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Analysis of gas composition in oil-filled faulty equipment with acetylene as the key gas

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The article presents results of oil-dissolved gas analysis for 239 units of high-voltage equipment with faults under which acetylene is the key gas. The analysis revealed 13 types of fault with acetylene as the key gas that are differentiated by values of the dissolved gas ratios, their concentrations, and fault nomographs. For each type of fault, graphic domains are plotted that, unlike the nomographs, allow taking into account a possible coordinate drift. A graphic domain based fault identification technique is introduced. The types of fault are briefly described, examples of their identification by different investigators given. Duval Triangle based comparative analysis of the equipment diagnosis data is performed. It is revealed that diagnoses made by different methods may differ significantly both from each other and from actual diagnoses. The results presented allow increasing fault identification accuracy via dissolved gas analysis data.

Keywords: dissolved gas analysis, high-voltage equipment, fault identification, acetylene concentration, electric discharge, gas ratio, gas percentage, Duval Triangle, fault nomographs, graphic domains

INTRODUCTION

Dissolved gas analysis (DGA) is among the basic non-destructive test methods of assessing high-voltage equipment insulation condition. This method takes into account the effect of any electrical or thermal process inside the equipment resulting in the destruction of the insulation and formation of corresponding gases. Every fault type generates a strictly specified spectrum of gases, which allows both detecting the fault and identifying its type (an electrical, a thermal, or a complex fault). DGA analyzes concentrations of the following gases: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2). At present, problems of gas formation in oil-filled equipment under various faults are studied and realized both in the existing international, national, and industrial standards [1–6] and in publications [7–10].

According to the existing concepts, the greatest danger for the equipment is represented by defects for which the gas with the maximum content is acetylene, since the formation of this gas requires maximum energy costs. It is believed that such defects are discharges with high energy density. For their recognition in the existing standards [1–6] the following values of the characteristic gas ratios are regulated: $C_2H_2/C_2H_4>1$, $0.1<CH_4/H_2<1$, and $C_2H_4/C_2H_6>2$. At the same time, the gases percentage value for such defects is practically not investigated, which creates objective difficulties in recognizing the type of defect using the key gas method. It should be taken into account that the maximum content of acetylene in oil samples can also occur for serviceable normally operating equipment [11, 12] or for serviceable equipment under the influence of atmospheric overvoltages or short-circuit currents [13, 14]. In some cases, this can lead to false rejection of the equipment. Many literature sources [14–23] present DGA results equipment with defects for which the gas with the maximum content is acetylene. As the analysis has shown, in some cases for such equipment both the gases ratio values and nomographs of defects may differ significantly from the reference nomographs and from the gases ratio values which are regulated by applicable standards. The latter circumstance causes difficulty in fault type identification and may result in a mistake in the equipment health diagnosis.

In this regard, the purpose of the research is to improve the recognition reliability of the type of defects in the equipment, according to the results of DGA, through a comprehensive analysis of the gases ratio values, the gases percentage, as well as defect nomographs in defective equipment with a maximum content of acetylene.

INVESTIGATION

The original procedure of complex analysis of gas content in oil-filled equipment with defects of different types was used to process the initial data. The difference between the proposed method and the existing ones is that both the gas ratios values and the values of their percentage, as well as the values of each gas concentrations to the gas with the maximum content are used to determine the type of defect. At the same time, in most of the known techniques to determine the type of defect, only one of the listed criteria is used. In addition, the numerical values of the gas ratios, the gases percentage and the ratio of gas concentrations are not determined by analytical calculations, which are based on the evaluation of the energy cost required for breaking certain chemical bonds in hydrocarbon molecules. They are determined on the basis of statistical analysis of the results of DGA equipment to the prescribed defects. This approach allows us to take into account the change in gas content in the equipment which are caused by secondary gases transformations, and not only the levels of energy impacts.

The initial data in the given research were DGA results for 239 units of faulty samples with acetylene as the key gas.These data were obtained by the author both due to cooperation with Ukrainian utilities and from open publications, for example, in [14–23]. The DGA data were split into several groups according to the fault type identified. For every equipment unit, the values of the gas ratios were calculated. The analysis was made for the following gas ratios: C_2H_2/C_2H_4, CH_4/H_2, C_2H_4/C_2H_6, the values of which are regulated by [1, 2, 5, 6]. Besides, the values of the C_2H_2/CH_4 and C_2H_2/C_2H_6 ratios specified by the Doernenberg ratio method [3] and the values of the C_2H_6/CH_4 ratio specified by the Rogers ratio method [4] were calculated. For the purpose of error reduction, the computations were only made under condition of the available gas ratio values exceeding the values of the detectable oil-dissolved gas limits. The latter depend on both chromatograph sensitivity and the detection technique applied, and according to [5] these values are the following: H_2=50, CH_4=C_2H_6=C_2H_4=15, and C_2H_2=3 μl/l. If the calculated values fell beyond the range defined in the standards for the considered fault, the DGA data for the equipment unit analysed were transferred to another group.

Then for every equipment unit, the gas percentage was determined as [24]

$$A_{i\%} = 100\frac{A_i}{\sum}, \quad (1)$$

where $A_{i\%}$ is the percentage of considered gas, A_i is gas concentration, and Σ is the total concentration of hydrocarbon gases and hydrogen in the oil sample.

The calculated values were compared with each other, and in the case of difference in the percentage, the DGA results were transferred to another group.

As a graphical interpretation method, the nomograph method was applied. The method [5, 6] consists in determining the key gas in the analysed oil sample and calculating the ratio of each gas to the key gas. A nomograph is plotted with x-axis presenting the following strict sequence of gases: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, and y-axis presenting the calculated ratios. The plotted points are connected with a line. The obtained graph is compared with the reference nomographs, and the one which fits the best is chosen. It is this nomograph that identifies the fault type. With this method application, nomographs were plotted for every equipment unit. The nomographs were compared, and in case they visually differed from each other, they were transferred to another group even if their ratio values and percentages were close.

As shown in [25], even for the same fault in the equipment of the same type, plotted nomographs may significantly differ both from each other and from the reference nomographs. To consider nomograph coordinate value drift, the authors of [26] suggested using the reference domains rather than the reference nomographs, the domains plotted with application of DGA results for equipment under the same type of fault. The maximum and minimum values of coordinates (ratios of each gas to the key gas) sets serve as the reference domain boundaries. To identify the fault type by means of graphic domains, the distance to the set is used as a diagnostic criterion (precedent diagnosis) in [26].

This technique assesses the diagnostic distance from the fault nomograph plotted on the basis of DGA data for the tested equipment to all the nomographs forming the domain of the given diagnosis:

$$l_i^S = \sqrt[v]{\left|H_{2i}^* - H_2\right|^v + \left|CH_{4_i}^* - CH_4\right|^v + \left|C_2H_{6_i}^* - C_2H_6\right|^v + \left|C_2H_{4_i}^* - C_2H_4\right|^v + \left|C_2H_{2_i}^* - C_2H_2\right|^v}, \quad (2)$$

where H^*_{2i}, CH^*_{4i}, $C_2H^*_{6i}$, $C_2H^*_{4i}$, $C_2H^*_{2i}$ are coordinate values of nomograph i that belongs to the graphic domain of diagnosis S; H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 are coordinate values of the nomograph calculated for concentrations of dissolved gases in the tested equipment; v is the measure of distance ($v = 2$).

The obtained values of diagnostic distances are compared, the minimum distance memorized. The object under diagnosis is localized to the domain with the minimum diagnostic distance:

$$\mathbf{x} \in S_i \quad if \;\; l_i = \min\left(\min_{a_k^s \in S_k}\right). \quad (3)$$

This approach allows both unmistakably localizing the tested object nomograph to the specific domain even under intersections of the domain boundaries and detecting the analogous object with the closest coordinate values within the domain, which makes it possible to identify the fault type and detect the probable cause of its incipience.

In addition to the graphic domain technique, each specified data set was processed with the Duval Triangle method [7], which allowed performing analysis of the method applicability to fault type identification in the situation with acetylene being the key gas.

The decision on the fault type is first made on the basis of gas ratios and gas percentages with further correction through assessing whether the plotted nomograph belongs to the fault reference domain.

CALCULATION RESULTS

According to the calculation results, the author formed 13 groups of defects with identical values of gas ratios, close gas content and similar nomographs. It should be noted that in most existing standards [1–6], for defects with a maximum acetylene content, only one type of defects is regulated – high-energy discharges (arc discharges).

