УДК 621.31:543.2:519.2 **doi: 10.20998/2313-8890.2026.02.13**

Shutenko Oleg, Candidate of Technical Sciences, Associate Professor, Associate Professor of the Department of Electric Power Transmission, +38(067)122-80-21, oleg.shutenko@khpi.edu.ua, ORCID ID: 0000-0003-3141-7709
National Technical University «Kharkiv Polytechnic Institute»
2 Kyrpychova St., Kharkiv, 61002
Dovgalyuk Volodymyr, postgraduate student of the Department of Electric Power Transmission, +38(068)653-12-28, volodymyr.dovhaliuk@ieee.khpi.edu.ua, ORCID ID: 0009-0001-6313-8053
National Technical University «Kharkiv Polytechnic Institute»
2 Kyrpychova St., Kharkiv, 61002

ANALYSIS OF THE EFFECT OF OIL PROTECTION TYPE ON THE DISSOLVED GAS CONTENT IN SERVICEABLE TRANSFORMERS

Abstract. *The results of an analysis of the concentration of gases dissolved in oil are presented for 426 serviceable 110-330 kV transformers of the non-hermetic construction. The analysis revealed that, for transformers of non-hermetic execution, the presence of free access to atmospheric oxygen leads not only to accelerated oxidation of the oil compared to transformers with nitrogen and film protection, but also to significant differences, both quantitative and qualitative, in the composition of gases dissolved in the oil. In particular, the analysis revealed an extremely low hydrogen content (in oil samples taken from transformers of non-hermetic construction, a maximum hydrogen content was detected in only 3.23 % of all samples). This characteristic is due to the diffusion of hydrogen into the atmosphere, owing to its low solubility coefficient in oil. Another characteristic feature of the gas content in the oil of serviceable transformers of non- hermetic construction is the abnormally high ethylene content (in oil samples taken from the tanks of transformers of non- hermetic construction, a maximum ethylene content was detected in 47.96 % of all samples). However, such a high ethylene content is not caused by the degradation of hydrocarbons present in transformer oils, but is the result of secondary oxidative reactions that occur intensively in the presence of free oxygen from the air. The characteristics of the qualitative composition of the oil samples described above are also reflected in the quantitative analysis of gas concentration levels. In particular, the number of oil samples in which the concentration of a particular gas is below the chromatograph's detection limit is determined not only by the amount of energy required to break the chemical bonds between specific hydrocarbon compounds, but also by the solubility coefficients of that gas in the oil. The analysis showed that the proportion of samples from serviceable transformers in which gases concentrations exceeded the limit values corresponding to Level III (i.e. the presence of a defect) did not exceed 10 %. However, the percentage of samples exceeding Level III varied significantly for each gas. The paper also presents the results of an analysis of the distribution laws governing the ratios and gases growth rates in serviceable transformers of non-hermetic construction. The results presented in the article indicate that the type of transformer oil protection has a significant influence on the content of gases dissolved in the oil and, consequently, that this influence must be taken into account when adjusting the limit values for gases concentrations and growth rates.*

Keywords: *diagnostics, power transformers, non-hermetic construction, dissolved gas analysis, concentration distribution, gas with the highest concentration, diffusion of gases into the atmosphere, gas growth rate, Laplace distribution, gas ratio, Weibull distribution, correlation between gases dissolved in oil.*

Шутенко Олег Володимирович, канд. техн. наук, доцент, доцент кафедри передачі електричної енергії, +38(067)122-80-21, oleg.shutenko@khpi.edu.ua, ORCID ID: 0000-0003-3141-7709
Національний технічний університет «Харківський політехнічний інститут»
вул. Кирпичова, 2, Харків, 61002
Довгалюк Володимир Вікторович, аспірант кафедри кафедри передачі електричної енергії, +38(068)653-12-28, volodymyr.dovhaliuk@ieee.khpi.edu.ua, ORCID ID: 0009-0001-6313-8053
Національний технічний університет «Харківський політехнічний інститут»
вул. Кирпичова, 2, Харків, 61002

АНАЛІЗ ВПЛИВУ ТИПУ ЗАХИСТУ МАСЕЛ НА ВМІСТ РОЗЧИНЕНИХ ГАЗІВ У СПРАВНИХ ТРАНСФОРМАТОРАХ

Анотація. *Наведено результати аналізу вмісту розчинених у маслі газів для 426 справних трансформаторів, напругою 110-330 кВ негерметичної конструкції. За результатами аналізу встановлено, що для трансформаторів негерметичного виконання наявність вільного доступу кисню повітря призводить не тільки до прискореного окислення масел порівняно з трансформаторами з азотним і плівковим захистом, але й до суттєвих як кількісних, так і якісних відмінностей у складі розчинених в маслі газів. Зокрема, за результатами аналізу встановлено вкрай низький вміст водню (у пробах масла з баків трансформаторів негерметичної конструкції максимальний вміст водню виявлено лише у 3,23 % усіх проб). Ця особливість зумовлена процесами дифузії водню в атмосферу через низьке значення його коефіцієнта розчинності в маслі. Ще однією характерною особливістю газовмісту масел у справних трансформаторах негерметичної конструкції є аномально високий вміст етилену (у пробах масла з баків трансформаторів негерметичної конструкції максимальний вміст етилену виявлено у 47,96 % усіх проб). При цьому такий високий вміст етилену обумовлений не процесами деструкції вуглеводнів, що входять до складу трансформаторних масел, а є наслідком вторинних окислювальних реакцій, які інтенсивно розвиваються в умовах вільного доступу кисню повітря. Наведені особливості якісного складу проб масел також відображаються під час кількісного аналізу рівнів концентрації газів. Зокрема, кількість проб масел, у яких концентрація того чи іншого газу знаходиться нижче межі виявлення хроматографом, визначається не тільки кількістю енергії, необхідною для розриву хімічних зв'язків між тими чи іншими вуглеводневими сполуками, але й значеннями коефіцієнтів розчинності того чи іншого газу в маслі. Як показав аналіз, кількість проб із справних трансформаторів, у яких зафіксовано перевищення концентрацій газів понад граничні значення, що відповідають рівню III (тобто наявності дефекту), не перевищує 10 %. При цьому відсоток перевищення рівня III для кожного з газів істотно відрізняється. Також у роботі наведено результати аналізу законів розподілу співвідношень і швидкостей наростання газів у справних трансформаторах негерметичної конструкції. Наведені в статті результати свідчать про наявність значного впливу типу захисту трансформаторних масел на вміст розчинених у маслі газів і, як наслідок, про необхідність врахування цього впливу при коригуванні граничних значень концентрацій і швидкостей наростання газів.*

Ключові слова: *діагностика, силові трансформатори, негерметична конструкція, аналіз розчинених в маслі газів, розподіл за рівнями концентрацій, газ із максимальним вмістом, дифузія газів в атмосферу, швидкості наростання концентрацій газів, розподіл Лапласа, співвідношення газів, розподіл Вейбулла, кореляція між розчиненими вмаслі газами.*

Introduction. Against the backdrop of relentless attacks on Ukraine's energy infrastructure, ensuring the operational reliability of existing power grid equipment is not merely a pressing issue, but a matter of national importance. It is fundamentally impossible to address this issue without developing new methods and improving existing ones for diagnosing the condition of electrical power equipment.

One method of early diagnosis that not only enables the detection of faults in oil-filled equipment at an early stage but also identifies their type is dissolved gas analysis (DGA). This method was first introduced in the late 1970s in England. Currently, there is not a single major energy company that does not use the DGA method to diagnose the condition of oil-filled equipment in power grids. The physical basis of the method lies in the fact that both electrical discharges and localised overheating, as well as combinations of these, lead to the destruction of transformer oil molecules and the formation of gases. It is believed that the composition of the gases released is determined by the amount of energy released and corresponds precisely to a particular type of defect.

