including 1 monograph.

Oleksii Kulyk received BSc and MSc at the Institute of Energy, Electronics and Electromechanics of the National Technical University "Kharkiv Polytechnic Institute" in 2019, with a degree in electrical energetics, electrical engineering and electromechanics. He is currently a Ph.D. candidate at same university. His current research interests are diagnostics of high-voltage oil-filled equipment.