Table 1 shows the gases percentage obtained by the author as alculation results. It also indicates the amount of sample values (N) for which gases percentages are obtained and the type of

Table 1. **Gases percentage for defects with maximum acetylene content**

No.	Fault group	Gas concentration, %				
		H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
1	Partial discharges of high energy density. *N* = 3	15–35	1.5–8	1.1–8	0.8–3	55–75
2	Low energy discharges. *N* = 10	10–36	4–25	4–14	5–22	33–67
3	Low energy discharges. *N* = 12	5–37	1.2–16	10–32	2–22	25–60
4	Low energy discharges and overheating. *N* = 9	3–19	5–20	15–25	14–22	20–50
5	Low energy discharges and overheating. *N* = 9	7–22	20–30	5–14	9–16	29–46
6	Low energy discharges and overheating. *N* = 3	9–16	9–17	4–12	10–30	40–55
7	Electrical discharges and overheating. *N* = 4	0–2.2	1.5–3	5–12	20–30	60–70
8	Electrical discharges and overheating. *N* = 22	0.1–12	1.5–17	0–8	3–35	45–93
9	Electrical discharges and overheating. *N* = 16	0–25	20–40	0.1–5	4–22	28–53
10	Electrical discharges and overheating. *N* = 16	6–22	15–28	0.75–6	20–35	25–50
11	Low energy discharges. *N* = 3	25–45	1–4	0.2–15	4–15	35–55
12	High energy discharges. *N* = 14	0–2	0–1	0–5	1–45	50–98
13	High energy discharges. *N* = 120	4–44	0–23	0–11	1–36	28–88

defect that corresponds to the actual damage detected, and corresponds to the types of defects regulated by applicable standards. Table 2 shows the values of gas ratios for groups of defects from Table 1, obtained by the author as calculation results.

Analysing the results given in Tables 1 and 2, it is easy to see that in the conditions of real operation in defective equipment with a maximum acetylene content both the gases percentage and the gas ratios values correspond not only to discharges with high energy density, but also to defects of another type.

The ranges of gas percentages and gas ratios shown in Tables 1 and 2 make it possible to detect a greater number of defects, which will significantly improve the operational reliability of the equipment.

Table 2. **The gases ratio values for defects, with a maximum content of acetylene**

No.	Gas ratio values					
	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	0.05–0.3	0.63–0.75	0.25–0.75	6.5–37.5	17.3–59.1	26–78
2	0.353–0.854	0.194–1.45	1.0–1.765	1.48–4.032	2.77–7.64	1.78–4.33
3	0.78–0.922	2.0–6.14	0.49–1.0	2.4–11.6	1.04–4.65	1.33–8.5
4	1.09–2.013	2.72–6.27	0.43–0.66	4.54–9.26	1.07–1.94	1.96–3.33
5	1.089–3.37	0.25–0.606	1.0–2.0	1.15–2.12	2.4–6.5	2.34–4.44
6	1.05–1.25	0.25–1.1	1.5–2.5	3.2–4.1	4–7.3	1.75–5.3
7	1.1–11.4	2–5.89	2.15–4.34	23.1–34.3	5.7–11.5	2.29–2.67
8	1.08–5.6	0.099–0.697	2.72–18.32	3.0–49.09	6.54–78.25	1.48–24.57
9	1.05–7.5	0.007–0.2	4.0–35.5	1.07–2.32	8.5–180.6	1.52–10.6
10	1–1.741	0.084–0.26	4.6–14.9	1.17–3.09	6.06–15.4	1.029–1.93
11	0.05–0.086	0.01–0.08	2.75–15.2	12.9–44	3–161	2.8–10.6
12	0.147–0.66	4.8–67.2	7.8–104.4	103–1020	15–167.2	1.2–92
13	0.11–0.991	0.063–1.4	2.06–30.9	1.26–31.6	3.46–249.3	1.02–18.5

ANALYSIS OF FAULTS

Partial discharges of high energy density (fault group 1)

With the development of defects from the group No. 1 the main gases are acetylene and hydrogen. Conversely, methane and ethane concentrations keep below 10%, and ethylene concentration is even lower, not exceeding 3% (see Table 1, No. 1). Consequently, the gas ratio values for equipment with such faults equally correspond to faults of two types: low energy and high energy discharges (C_2H_2/C_2H_4>>1) and partial discharges (CH_4/CH_2<0.1 and C_2H_4/C_2H_6<1). In publication [15], such a fault was identified as a potential discharge with high energy, and in [24] – as partial discharges of high energy density. In [16], for equipment with comparable gas ratios and similar gas composition, the diagnosis was "low energy arcing". Figure 1a presents the graphical domain plotted on DGA data from equipment under such faults (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines show the lower and the upper boundaries of the fault domain). Figure 1b presents results of the equipment diagnosis under the faults of group No. 1 with application of Duval Triangle. As one can see from the figure, according to the Duval Triangle method, the gas composition within the equipment corresponds to low energy discharges.

Low energy discharges (fault group 2)

For defects from the group No. 2 there is also a high content of acetylene and hydrogen. The concentrations of methane and ethylene are very close, while ethane concentration is a bit lower than that of ethylene. As it is shown from Table 2, the gas ratios for this group of faults correspond to low energy discharges. It is this diagnosis that was made in [27, 7] for equipment with those gas composition and gas ratios. In [16], for equipment with similar gas composition and gas ratios, the diagnosis was "low energy arcing". In a 25000 kVA 110 kV transformer with the same gas composition, discharge tracing was found on the major insulation surface. Figure 2a presents the graphical domain plotted on the DGA results for the equipment under faults of group No. 2 (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines show the lower and the upper boundaries of the fault domain). Results of Duval Triangle based diagnosis of these faults are shown in Fig. 2b. The figure demonstrates that the faults were identified as low energy discharges practically for all cases analysed.

Low energy discharges (fault group 3)

With the development of defects from the group No. 3 the main gases are acetylene, ethane and hydrogen. It is proved by the graphical domain plotted on the DGA data from equipment under

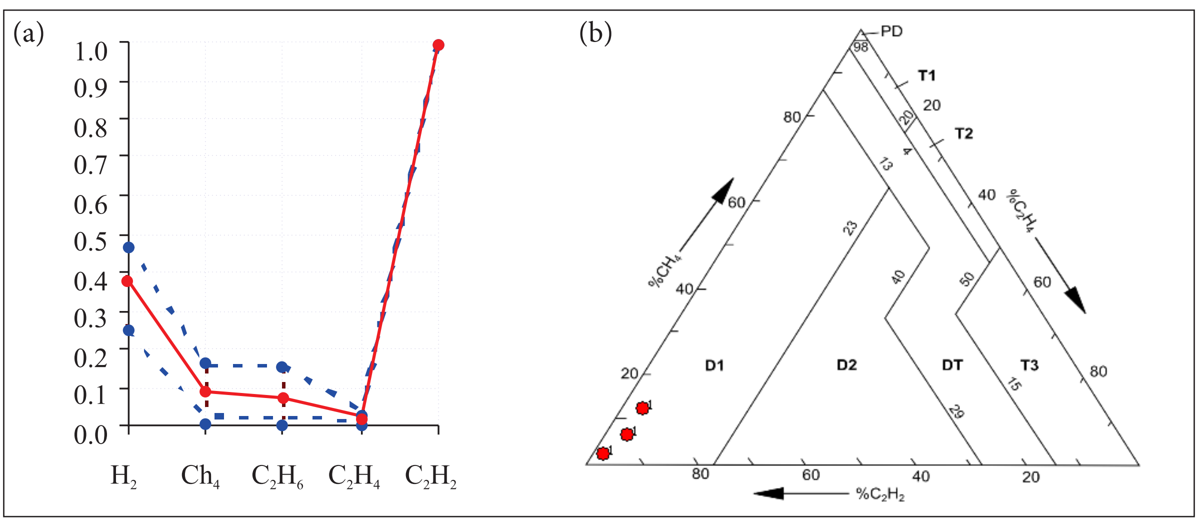

Fig. 1. Graphical domain and diagnosis results of partial discharges of high energy density with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