When interpreting DGA results to identify the presence of a defect, criteria based on concentration thresholds and gases growth rate thresholds are used. To identify the type of defect, the values of gases ratios, or the values of the percentage content of gases, or the values of the ratios of gases to the gas with the maximum content are used. That is, the procedure for interpreting DGA results includes both a quantitative analysis of the released gases and their qualitative composition. Obviously, the accuracy of the interpretation of DGA results – and, consequently, the operational reliability of the equipment being diagnosed – will largely depend on how correctly the threshold values for gases concentrations and growth rates are defined, as well as on how appropriately the diagnostic regions are defined within a given diagnostic space.

It is fundamentally impossible to fulfil these conditions without taking into account the factors that influence the quantitative and qualitative content of gases dissolved in the oil, in both serviceable and defective equipment. This article presents the results of an analysis of the influence of the type of oil protection on the gas content in serviceable transformers of non-hermetic construction.

Analysis of publications. Currently, procedures for interpreting DGA results – both in terms of defect detection and defect classification – are governed by existing international and national standards [1–3], as well as by methods that have become "classic" [4–11] and relatively new proprietary techniques [12–20]. Despite the diversity of existing methods, research into improving the reliability of DGA result interpretation methods continues. One of the highest-priority areas is the use of modern mathematical tools. Thus, in [21, 22], machine learning methods were used for defect type recognition; specifically, in [21] the support vector machine (SVM) method was used, and in [22] the relevance vector machine (RVM) method. In publication [23], fuzzy logic was used for the same purposes; in [24], the extreme learning machine method was employed; in [25], the Adaptive Neuro-Fuzzy Inference System was used; and in [26], K-Nearest Neighbours (KNN) was applied. In [27], a hybrid model was proposed that combines a deep convolutional neural network with a long short-term memory (LSTM) network for detecting internal defects in transformers, achieving a training accuracy of 95 % and a testing accuracy of 93.3 %. In [28], an architecture of optimised machine learning algorithms was developed, combining statistical feature selection based on the χ^2 criterion with hyperparameter optimisation algorithms using the random search method, with the aim of improving the accuracy of transformer defect classification based on DGA data, thereby overcoming the limitations of traditional methods and enhancing diagnostic accuracy. In [29], a new hybrid index system incorporating artificial intelligence is proposed, capable of overcoming the limitations of traditional diagnostic methods. The proposed methodology generalises the various DGA results of traditional methods into a single weighted index, which, in turn, becomes the subject of fine-tuning for machine learning ensemble classifiers.

Concurrently, research continues into the gas content of oil-filled equipment in various conditions. Thus, [30–37] present the results of an analysis of gases content in equipment with defects of various types, including combined defects. A considerable number of publications are also devoted to the analysis of random gas formation in serviceable oil-filled equipment [38–41]. At the same time, the gas content of oils in serviceable transformers of different designs and with different types of oil protection has not been sufficiently investigated, which prompted the writing of this article.

Presentation of the main research material. To investigate the gas content in the oil of serviceable transformers of non-hermetic construction, the results of DGA were used for 110 kV and 330 kV transformers in operation across four regions of Ukraine. In total, data for 426 transformers of non-hermetic construction were analysed. In the first stage of the research, an analysis of gas distribution by concentration levels was carried out in accordance with the recommendations given in [3]. According to this methodology, gas concentration values are compared with established levels corresponding to the normal or defective technical condition of the equipment. If the concentration of at least one gas corresponds to Level 2, a decision regarding the technical condition of the transformer is made based on an analysis of the rate of increase in the total concentration of hydrocarbon gases. A defect is considered to be present if this rate exceeds 30 ml/day. If the concentration of at least one of the gases corresponds to Level 3, a fault is predicted regardless of the gas growth rate.

The standardised concentration levels (indicated in bold), as well as the results of the analysis of gas distributions according to these levels, are given in Table 1. During the analysis, it should be noted that for transformers of non-hermetic construction, the determined gas concentrations in the oil do not correspond to the actual volumes of gases formed due to their diffusion into the atmosphere. The rate of gas diffusion from the main volume of oil into the atmosphere is determined by the solubility coefficients of gases in oil, which vary for different gases and change significantly with temperature. Consequently, the lower the solubility of a gas in transformer oil, the greater the amount of gas that diffuses into the atmosphere. Thus, the gas concentrations measured at any given time in non-hermetic equipment reflect the difference between the amount of gas generated and the amount of gas that has diffused into the surrounding environment. Consequently, the measured concentrations may be significantly lower than the actual values of the generated gases [42].

Table 1 – Results of the analysis of gas distribution by concentration levels in 110–330 kV transformers of non-hermetic construction

Concentration levels	**Gases**				
	H_2	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**
Below the chromatograph’s limit of detection	5161 (69,81 %)	2304 (31,2 %)	1957 (26,47 %)	1090 (14,7 %)	4551 (61,6 %)
Below the analytical limit of quantification	**0,005**	**0,0015**			**0,0003**
	2106 (28,49 %)	3342 (45,2 %)	4485 (60,67 %)	3763 (50,9 %)	1602 (21,7 %)
Level I	**<0,01**	**<0,005**		**<0,0015**	**<0,00005**
	71 (0,96 %)	1160 (15,7 %)	619 (8,37 %)	-	-
Level II	**0,01-0,015**	**0,005-0,012**	**0,0015-0,01**		**0,00005-0,001**
	26 (0,35 %)	367 (4,96 %)	153 (2,07 %)	1914 (25,9 %)	982 (13,3 %)
Level III	**>0,015**	**>0,012**	**>0,01**		**>0,001**
	29 (0,39 %)	220 (2,98 %)	179 (2,42 %)	626 (8,5 %)	258 (3,5 %)

Since gas diffusion rates depend to a large extent on the design features of transformers, the temperature of the oil and the ambient environment, and other factors [42], it is practically impossible to obtain a reliable estimate of the actual concentrations of gases formed in the oil of non-hermetic equipment based on the results of periodic monitoring. Consequently, the results presented in Table 1 do not reflect the absolute values of the gases formed, but rather the difference between gas formation and gas removal processes via diffusion.

Analysis of hydrogen concentrations. Analysis of the data in Table 1 shows that, out of 7,393 hydrogen concentration measurements, in 5,161 cases (69.81 %) the values did not exceed the gas chromatograph’s detection limit. A further 2,106 values (28.49 %) did not exceed the analytical detection limit, which, according to [3], is 0.005 % vol. Only 71 measurements (0.96 %) corresponded to Level I (less than 0.01 % vol.). Level II (0.01–0.015 % vol.) was met by 26 values (0.35 %), and Level III (over 0.015 % vol.) by 29 values (0.39 %).

Thus, the vast majority of hydrogen concentration measurements in oils from serviceable transformers of non-hermetic construction are characterised by values not exceeding the analytical detection limit, and instances of exceeding the limit levels are rare.

Analysis of methane concentrations. Methane concentrations not exceeding the detection limit of the gas chromatograph were recorded in 2,304 oil samples, accounting for 31.2 % of all measurements for this gas. A further 3,342 values (45.2 %) did not exceed the analytical detection limit (0.0015 % by volume). Level I (up to 0.005 % vol.) included 1,160 values (15.69 %), Level II (0.005–0.012 % vol.) – 367 values (4.96 %), and 220 values (2.98 %) were classified as Level III (above 0.012 % by volume).

Thus, methane is characterised by a significantly higher proportion of values exceeding the analytical detection limit compared to hydrogen.

Analysis of ethane concentrations. Ethane concentrations did not exceed the detection limit in 1,957 oil samples (26.47 %). In 4,485 samples (60.67 %), the ethane concentration values were below the analytical detection limit (0.0015 % by volume). 619 values (8.37 %) were classified as Level I (up to 0.005 % by volume), 153 values (2.07 %) were classified as Level II (0.005–0.01 % by volume), and 179 values (2.42 %) as level III (above 0.01 % by volume).

Analysis of ethylene concentrations. Of the 7,393 ethylene concentration measurements, 1,090 (14.74 %) did not exceed the chromatograph's detection limit, whilst 3,763 values (50.90 %) were below the analytical recognition threshold, which for ethylene is 0.0015 % by volume. It should be noted that for this gas, the analytical detection limit coincides with the upper limit of level I; therefore, all such values are subsequently classified as concentrations not exceeding the analytical detection limit.

Concentration values corresponding to Level II (0.0015–0.01 % by volume) were recorded in 1,914 samples (25.89 %), and those corresponding to Level III (above 0.01 % by volume) in 626 samples (8.47 %).

Analysis of acetylene concentrations. Acetylene concentrations not exceeding the detection limit were recorded in 4,551 oil samples (61.56 %); in a further 1,602 cases (21.67 %), the concentrations were below the analytical recognition threshold. Since the analytical threshold for acetylene (0.0003 % by volume) exceeds the upper limit of Level I, concentration values exceeding the analytical threshold but below Level III were classified as level II (0.00005–0.001 % by volume).

Level II comprises 982 values (13.28 %), and Level III (above 0.001 % vol.) comprises 258 values (3.49 %).

Summary of results by concentration level. Despite the diffusion of gases into the environment and, consequently, a reduction in the observed concentrations, the proportion of measurements corresponding to the defect level (Level III) is: for ethylene – 8.5 %, acetylene – 3.5 %, methane – 2.98 %, ethane – 2.42 %, hydrogen – 0.39 %. However, there are no actual defects in the equipment under analysis.

The analysis showed that the main causes of short-term increases in gas concentrations in serviceable transformers are emergency conditions in the electrical network (short circuits, overvoltages), as well as increased load. Furthermore, such abnormally high gas concentration values may result from methodological errors during GC analysis, particularly if the chromatograph is not correctly calibrated. Summarising the data presented, it can be stated that in transformers of non-hermetic construction, ethylene has the highest number of concentration values exceeding the analytical detection limit – 2,540 measurements (34.36 %). Next in terms of frequency of exceedances are methane – 1,747 (23.63 %), acetylene – 1,240 (16.77 %), ethane – 951 (12.86 %) and hydrogen – 126 (1.70 %).

Analysis of results based on the criterion of the gas with the highest concentration. Similar conclusions can be drawn by analysing the distribution of the results of the analysis of dissolved gases in oil based on the criterion of the gas with the highest concentration. The results of this analysis are presented in Table 2.

As shown in Table 2, in 942 out of 7,393 cases, the concentrations of hydrogen and hydrocarbon gases were below the chromatograph’s detection limit, accounting for 12.74 % of all measurements. The largest proportion of samples corresponded to the highest concentrations of ethylene – 47.96 %. Next in prevalence is methane – 20.48 %, followed by ethane – 5.15 % and acetylene – 5.03 %. The smallest number of samples with the highest concentration is characteristic of hydrogen – 3.23 %.

Table 2 – Distribution of DGA results for gas with the highest concentration

Gas with the highest concentration	**Number of measurements**	**%**
Below the detection limit	942	12,74
H_2	239	3,23
CH_4	1514	20,48
C_2H_6	381	5,15
C_2H_4	3545	47,96
C_2H_2	372	5,03
CH_4-C_2H_4	75	1,01
CH_4-C_2H_6	22	0,30
CH_4-C_2H_2	7	0,09
CH_4-H_2	15	0,20
C_2H_4-C_2H_6	66	0,89
C_2H_4-C_2H_2	91	1,23
C_2H_4-H_2	10	0,14
C_2H_6-C_2H_2	32	0,43
CH_4-C_2H_4-C_2H_6	35	0,47
CH_4-C_2H_4-C_2H_2	1	0,01
CH_4-C_2H_4-H_2	2	0,03
CH_4-C_2H_6-C_2H_2	3	0,04
CH_4-C_2H_6-H_2	1	0,01
C_2H_4-C_2H_6-C_2H_2	33	0,45
C_2H_4-C_2H_6-H_2	2	0,03
CH_4-C_2H_4-C_2H_6-C_2H_2	2	0,03
CH_4-C_2H_4-C_2H_6-H_2	3	0,04
In total	*7393*	*100*

The proportion of samples in which several gases simultaneously have the maximum concentration value is relatively small and totals 5.41 % of the total number of measurements.

Distribution of gases by concentration levels in samples with the highest content of various gases. Since the highest concentration values in the analysed sample were recorded for all five hydrocarbon gases and hydrogen, it is appropriate to analyse how the concentrations of all gases are distributed by level in oil samples where a specific gas has the highest concentration. The results of this analysis are presented in Table 3.

Table 3 – Distribution of gases by concentration levels in oil samples with the highest concentrations of various gases

Gas	**Concentration**				
	Below the detection limit	**Below the analytical level of recognition**	**Level I**	**Level II**	**Level III**
Maximum concentration of H_2					
H_2	-	160	49	18	12
	0,000	66,946	20,502	7,531	5,021
CH_4	13	140	69	14	3
	5,439	58,577	28,870	5,858	1,255
C_2H_4	21	138	-	79	1
	8,787	57,741	0,000	33,054	0,418
C_2H_6	38	184	14	1	2
	15,900	76,987	5,858	0,418	0,837
C_2H_2	151	40	-	36	12
	63,180	16,736	0,000	15,063	5,021
Maximum concentration of CH_4					
H_2	802	686	14	4	8
	52,972	45,310	0,925	0,264	0,528
CH_4	-	629	601	180	104
	0,000	41,546	39,696	11,889	6,869
C_2H_4	92	1070	-	288	64
	6,077	70,674	0,000	19,022	4,227
C_2H_6	140	986	277	53	58
	9,247	65,125	18,296	3,501	3,831
C_2H_2	1115	273	-	114	12
	73,646	18,032	0,000	7,530	0,793
Maximum concentration of C_2H_4					
H_2	2400	1124	8	4	9
	67,701	31,707	0,226	0,113	0,254
CH_4	984	1909	417	143	92
	27,757	53,850	11,763	4,034	2,595
C_2H_4	-	1583	-	1432	530
	0,000	44,654	0,000	40,395	14,951
C_2H_6	804	2383	221	55	82
	22,680	67,221	6,234	1,551	2,313
C_2H_2	2012	903	-	491	139
	56,756	25,472	0,000	13,850	3,921
Maximum concentration of C_2H_6					
H_2	335	46	-	-	-
	87,927	12,073	0,000	0,000	0,000
CH_4	110	182	56	20	13
	28,871	47,769	14,698	5,249	3,412
C_2H_4	39	277	-	53	12
	10,236	72,703	0,000	13,911	3,150
C_2H_6	-	218	86	42	35
	0,000	57,218	22,572	11,024	9,186

Continued from Table 3.