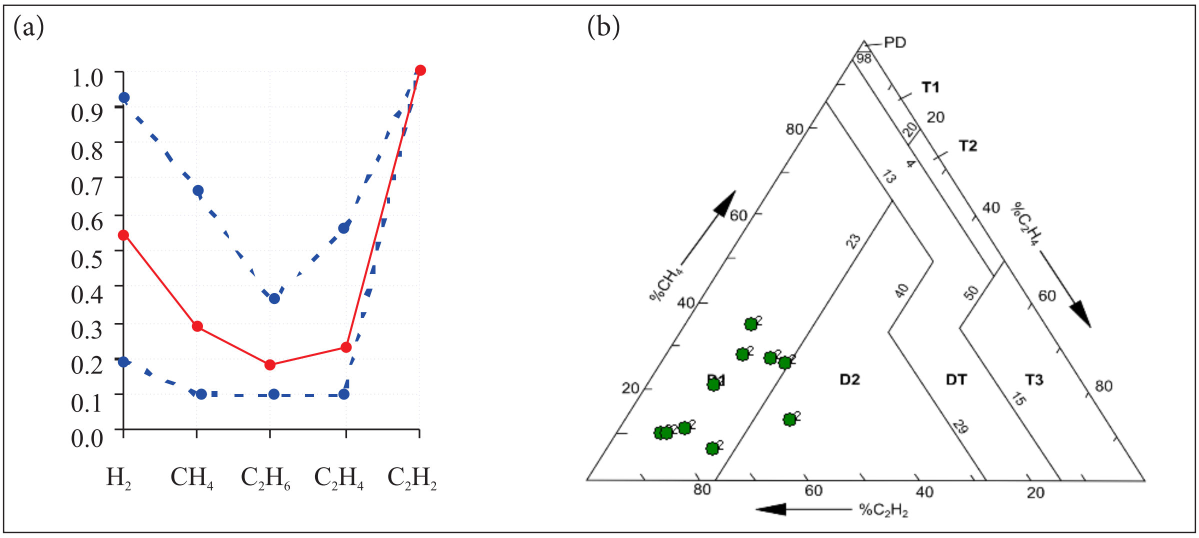

Fig. 2. Graphical domain and diagnosis results of low energy discharges (fault group 2) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

such faults (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines mark the lower and the upper boundaries of the defect domain) which is given in Fig. 3a. It should be noted that faults with this gas composition are practically not described in the current standards [1–6]. At the same time, open publications present DGA results for equipment with such gas composition. For example, similar DGA data of 02.05.2010 from a 66 kVA 11 kV transformer, in which high energy electrical discharge was detected, are described in [28]. In [7], diagnosis "arcing between springs of contacts" was made for equipment with the same gas composition. The author of [14] describes DGA examples from a 40000 kVA 115/22 kV transformer with the comparable gas composition with application of the key gas method, Rogers ratio method, and the author's technique. On the basis of the obtained results, the existence of discharges and overheating was detected. DGA data from the equipment under faults of group No. 3 with Duval Triangle application are shown in Fig. 3b.

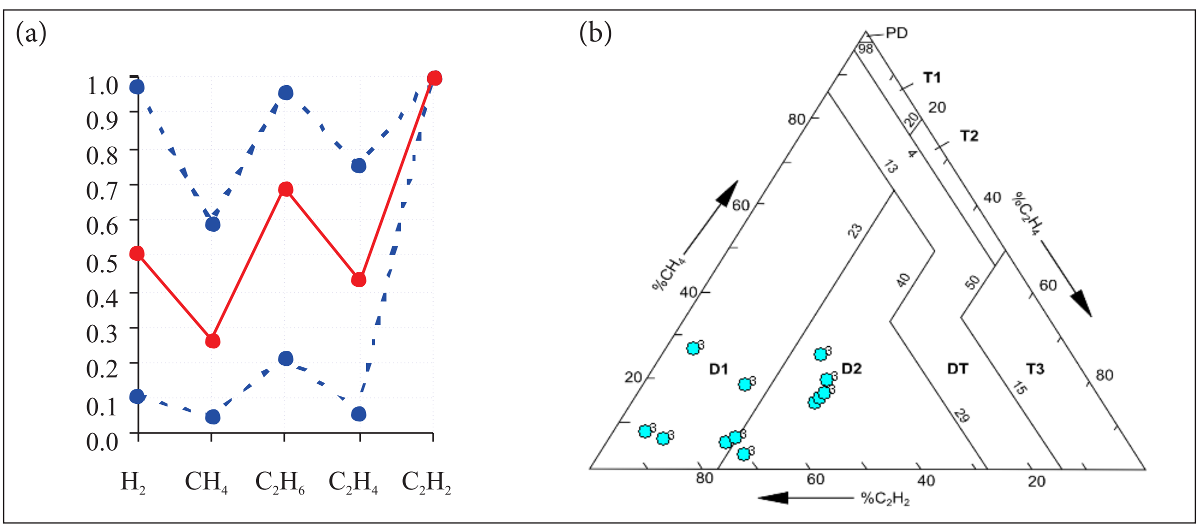

Fig. 3. Graphical domain and diagnosis results of low energy discharges (fault group 3) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

As one can see from the figure, application of Duval Triangle to DGA data from the equipment with faults of group No. 3 allowed identifying low energy and high energy discharges. At this, the C_2H_4/C_2H_6 ratio is less than 1 ($C_2H_4/C_2H_6 \le 1$) for all the equipment analysed, which is shown in Table 2. In the author's opinion, such divergence is caused by neglecting ethane concentration in the Duval Triangle.

Low energy discharges and overheating (fault group 4)

The gas composition in the equipment with faults of group No. 4 is analogous to that in the equipment with faults of group No. 3; however, methane concentration is higher than hydrogen concentration. According to the current standards, e.g. [5], the CH_4/H_2 ratio >1 indicates the existence of overheating, while the C_2H_2/C_2H_4 ratio above 1 (C_2H_2/C_2H_4>1) identifies discharges. Really, after the opening-up of a 135000 kVA 500 kV transformer with a similar gas composition, discharge tracing and insulation burn-out were diagnosed [25]. In a 80000 kVA 220 kV transformer, stud insulation burn-out, stud metal burn-out, and strengthening stud contact with the cantilever were detected after opening-up. Figure 4a presents the graphical domain plotted on the DGA data from the equipment with faults of group No. 4 (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines mark the lower and the upper boundaries of the fault domain). As one can see from the figure, ethylene concentration is lower than that of ethane (C_2H_4/C_2H_6<1, see Table 2) for all 9 transformers included into the considered group of faults. At the same time, application of Duval Triangle to the transformer diagnosis (Fig. 4b) detected the existence of low energy and high energy discharges.

Low energy discharges and overheating (fault group 5)

For defects from the group No. 5, the content of acetylene is higher than the content of ethylene (C_2H_2/C_2H_4>1); however, methane concentration is higher than hydrogen concentration (CH_4/H_2>1), and ethylene concentration is somewhat higher than that of ethane ($1<C_2H_4/C_2H_6<2$). Figure 5a shows the graphical domain plotted on the DGA data for the equipment with the given fault (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines mark the lower and the upper boundaries of the fault domain).

It is shown in [25] that such gas combination corresponds to low energy discharges which go together with overheating. For example, in a 135000 kVA 500 kV autotransformer with a similar gas composition, the upper cantilever

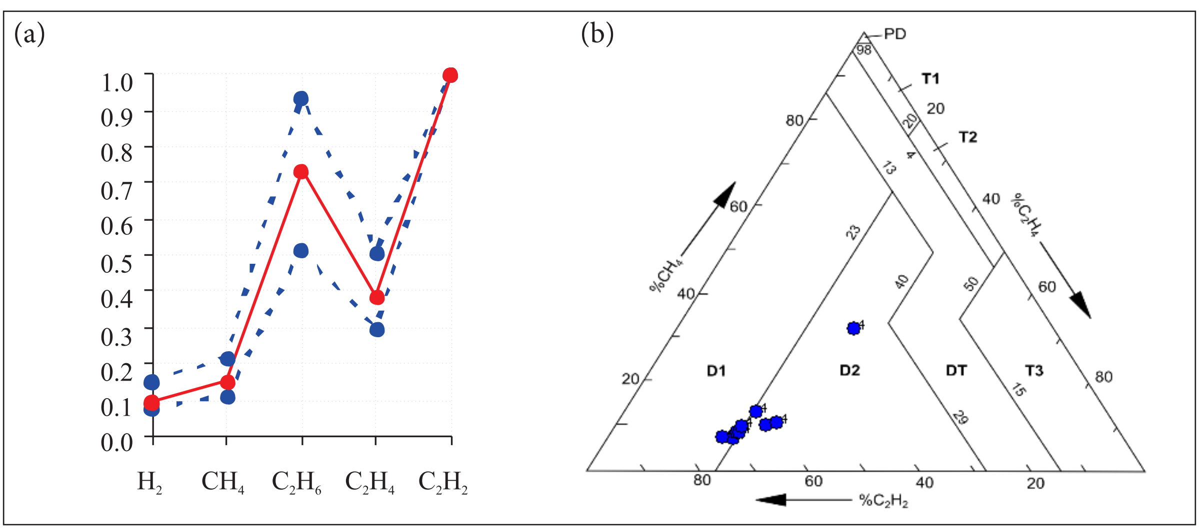

Fig. 4. Graphical domain and diagnosis results of low energy discharges and overheating (fault group 4) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