Gas	Concentration				
	Below the detection limit	Below the analytical level of recognition	Level I	Level II	Level III
C_2H_2	203	99	-	76	3
	53,281	25,984	0,000	19,948	0,787
Maximum concentration of C_2H_2					
H_2	347	25	-	-	-
	93,280	6,720	0,000	0,000	0,000
CH_4	161	196	8	2	5
	43,280	52,688	2,151	0,538	1,344
C_2H_4	49	270	-	37	16
	13,172	72,581	0,000	9,946	4,301
C_2H_6	101	268	3	-	-
	27,151	72,043	0,806	0,000	0,000
C_2H_2	-	80	-	205	87
	0,000	21,505	0,000	55,108	23,387

Samples with the maximum hydrogen concentration. As can be seen from Table 3, in samples with the maximum hydrogen concentration, the vast majority of concentration values for all gases do not exceed the analytical detection limit or are below the detection limit. In particular, out of 239 samples, hydrogen concentrations exceeded the analytical threshold in only 33.03 % of cases, methane in 35.96 %, ethylene in 33.47 %, and acetylene in only 7.11 % of observations.

Given that, for ethylene, the analytical detection limit coincides with the upper limit of Level I, whilst the corresponding values for acetylene fall within Level II, it can be concluded that in samples with a maximum hydrogen concentration exceeding 60%, the concentrations of all gases are below the analytical detection limit.

Samples with a maximum methane concentration. In oil samples with a maximum methane concentration, the concentrations of gases exceeding the analytical detection limit are: for hydrogen – 1.72 %, for methane – 58.45 %, for ethylene – 23.25 %, for ethane – 25.62 %, and for acetylene – only 8.32 %.

Thus, in samples with the highest methane content, the most common gases, apart from methane itself, are ethylene and ethane.

Samples with the highest ethane concentration. Ethane is one of the gases for which the number of samples with the highest concentration is relatively small. Only acetylene has a smaller number of such samples. Of the 381 samples in which the maximum concentration of ethane was recorded, the proportion exceeding the analytical detection limit was: 42.78 % for ethane, 23.36 % for methane, 17.06 % for ethylene and 20.73 % for acetylene. At the same time, hydrogen concentrations in all samples did not exceed the analytical detection limit.

Samples with the highest concentration of ethylene. The largest number of measurements with the highest concentration was for ethylene – 3,545 samples, accounting for 47.96 % of the total sample. In samples with the highest ethylene content, the following concentrations do not exceed the analytical detection limit: 99.4 % of hydrogen concentrations, 81.6 % of methane concentrations, 44.65 % of ethane concentrations and 82.2 % of acetylene concentrations.

This indicates that in such samples, among all gases other than ethylene, methane most frequently exceeds the analytical detection limit, followed by acetylene and ethane, whilst hydrogen is characterised by the lowest concentration values.

Samples with the highest acetylene concentration. The analysis showed that in fault-free equipment, acetylene concentrations may exceed those of other gases. However, unlike samples with the highest ethane concentration, the proportion of samples with the highest acetylene content, in which concentrations correspond to Level III, is 23.4 %.

At the same time, the concentrations of other gases in such samples generally do not exceed the analytical detection limit: 100 % of hydrogen concentrations, 96 % of methane, 85.75 % of acetylene and 99.2 % of ethane concentrations remain below the established threshold.

This means that deciding on the defective condition of equipment solely on the basis of acetylene concentrations exceeding the analytical detection threshold, without comprehensively taking into account the concentrations of other gases, as stipulated in [3], may lead to the erroneous rejection of serviceable equipment.

Generalisation based on the key gas criterion. The total number of oil samples in which several gases simultaneously have the highest concentration is 400, or 5.41 % of the entire sample. The composition of such samples is indicative: ethylene is present in 79.95 % of them, ethane in 49.62 %, methane in 41.6 %, acetylene in 34.08 %, and hydrogen in only 8.02 %.

For samples containing multiple gases, the maximum concentrations are characterised by extremely low values. Even in cases where two gases have the highest concentration, the proportion of samples in which both gases exceed the analytical detection limit remains negligible.

Thus, in the absence of defects in non-hermetically sealed transformers, the gases with the highest concentration are predominantly ethylene and methane, whilst the content of hydrogen and ethane remains extremely low.

The results obtained do not align with traditional views on the gas composition of transformer oil in serviceable equipment. Typically, the process of gas formation in oil is considered from the perspective of the energy required to break the chemical bonds in hydrocarbon molecules. Under low-temperature conditions, hydrogen and saturated hydrocarbons (methane, ethane) are primarily formed, whereas unsaturated hydrocarbons (ethylene, acetylene) are formed mainly as a result of high-temperature processes [43]. This approach schematically illustrates the temperature dependence of gas formation [44], shown in Fig. 1.

According to this model, in normally operating, serviceable transformers, the gases present in the highest concentrations should be hydrogen and methane, whilst unsaturated hydrocarbons should be virtually absent. However, as can be seen from the results presented in Tables 1 and 2, this pattern is not observed in non-hermetically sealed transformers.

According to classical theories, the predominance of hydrogen in the gas mixture of transformer oil is due to the fact that breaking hydrogen bonds requires the least amount of energy. This is precisely why, in hermetically sealed transformers, hydrogen is usually the gas with the highest concentration [42]. At the same time, the results presented in Tables 1 and 2 show that the number of samples with the highest hydrogen concentration in transformers of non-hermetic construction is minimal compared to other gases. This feature can be explained by the low solubility of hydrogen in transformer oil. Consequently, a significant portion of the hydrogen rapidly diffuses into the atmosphere, and its concentration in the oil remains low even in the presence of gas-forming processes.

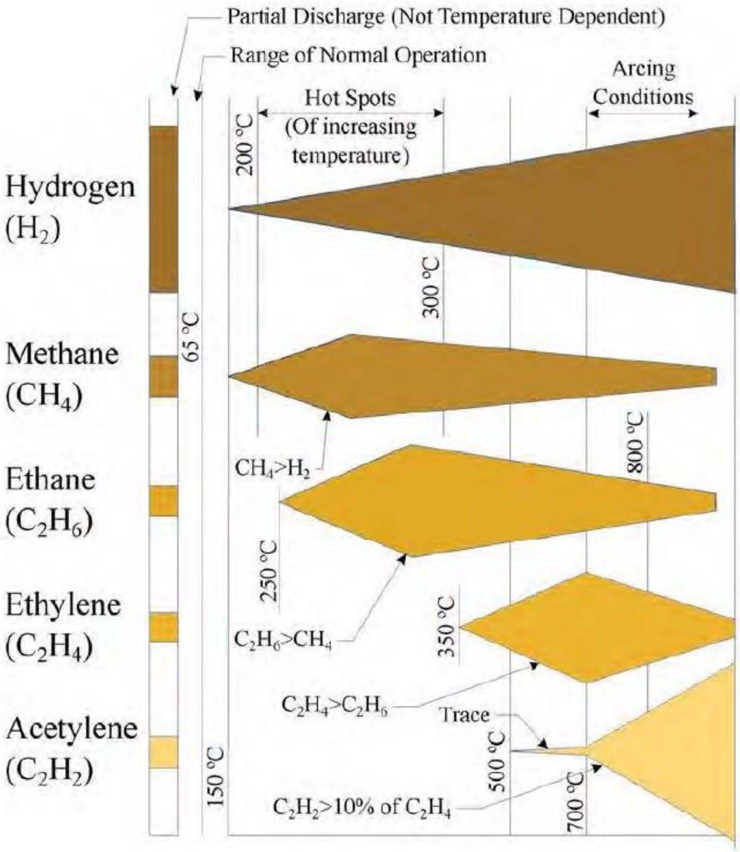


Figure 1 – Temperature dependence of gas formation processes in transformer oil

Thus, the low hydrogen content in the oils of transformers of non-hermetic construction does not indicate the absence of gas-forming processes, but is a consequence of the intensive diffusion of this gas into the surrounding environment. As shown in [41, 45, 46], the unusually high ethylene content in transformers of non-hermetic construction is caused by the oxidation of transformer oil by atmospheric oxygen in the presence of a copper catalyst. These reactions result in the formation of unsaturated hydrocarbons, specifically ethylene, propylene, 1-butene and 2-butene. In addition to unsaturated hydrocarbons, hydrogen and methane are also formed during the oxidation process. However, due to their low solubility in oil and intense diffusion, these gases do not accumulate in significant concentrations, unlike ethylene, which has higher solubility and, consequently, a greater capacity to accumulate in the oil. This explains the dominance of ethylene as the key gas in most oil samples from serviceable transformers of non-hermetic construction.

The relatively large number of samples with a maximum acetylene content deserves particular attention. According to current standards [3], acetylene concentrations exceeding the analytical detection limit are traditionally interpreted as an indication of high-energy discharges or zones with temperatures exceeding 750–800°C. In normally operating equipment, acetylene should be absent or present at concentrations below the analytical detection limit. However, the results of this study indicate that in serviceable transformers of non-hermetic construction, acetylene may be present as a gas with a maximum concentration, and the number of such samples is comparable to the number of samples with the maximum ethane content, whilst the acetylene concentration values generally do not exceed the analytical detection threshold. In [47, 48], it is noted that atypical (not associated with pyrolysis) formation of acetylene in concentrations up to 0.002 % vol. is possible even at temperatures of 12–16°C, for example, in medical syringes with nickel-plated components. Furthermore, atypical acetylene formation may be observed when fresh oil is added to equipment with high operating hours. It is also noted in [47] that acetylene may form as a result of the decomposition of liquid hydrocarbons that already contain acetylene radicals even before the oil is poured into the transformer. The formation of such radicals is possible during localised high-temperature effects in the production process of transformer oil. The formation of acetylene radicals as a result of the breakdown of aromatic hydrocarbons at the transformer's operating temperatures cannot be ruled out either.

Taken together, these factors mean that the values of the diagnostic criteria used to interpret DGA results in non-hermetic equipment may exceed the limits traditionally considered characteristic of a serviceable condition.

As an example, Table 4 shows the limit values for gas concentrations recommended by the most widely used international standards and methodologies for interpreting DGA results.

Table 4 – Limit values for gas concentrations recommended by various methods of DGA interpretation

Methodology	**Concentrations of gases dissolved in oil, % by volume**				
	H_2	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**
IEC 60599	0,006	0,004	0,005	0,006	0,0003
	0,015	0,011	0,009	0,028	0,005
IEEE Std C57.104	0,01	0,012	0,0065	0,005	0,0035
	0,077	0,04	0,01	0,01	0,005
	0,18	0,18	0,015	0,02	0,008
	0,1801	0,1	0,0151	0,0201	0,0081
СОУ-Н ЕЕ 46.501:2006	0,01	0,005	0,005	0,0015	0,00005
	0,015	0,012	0,01	0,01	0,001
Energopomiar (Poland)	0,05	0,02	0,017	0,026	0,007
The Duvall Method	0,01	0,0075	0,0075	0,0075	0,0003
The Dornburg Method	0,02	0,005	0,0035	0,008	0,0005
EDF, (France)	0,013	0,013	0,015	0,0044	0,00004
BBC, (Switzerland)	0,02	0,005	0,0015	0,006	0,0015
OY STROMBERG (Finland)	0,01	0,01	0,015	0,01	0,003
HYDRO QUEBEC (Canada)	0,025	0,0033	0,0015	0,004	0,0025
SECR (Japan)	0,04	0,015	0,015	0,02	0,00005
California state university (USA)	0,015	0,0025	0,001	0,002	0,0015
	0,1	0,008	0,0035	0,01	0,007
Northern Technology & Testing (USA)	0,15	0,008	0,0035	0,015	0,0007
MSZ-09-00.0352 (Malaysia)	0,016	0,006	0,006	0,006	0,0004

An analysis of Table 4 shows that, in most standards, maximum limit concentrations are set for hydrogen and methane. The exceptions are the IEC 60599 standard, in which the maximum limit is set for ethylene, and the EDF and OY STROMBERG standards, where the highest permissible concentrations are specified for ethane.

However, as shown in this study, transformers of non-hermetic construction are characterised precisely by elevated ethylene concentrations and comparatively low hydrogen concentrations. According to the data in Table 1, Levels II and III correspond to 34.4 % of ethylene concentrations, 16.8 % of acetylene, 7.94 % of methane, 4.49 % of ethane and only 0.74 % of hydrogen concentrations. This distribution significantly increases the risk of false rejection of equipment under current regulatory criteria.

A quantitative assessment of the risks associated with the use of standard gas concentration limits during the diagnosis of non-hermetic 110 kV transformers is presented in [49], which demonstrates that the lowest risks of misdiagnosis are achieved by using gas concentration limits derived using the minimum risk method, taking into account the type of oil protection and the operating conditions of the transformers.

Analysis of gas rise rates. The type of transformer oil protection has a significant impact not only on the absolute values of gas concentrations, but also on the rates at which they rise. The analysis of the distribution laws of gas growth rates carried out in [50] showed that, in the absence of defects in non-hermetic transformers, growth rates can have both positive values (gas formation) and negative values (gas diffusion from the oil into the atmosphere).

Furthermore, in the absence of external fault conditions from the power supply network, the distributions of the rates of increase are observed to be symmetric about the mathematical expectation. Such symmetry indicates the existence of a dynamic equilibrium between the amount of gas formed in the oil and the amount of gas leaving it due to diffusion.

The values of the mathematical expectations of the rise rates for the same gas under different operating conditions vary only slightly. At the same time, operating factors significantly influence the dispersion of gas rise rates. This is illustrated in Fig. 2, which shows the theoretical Laplace distribution density functions for the minimum and maximum values of ethylene rise rates in serviceable transformers of non-hermetic construction.

Furthermore, the results obtained indicate that the rates of increase vary significantly for different gases. The highest rates are characteristic of ethylene and methane, whilst the lowest values are observed for hydrogen and acetylene. This means that the use of a single limit value for the rate of increase – 30 ml/day – both for the sum of hydrocarbon gases and for each individual gas, as recommended in [3], is not sufficiently justified.