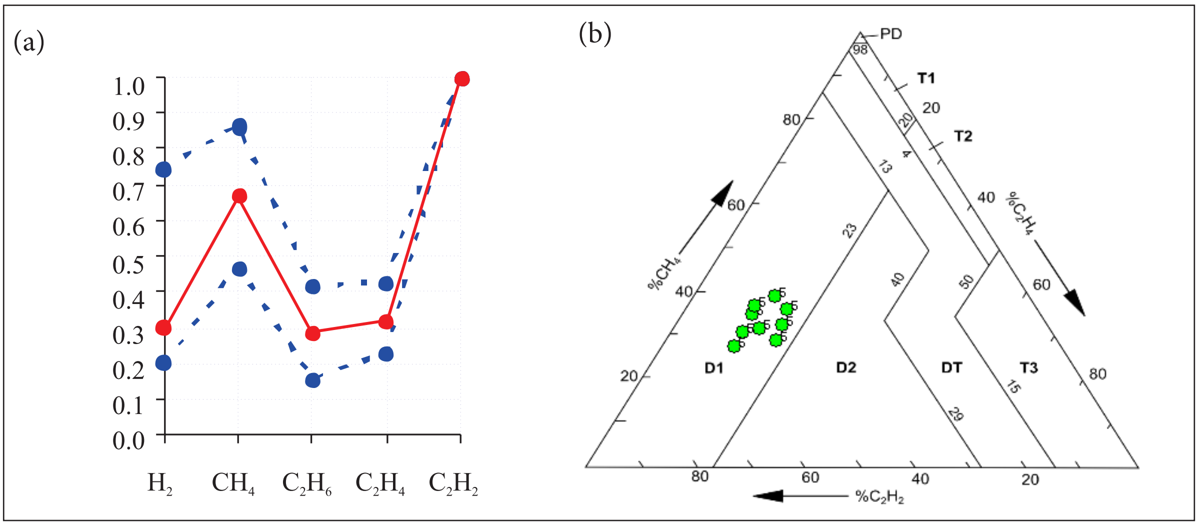

Fig. 5. Graphical domain and diagnosis results of low energy discharges and overheating (fault group 5) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

burn in the joint with the tank guide angle bar was detected. The burning was caused by local discharges. The same diagnosis ("mixed faults diagnosed are: winding circulating currents and core circulating currents") was made in [29] for a 200000 kVA 11/132 kV transformer. In [16], for equipment with the same gas combination, the diagnosis was "arcing". In [30], however, the fault with a similar gas combination was diagnosed as low energy discharges. The same diagnosis was made with application of Duval Triangle for the equipment from group No. 5 (see Fig. 5b.) The difference between the actual diagnosis and the diagnosis made with Duval Triangle may be caused by ignoring hydrogen concentration in the Duval Triangle diagnosis of the equipment.

Low energy discharges and overheating (fault group 6)

For defects from the group No. 6 there is a slight excess of methane over hydrogen and ethane. Besides, ethylene concentration is higher against ethane concentration. It is the latter circumstance

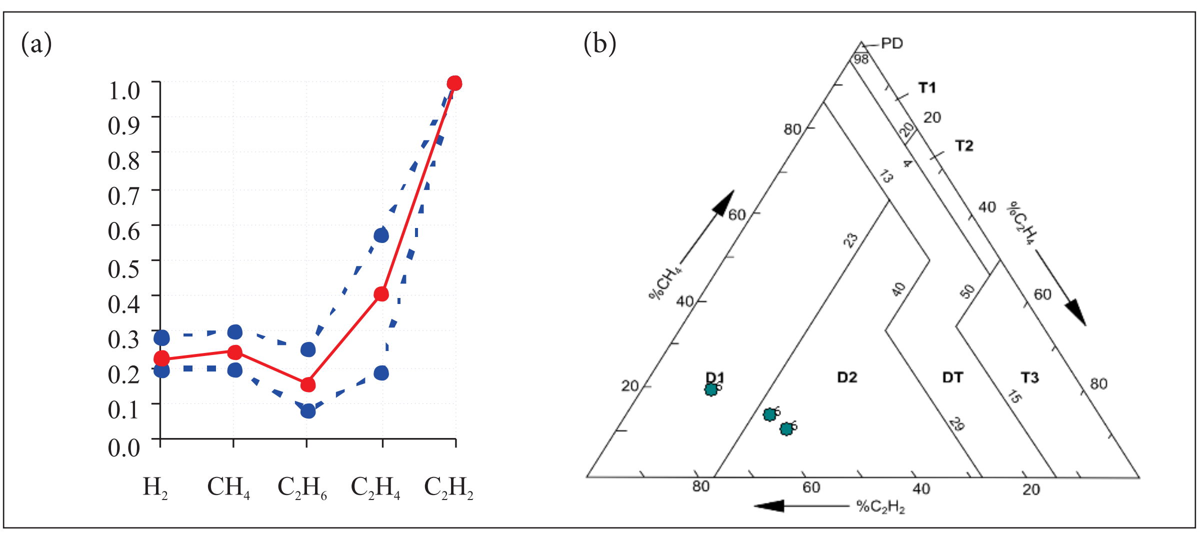

Fig. 6. Graphical domain and diagnosis results of low energy discharges and overheating (fault group 6) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

that caused such faults to be identified as arcing in most publications. In [23], the diagnosis for equipment with the same gas composition and similar values of gas ratios was "arcing", in [16] – "low energy arcing", and according to [12], in a 330 kV instrument transformer arc discharges were diagnosed. Figure 4a presents the graphical domain for the given fault (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines mark the lower and the upper boundaries of the fault domain) that looks somewhat similar to the graphical domain introduced in Fig. 2a. Figure 6b shows results of the equipment diagnosis with application of Duval Triangle. As one can see from the figure, Duval Triangle diagnosis revealed the existence of discharges of high and low energy density, which agrees well with the actual state of the equipment.

Electrical discharges and overheating (fault group 7)

For defects from the group No. 7, the methane content also exceeds the hydrogen content. This group is wholly formed of DGA data from high-voltage non-hermetic bushings. The main faults detected in the high-voltage bushings with such gas composition are burning-out of the measuring tap insulation and layers and burning-out of the major insulation. As it is presented in Table 2, for those faults ethylene concentration is higher than ethane concentration ($C_2H_4/C_2H_6>2$), which indicates high intensity of discharges. The graphical domain plotted on DGA results for the equipment from group of faults No. 7 (see Fig. 7a) bears some resemblance to the domain plotted on DGA data from the equipment from group of faults No. 2. In Fig. 7a, the solid line marks the center of the domain that coincides with the fault nomograph; the dashed lines show the lower and the upper boundaries of the fault domain. In the equipment from group of faults No. 7, however, methane concentration is higher against hydrogen, and ethylene concentration is higher. It is the high concentration of ethylene that was the cause of the diagnosis "high energy discharges" made for the bushings from group No. 7 diagnosed with application of Duval Triangle (see Fig. 7b).

Electrical discharges and overheating (fault group 8)

The gas content for a group of defects No. 8 is similar to that in the equipment from the group of defects No. 5. This is evidenced by the data given in Table 1, as well as the graphics area on Fig. 8a. Like in other figures, the solid line in Fig. 8a indicates the center of the domain that coincides with the fault nomograph; the dashed lines mark the lower and the upper boundaries of the fault domain. The difference is that ethylene concentration in the equipment from

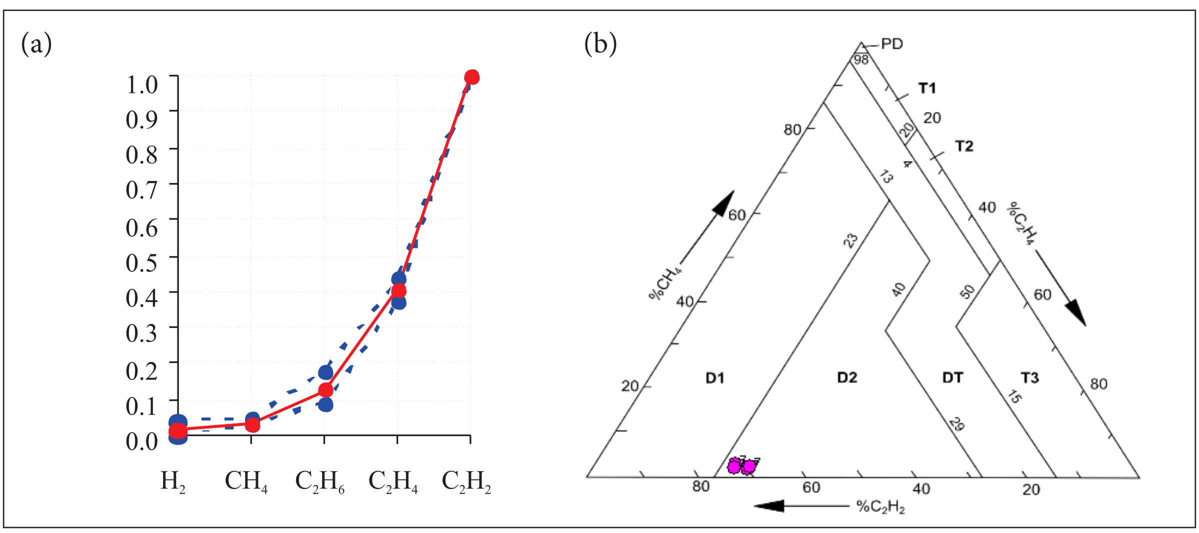

Fig. 7. Graphical domain and diagnosis results of electrical discharges and overheating (fault group 7) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

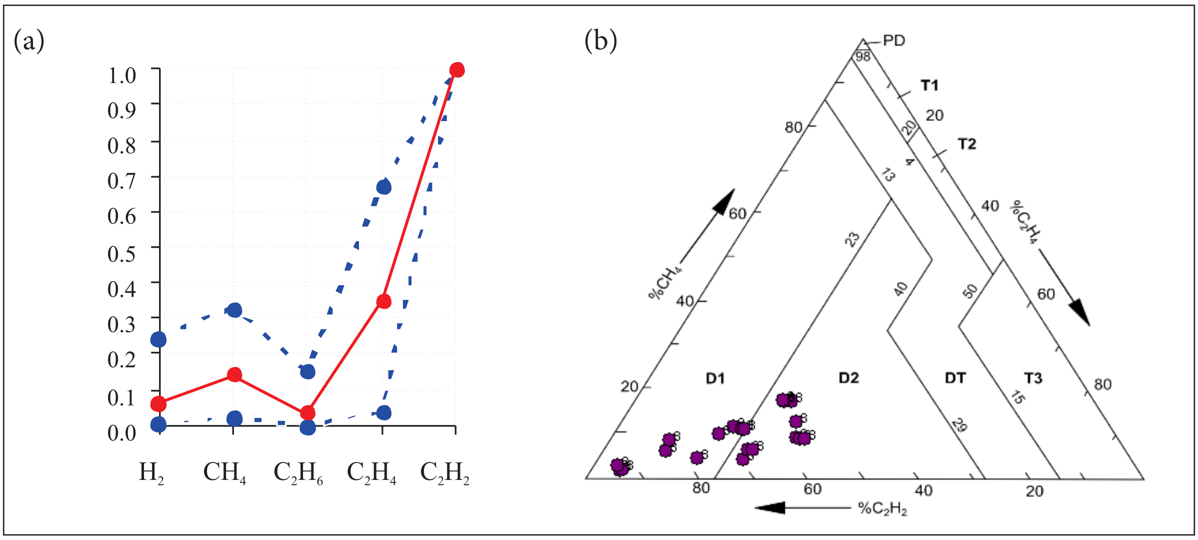

Fig. 8. Graphical domain and diagnosis results of electrical discharges and overheating (fault group 8) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

group of faults No. 8 is higher against ethane concentration ($C_2H_4/C_2H_6>2$). According to [5], the domain in Fig. 8a corresponds to electrical discharges and overheating.

For example, in a high-voltage bushing with that gas composition, insulation failure between the layers and burning-out of 40% of the core was detected. In [10], "severe local overheating and arcing not involving cellulose" were diagnosed in the equipment with analogous gas composition. In [7], a close gas composition was detected for a high-voltage breaker with "severe thermal damage". In some publications, however, for equipment with that gas composition, the diagnosis made was "electrical discharges". For example, in [21, 22] such faults were identified as high energy discharges, and in [20] – as discharges. The diagnosis of the equipment from group of faults No. 8 with Duval Triangle revealed the existence of discharges of low energy density and discharges of high energy density (see Fig. 8b).

The analysis showed that the diagnosis of "discharges of low energy density" was made for equipment with comparatively low ethylene concentration (below 20%). In equipment with the concentration of ethylene over 20%, Duval Triangle diagnosed "high energy discharges". However, one can see from Table 2 that for all the equipment from group of faults No. 8 the C_2H_4/C_2H_6 ratio is above 2 ($C_2H_4/C_2H_6>2$), which is characteristic [1–6] of high energy discharges. It is evident that the differences in the diagnoses made resulted from neglecting ethane concentration in the Duval Triangle diagnostics.

Electrical discharges and overheating (fault group 9)

For defects from group No. 9 there is a similar content of gases with groups of defects No. 8 and No. 5. The concentration of methane in the equipment from group of faults No. 9, however, is higher, which presented in Table 1 and from the graphical domain of the fault shown in Fig. 9a. In the figure, the solid line indicates the center of the domain that coincides with the fault nomograph; the dashed lines mark the lower and the upper boundaries of the fault domain. In a 90000 kVA 400 kV autotransformer with the analogous gas combination [25], carbonization of insulation and discharge tracing were detected. In [31] for equipment with the same gas combination, diagnosis of "high temperature overheating fault model" was made, in [18] – "arcing", in [7] – "arcing in oil".

With application of Duval Triangle (Fig. 9b), diagnoses of "low energy discharges" and "high energy discharges" were made for the equipment from the considered group of faults. Like in the previous case, high energy discharges were identified for the equipment with the concentration

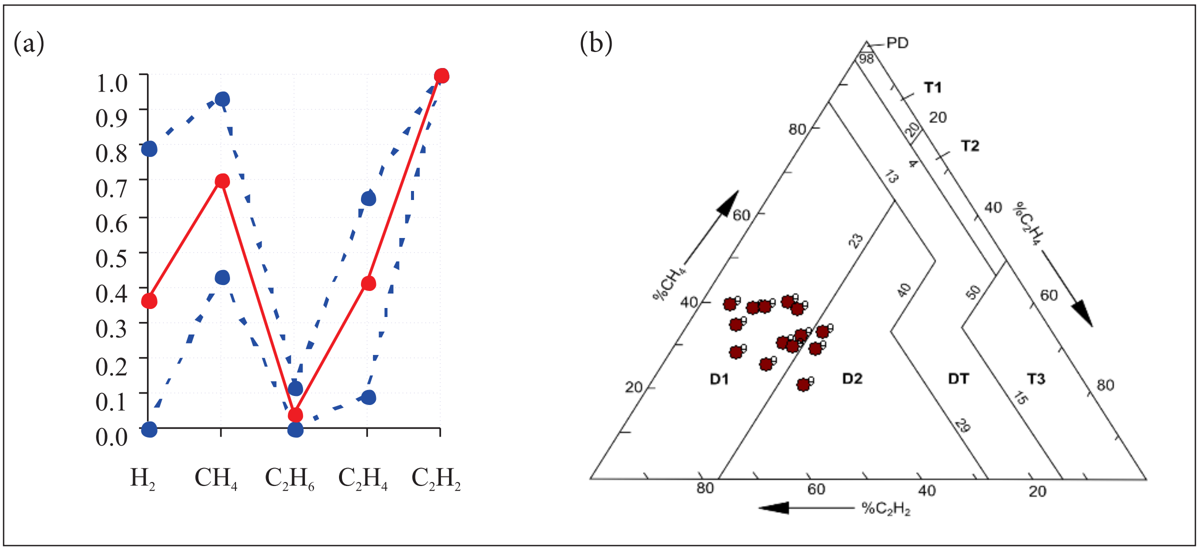

Fig. 9. Graphical domain and diagnosis results of electrical discharges and overheating (fault group 9) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

of ethylene above 25%. However, the concentrations of hydrogen and ethane were neglected.