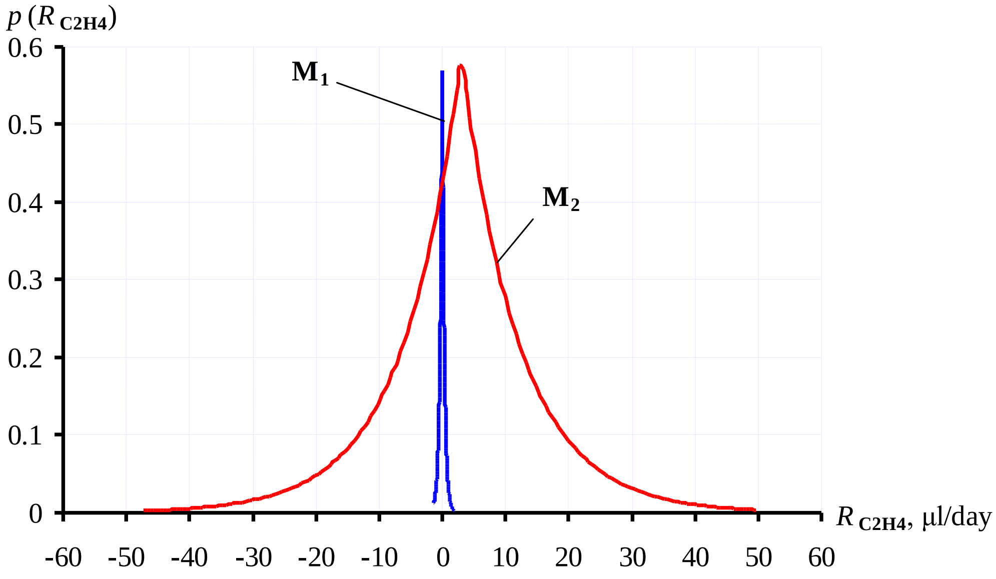
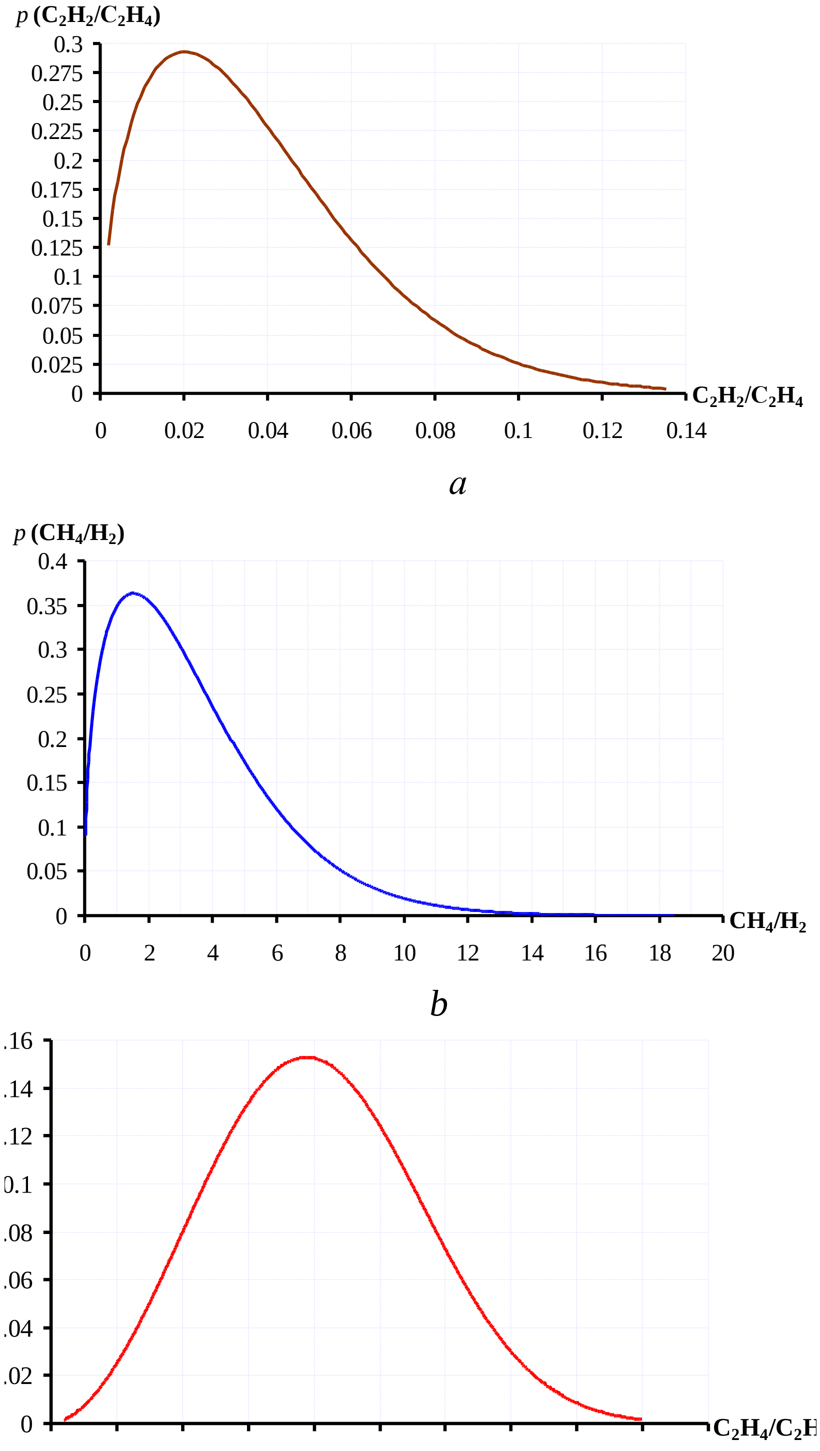


Figure 2 – Density functions of the theoretical Laplace distributions for the minimum and maximum rates of ethylene increase in serviceable transformers of non-hermetic construction

Therefore, it is advisable to determine the growth rate limits separately for each gas, taking into account the design of the transformer.

Analysis of gas mixtures. The results of the analysis of gas ratio values, calculated based on the DGA results for transformers of non-hermetic construction, are quite revealing. The regulatory document currently in force in Ukraine [3] stipulates the following gas ratio values for transformers in good working order: $0.1 < CH_4/H_2 < 1$, $0.2 < C_2H_4/C_2H_6$. At the same time, the C2H2/C2H4 ratio is considered atypical for a serviceable condition, as it is assumed that ethylene and acetylene should be absent in serviceable transformers.

However, studies have shown that, in the absence of defects in transformers of non-hermetic construction, the gas ratio values may exceed the limits specified in the standards for a serviceable condition. As an example, Fig. 3 shows the Weibull distribution densities for gases ratios obtained from DGA results of serviceable transformers of non-hermetic construction of the TDTN-25 110/35/10 kV type, filled with T-1500 grade oil. The initial sample comprised 1,076 values obtained for 54 transformers. To reduce the error, the calculation of gas pair ratios was performed only in cases where the concentrations of the gases comprising the relevant ratio exceeded the analytical detection threshold.



a

b

c

a – C_2H_2/C_2H_4; *b* – CH_4/H_2; *c* – C_2H_4/C_2H_6.

Figure 3 – Weibull distribution density functions for gas ratios in serviceable TDTN-25 110/35/10 kV transformers of non-hermetic construction