Electrical discharges and overheating (fault group 10)

According to data presented in [25], the nomograph (the solid line) in Fig. 10a corresponds to arcing and overheating. Such faults cause heavy failure of insulation. For example, after opening a 135000 kVA 500 kV autotransformer, the following faults were detected: contact between the upper cantilever and the tank guide with traces of the metal melting and short circuit of the center frame of the magnetic core to the conservator tank frame. In a 90000 kVA 400 kV autotransformer with the analogous gas composition, formation of short-circuit loop in the low-voltage winding press ring was detected. As one can see from Table 1, equipment with such faults is characterized by higher ethylene concentration as compared to the equipment from group of faults No. 9 and by higher methane

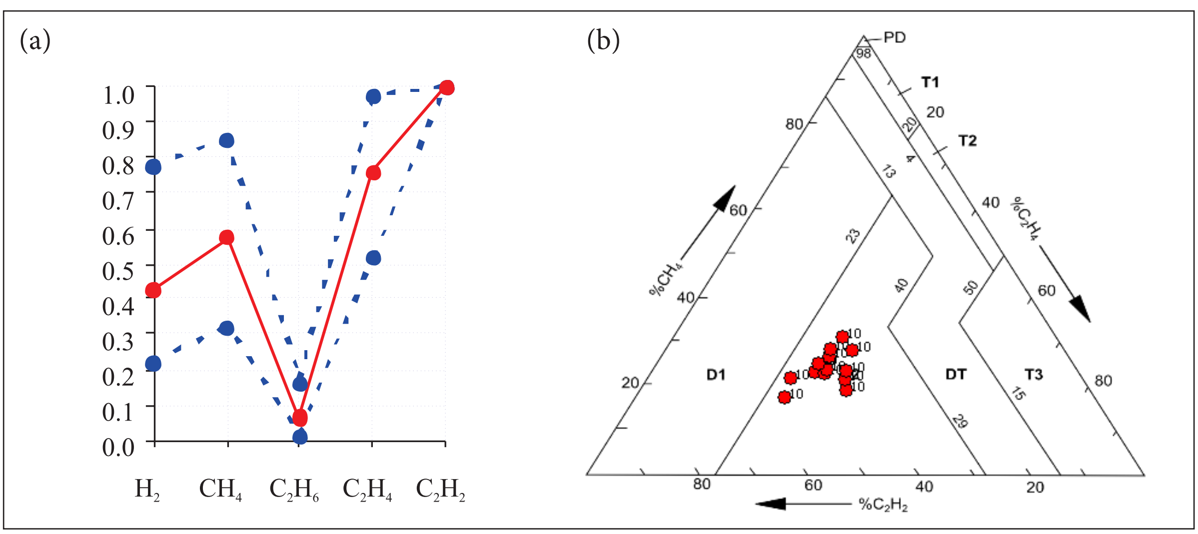

Fig. 10. Graphical domain and diagnosis results of electrical discharges and overheating (fault group 10) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

concentration as compared to the equipment from group of faults No. 8. For the equipment with that gas composition, in [28] the diagnosis of "arc with power follow-through, discharges of high energy" was made, in [7] – "acing in oil", and [33] – "arcing". The diagnosis with application of Duval Triangle (Fig. 10b) revealed the existence of high energy discharges in the equipment, but as Table 2 shows, in all equipment from this group of faults, the CH_4/H_2 ratio is above 1, which is specific to faults caused by overheating, according to most current standards.

Low energy discharges (fault group 11)

For the group of defects No. 11, the values of the ratio $C_2H_2/C_2H_4>1$ and $C_2H_4/C_2H_6>2$ (see Table 2, No. 11), what is typical of high energy discharges. Due to low concentration of CH_4, however, $CH_4/H_2<0.1$, which is specific to partial discharges. It is worth saying that faults with this gas combination are not described in the current standards [1–6]. In some publications [34, 16], the term of "low energy arc" is used to identify this fault. In [17] a similar fault is identified as "high energy discharge". It should be noted that the comparable gas combination for a 12000 kVA 69/13.8 kV transformer is presented in [14]. However, the cause of acetylene concentration growth turned out to be Buchholtz surge actuation during a thunderstorm rather than the transformer fault. Figure 11a presents the graphical domain plotted on DGA data from the equipment with low energy discharges (the solid line indicates the center of the domain that coincides with the fault nomograph, the dashed lines mark the lower and the upper boundaries of the fault domain).

As one can see from the figure, in the equipment with such faults higher concentrations of ethylene and ethane are observed as compared with those in the equipment with partial discharges of low energy density, which is also proved by the data in Table 1 (No. 11). Figure 11b presents diagnosis results for the equipment with arc discharges of low energy obtained with application of Duval Triangle. As it is presented in the figure, the Duval Triangle method allowed making the diagnoses of "low energy discharges" and "high energy discharges".

High energy discharges (fault group 12)

As it is presented in Table 2 for defects from the group No. 12 the values of the ratio $C_2H_2/C_2H_4>1$, $0.1<CH_4/H_2<1$ and $C_2H_4/C_2H_6>>2$, which according to the majority of known standards [1–6], corresponds to discharges of high energy. However, as it is presented in Table 1, in the equipment from this group of faults, the concentrations of unsaturated hydrocarbons (C_2H_2 and C_2H_4) are increased while the concentrations of saturated hydrocarbons (CH_4 and C_2H_6) and H_2 are extremely low. It is also proved by the graphical domain of the fault, given in Fig. 12a. In the

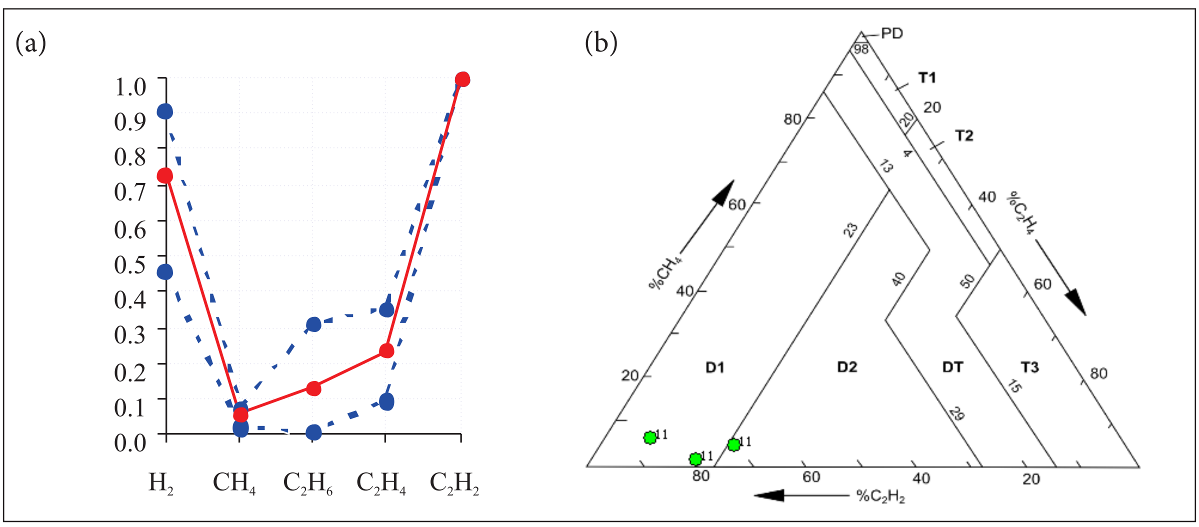

Fig. 11. Graphical domain and diagnosis results of low energy discharges (fault group 11) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