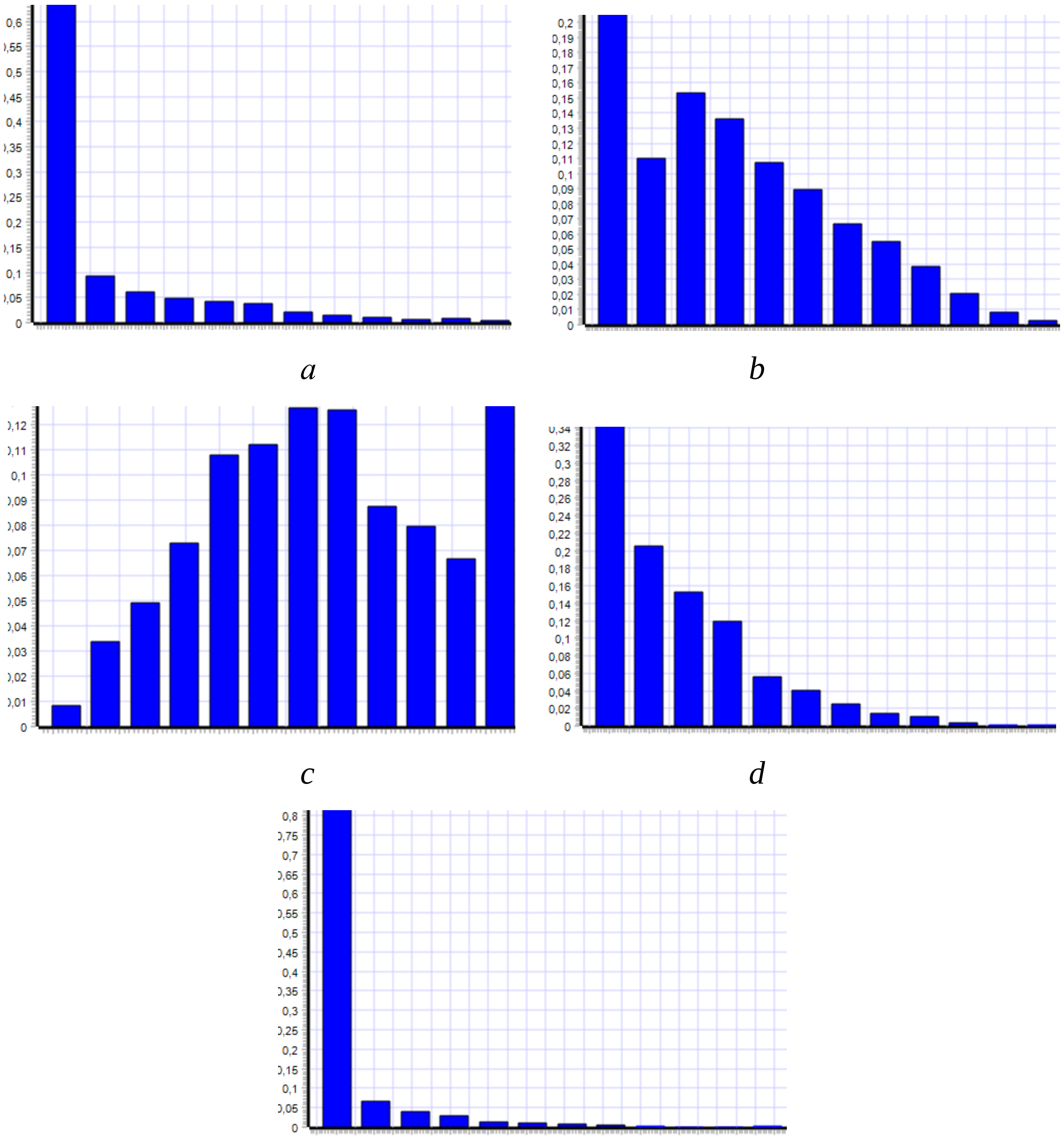
As can be seen from Fig. 3, the expected values for the distributions of the CH_4/H_2 and C_2H_4/C_2H_6 ratios fall within ranges that do not correspond to the serviceable condition of transformers, as defined by the standard currently in force in Ukraine [3]. Furthermore, the gas ratio distributions obtained by the authors indicate that in serviceable transformers of a non-sealed design, the values of the CH_4/H_2 and C_2H_4/C_2H_6 ratios will correspond to the presence of thermal defects with temperatures of 300–700°C and above 700°C. Taking into account the data in Table 1, namely the number of oil samples in which the gas concentration values correspond to Level III, i.e. the unequivocal presence of a defect, the correlation of gas ratio values with a defective condition increases the risk of ‘false rejection’ of equipment. In [45], it is proposed to use the ratio of the ethylene concentration to the total concentration of hydrocarbon gases for the diagnosis of thermal defects. It is recommended to assume that there are no thermal defects in non-sealed equipment provided that $C_2H_4/\sum C_xH_y \geq 79 \pm 7$ %, and in sealed equipment – $C_2H_4/\sum C_xH_y \leq 79 \pm 5$ %.

Analysis of the percentage content of gases in transformer oil samples. Another diagnostic criterion widely used to assess the technical condition of transformers is the percentage content of gases in transformer oil samples. This criterion is used in the key gas method [7], in Duvall’s triangles and pentagrams [10, 11, 20], and in Mansur’s pentagrams [18]. To reduce errors, the percentage content of gases was determined only for those oil samples in which the gas concentrations with the highest concentration exceeded the analytical detection limit. The percentage content of each gas in the sample was determined using the formula:

$$A_{i\%} = 100\frac{A_i}{\sum A_i}, \tag{1}$$

where $A_{i\%}$ is the percentage content of the i-th gas; A_i is the concentration of the i-th gas; ΣA_i is the sum of the concentrations of hydrogen and hydrocarbon gases in the oil sample

To determine the most probable percentage concentrations of gases in the oil samples, empirical distributions of percentage concentrations were constructed and analysed for each gas. As an example, Fig. 4 shows histograms of the empirical distribution of gas percentage concentrations in oil samples with the highest concentration of ethylene.



a *b*

c *d*

e

a – hydrogen; *b* – methane; *c* – ethylene; *d* – ethane; *e* – acetylene.

Figure 4 – Histograms of the empirical distribution of the percentage composition of gases in oil samples with the highest concentration of ethylene

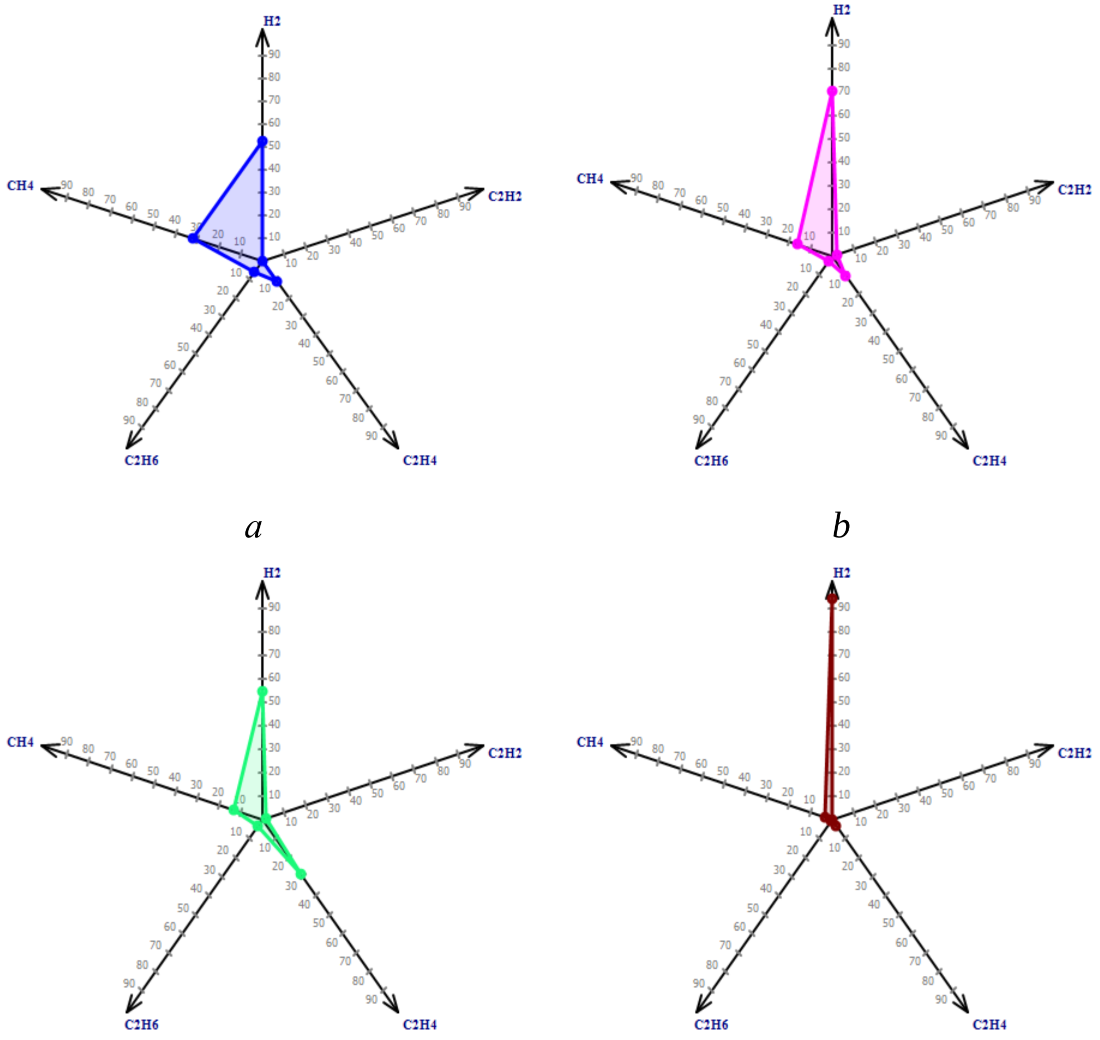
Five-ray diagrams were used to present the results graphically. The datasets for gases with the highest concentrations were divided into groups with similar percentage compositions, after which these values were averaged and plotted on the diagrams. The diagrams are ordered in descending order of the probability of the corresponding gas percentage ratios occurring.