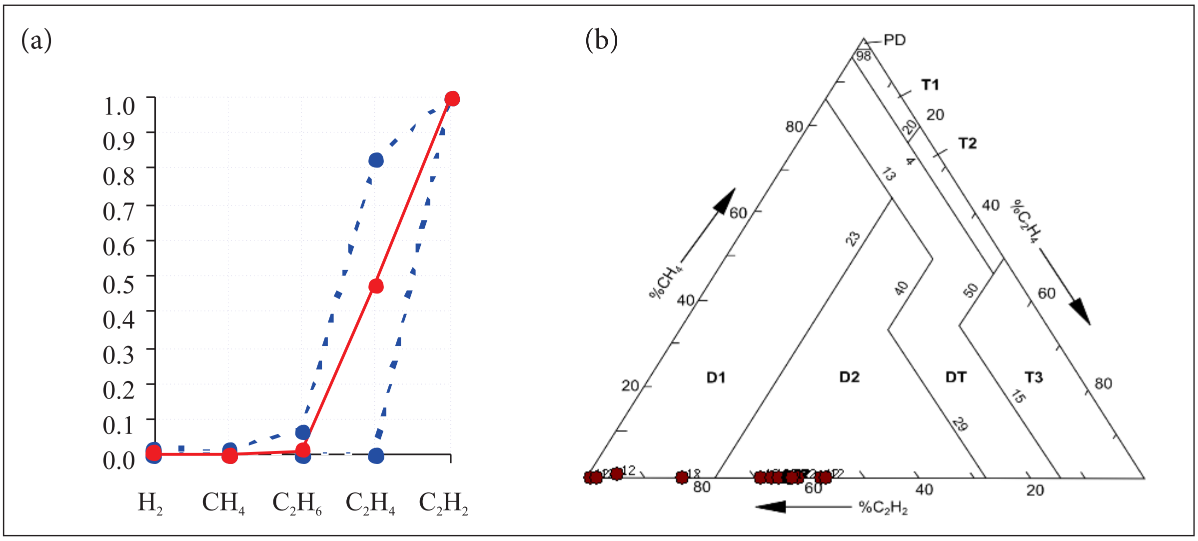

Fig. 12. Graphical domain and diagnosis results of high energy discharges (fault group 12) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

figure, the solid line indicates the center of the domain that coincides with the fault nomograph; the dashed lines show the lower and the upper boundaries of the fault domain.In a 16000 kVA 110/6 kV transformer with the same gas composition, discharges traces were detected due to nut unfastening on the low-voltage winding bushing pin. In [18] for the equipment with the same gas combination, the diagnosis of "partial discharges" was made, and in [19] – "high energy discharges". In [35], fault nomograph dynamics under the fault growth in the autotransformer in 220 kV substation "Buran" is analysed. Figure 13 presents fault nomograph dynamics under the fault growth. The figure shows that for the incipient fault the nomograph coincided with the nomograph given in Fig. 13a, and with the fault growth the nomograph began to correspond to creeping discharges. As one can see from the figure, the fault growth causes decrease in the concentrations of unsaturated hydrocarbons (C_2H_2 and C_2H_4) and increase in the concentrations of saturated hydrocarbons, namely methane in this case, and hydrogen. Application of the Duval Triangle method to diagnosis of the equipment from the group of faults No. 12 (see Fig. 12b) revealed the existence of low energy and high energy discharges. At the same time, as Fig. 12b shows, the diagnosis of low energy discharges was made for the equipment with higher concentration of acetylene and lower concentration of ethylene.

High energy discharges (fault group 13)

The content of gases to defects from the group No. 13 is fully compliant with high energy density discharges or arc discharges. It should be noted that in field conditions this gas combination may correspond to a number of faults. For example, in a 110 kV current transformer, the

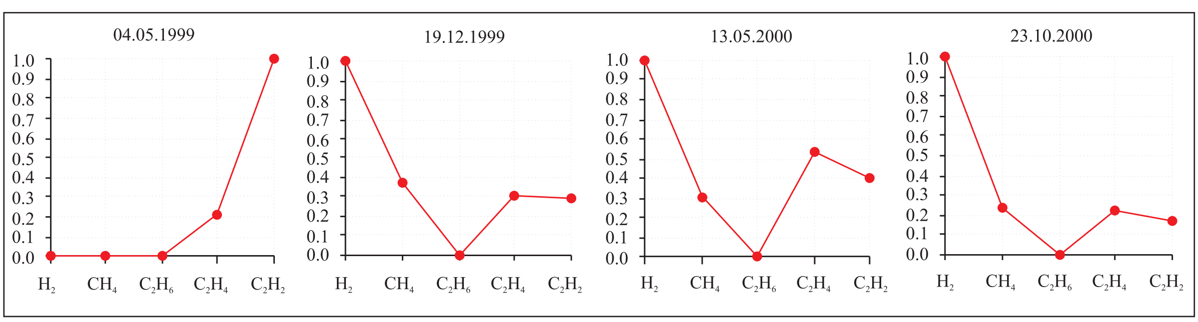

Fig. 13. Gas composition dynamics under fault growth in the autotransformer of 220 kV substation "Buran"

primary winding breaking from the coil support was detected. In a 25000 kVA 35/10 kV transformer, overheating and burnout of the on-load top changer contacts. The cause of a 31.500 kVA 110/10/6 kV transformer failure was a turn insulation fault. A 125000 kVA 220/110 kV autotransformer was damaged by creeping discharge [25]. In a 40000 kVA 330 kV transformer, on the high-voltage winding, two deformation waves and the coils flashover were detected. In a high-voltage bushing 500 kV, creeping discharge on the insulating cylinder was identified. In a bushing 220/2000 filled with oil GK, X-wax deposition was found. In most publications, for example [7, 16, 20, 27], the diagnosis made for equipment with such gas composition was arcing.

It should be noted that such gas combination may be caused by a reason different from the fault growth within the equipment. For example, the author of [13] introduces nomographs of faults specific to arch discharges with maximum concentration of acetylene. These nomographs were based on the DGA data from 31.500 kVA 110/35/6 kV transformer under short circuit current action. Figure 14a presents the graphical domain plotted with DGA results for the equipment with high energy arcing (the solid line indicates the center of the domain that coincides with the fault nomograph; the dashed lines mark the lower and the upper boundaries of the fault domain). Figure 14b shows Duval Triangle based diagnosis results for equipment with high energy discharges. As one can see from the figure, depending on ethylene concentration, the Duval Triangle detected the existence of both high energy discharges and low energy discharges.

Analysis of the data given in Table 1 reveals that gas concentration in the equipment with the same fault varies quite widely, which may cause difficulty in identifying the type of fault with application of this criterion. It is evident that despite a wide range of deviation, probabilities of realization of one or another gas percentage significantly differ. As an example, bar graphs of empirical gas percentage distribution in the equipment with high energy discharges from group of faults No. 13. The bar-graphs were plotted with application of the author's software program "ZR" intended for analysing laws of random value distributions [36]. Figure 15a presents a bar graph of empirical hydrogen percentage distribution in the equipment with high energy discharges from group of faults No. 13. From the figure, one can see that the distribution of hydrogen concentration values is somewhat symmetric with respect to the mathematical expectation. The probability of realization reaches maximum for hydrogen concentration levels ranging from 20 to 24%. As one can see from Fig. 15b, methane percentage distribution in the equipment with high

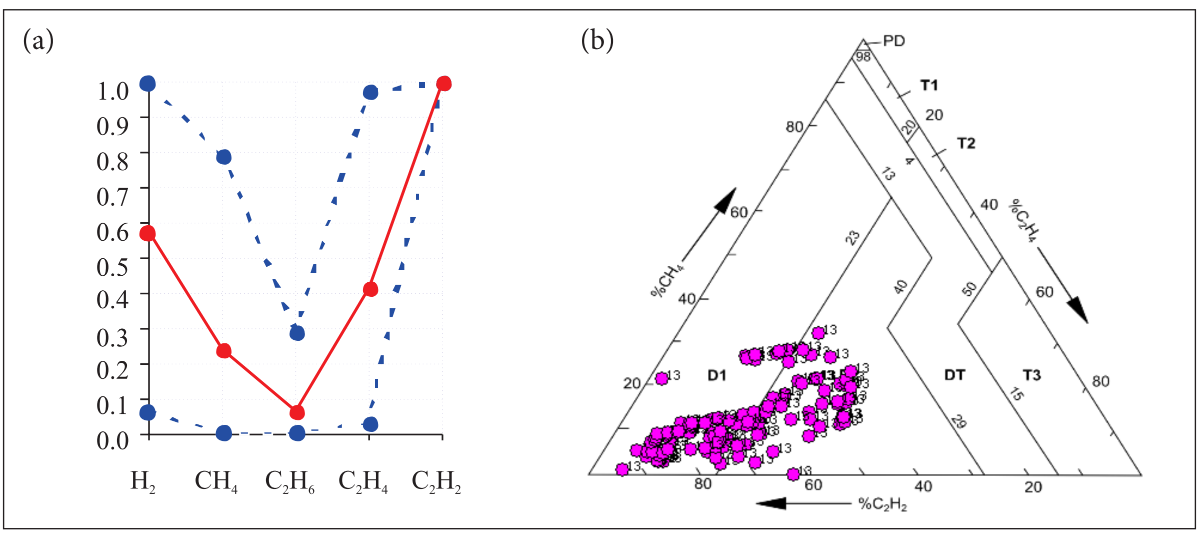

Fig. 14. Graphical domain and diagnosis results of high energy discharges (fault group 13) with Duval Triangle application: (a) graphical domain, (b) results of Duval Triangle based diagnosis

energy discharges is asymmetrical about the mathematical expectation. Realization of methane concentration at the level of 4–5% is the most probable; with further growth of methane concentration, the probability of its realization decreases. Also, ethane percentage distribution is asymmetrical about the mathematical expectation (see Fig. 15c). The figure demonstrates that probability of realization (82.5%) is the highest for low ethane concentration levels (1–4%); with ethane concentration growth their realization becomes less probable. The obtained bar graphs of empirical ethylene concentration distribution in the equipment with high energy discharges (Fig. 15d) currently fail to allow unambiguously concluding about the distribution symmetry despite the mathematical expectation being located in the center of the analysed range.

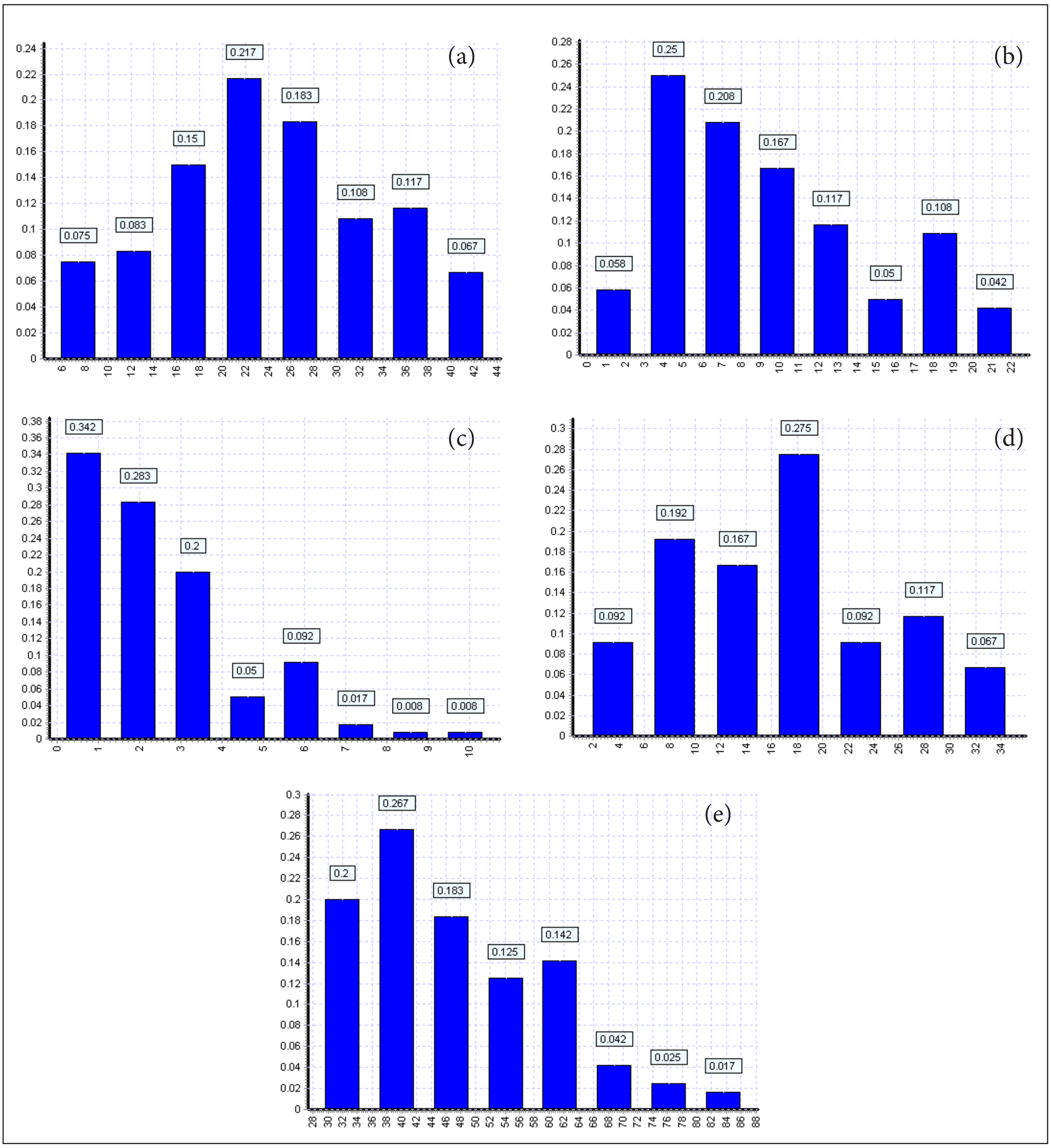

Fig. 15. Bar graphs of empirical gas percentage distribution in the equipment with high energy discharges from group of faults No. 13: (a) H_2, (b) CH_4, (c) C_2H_6, (d) C_2H_4, (e) C_2H_2

The most probable is ethylene concentration realization at the level of 16–20%. In spite of the fact that acetylene is the key gas in the equipment analysed and, consequently, acetylene coordinate is equal to 1 in all the graphical domains, Table 1 demonstrates that acetylene percentage varies significantly. From the bar graph given in Fig. 15e, it is evident that acetylene percentage distribution is asymmetrical about the mathematical expectation which is shifted to the region of relatively low levels. The probability of acetylene percentage realization reaches maximum for levels of 38–42%; further growth of acetylene concentration results in decreasing the probability of its realization. The results presented make it clear that precise identification of the fault requires both knowledge of the gas composition in the equipment with one or another fault and information on the probability of the gas percentage realization. It is especially important for faults with close gas compositions.

CONCLUSIONS

1. Gas ratios for some faults with acetylene being the key gas may have values that correspond to various faults, which makes their identification difficult and may result in incorrect diagnosis.

2. Fault nomographs plotted on the DGA data from faulty equipment with acetylene being the key gas may differ significantly both from each other and from the reference nomographs regulated by the current standards.

3. Duval Triangle application sometimes fails to make precise diagnosis. In the author's opinion, it results from neglecting concentrations of hydrogen and ethane in the Duval Triangle method.

4. The plotted bar graphs of empirical distributions revealed that despite significant spread of gas percentage values, the probability of one or another gas percentage realization varies considerably. To identify the type of fault correctly, it is necessary not only to know gas percentage values in equipment with one or another fault, but also to have information on the probability of their realization. It is especially essential for faults characterized by close gas compositions.

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DIDELE ACETILENO KONCENTRACIJA PASIŽYMINČIŲ DUJŲ, SUSIDARANČIŲ DĖL IZOLIACINĖS ALYVOS PAŽEIDIMŲ, SUDĖTIES ANALIZĖ, TAIKOMA ALYVA UŽPILDYTIEMS ĮRENGINIAMS

Santrauka

Straipsnyje pateikiami izoliacinėje alyvoje, kuria užpildomi aukštos įtampos įrenginiai, ištirpusių dujų, susidarančių dėl alyvos pažeidimų, tyrimo rezultatai. Tirti atvejai, kai dujų sudėtyje dominuoja acetilenas, iš viso 239 atvejai. Išskirta 13 alyvos pažeidimų tipų, kurie toliau skaidomi į smulkesnes grupes pagal ištirpusių dujų santykį, jų koncentraciją ir pažeidimų nomogramas. Kiekvienam tipui sudaryti grafiniai domenai, kurie, skirtingai nei nomogramos, leidžia atsižvelgti į galimą koordinačių poslinkį. Pristatomas grafiniais domenais grindžiamas pažeidimų identifikavimo būdas. Trumpai aprašomi pažeidimų tipai, pateikiama pažeidimų identifikavimo, kuriuos atliko skirtingi tyrėjai, pavyzdžių. Atlikta įrangos diagnostikos duomenų lyginamoji analizė remiantis Duvalio trikampio (*Duval Triangle*) metodu. Nustatyta, kad skirtingais diagnostikos metodais gauti duomenys gali labai skirtis tarpusavyje ir nuo faktinių duomenų. Pateikti rezultatai rodo, kad tinkamai interpretuojant ištirpusių dujų analizės duomenis galima tiksliau identifikuoti pažeidimus.

Raktažodžiai: ištirpusių dujų analizė, aukštos įtampos įranga, pažeidimų identifikavimas, acetileno koncentracija, elektros iškrova, dujų santykis, dujų procentinė dalis, Duvalio trikampis, gedimų nomogramos, grafinis domenas