An analysis of the distributions obtained revealed a number of distinctive features.

In oil samples with the highest hydrogen concentration, for all gases except methane, the probability of a gas being present decreases as its percentage concentration in the oil sample increases. This trend is observed even for hydrogen, which has the highest concentration of all gases in the sample. In oil samples with the highest hydrogen concentration, the percentage of hydrogen ranges from 40 to 100 %, with the highest probability occurring at hydrogen concentrations in the middle range (40–65 %). The percentage of methane ranges from 0 to 44 %, with the highest probability associated with both low methane concentrations (up to 10 %) and relatively high concentrations of this gas (20–36 %). The ethylene content ranges from 0 to 40 %, with values of 8–10 % having the highest probability. Ethane accounts for up to 20 % of the gas content, but the highest probability is for a content of this gas not exceeding 5 %. The acetylene content can reach 38 %, but the absence of this gas is the most likely scenario.

For 79 oil samples with hydrogen concentrations exceeding the analytical detection limit, five characteristic diagrams of the percentage composition of gases have been plotted. Fig. 5 shows four diagrams corresponding to the most probable variants of gas composition. The gas composition shown in Fig. 5 a has the highest probability of occurrence – 37.97 % (30 samples out of 79). For most samples with the highest hydrogen content, an elevated percentage of methane and ethylene (up to 30 % each) is characteristic, whilst the ethane content usually does not exceed 15 %, and acetylene is either absent or present in negligible amounts (up to 10 %).

In oil samples with the highest methane concentration, the percentage of hydrogen ranges from 0 to 42 %, methane from 32 to 100 %, ethylene from 0 to 48 %, ethane from 0 to 48 %, and acetylene from 0 to 40 % of the total volume. The probabilities of various gas percentage contents occurring differ. Thus, for hydrogen and acetylene, the most likely scenario is the absence of these gases in the oil sample (90 % for acetylene and 45 % for hydrogen). The probability of ethylene concentration is distributed relatively evenly, with a slight peak in the 0–8 % range; thereafter, from 10 to 34 %, the probability values remain virtually unchanged, and only in the 36–48 % range do the probability values decrease. The maximum probability of the percentage content of ethane in oil samples with the maximum concentration of methane occurs in the 14–16 % range. As the percentage content of ethane increases, the probability values decrease. The most probable percentage content of methane lies in the 40–55 % range; thereafter, as the percentage content of methane increases, the probability of its occurrence decreases.



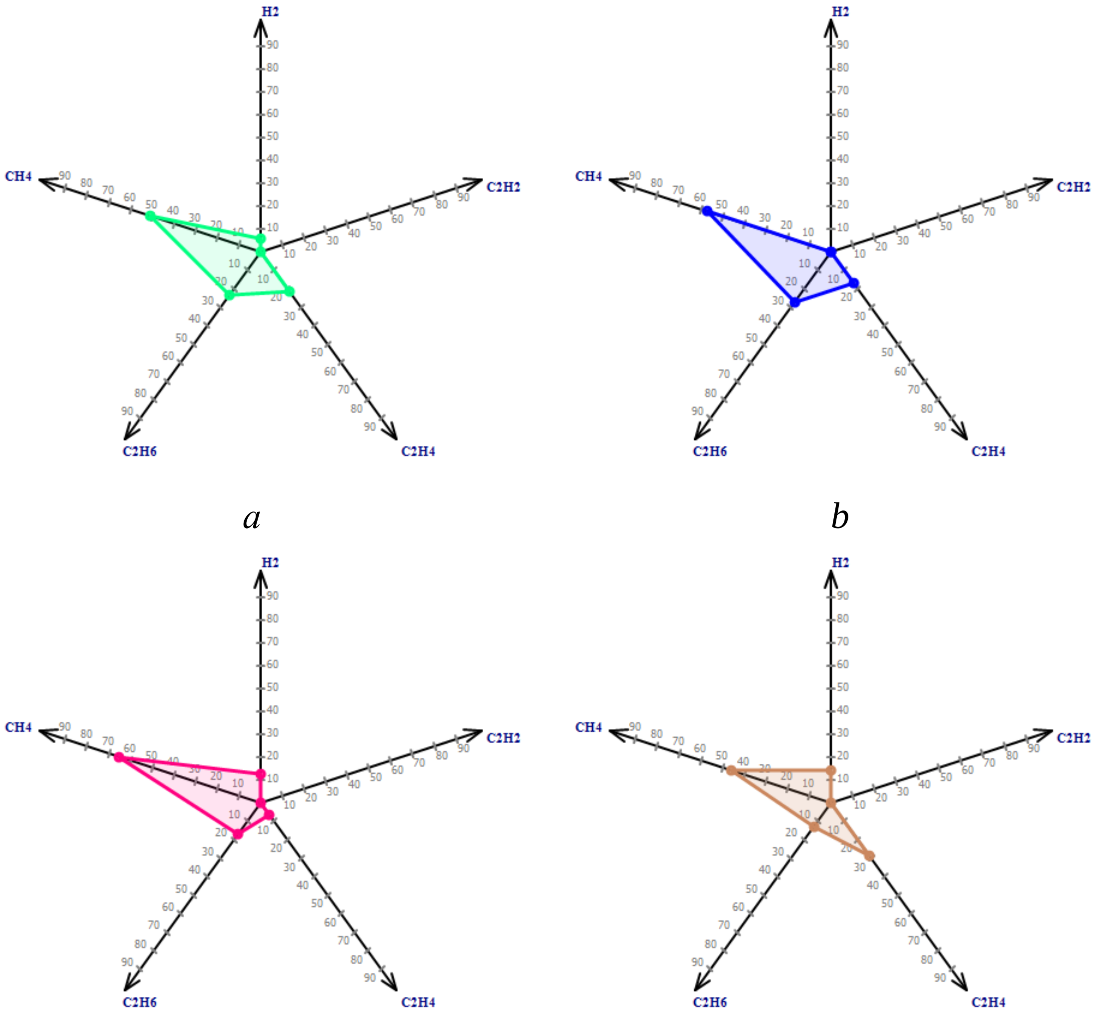
a *b*

c *d*

Figure 5 – Typical percentage composition of gases in oil samples with the highest hydrogen content

Of the 885 samples in which methane concentrations exceeded the analytical detection limit, 124 different gas composition profiles were recorded. However, the probabilities of these occurring vary significantly.

Fig. 6 shows the four most typical gas composition diagrams for samples with the highest methane content. The most common combination is one in which the percentage of methane is 50–60 %, ethylene and ethane 10–30 % each, and hydrogen up to 15 %. Acetylene is generally absent in such samples.



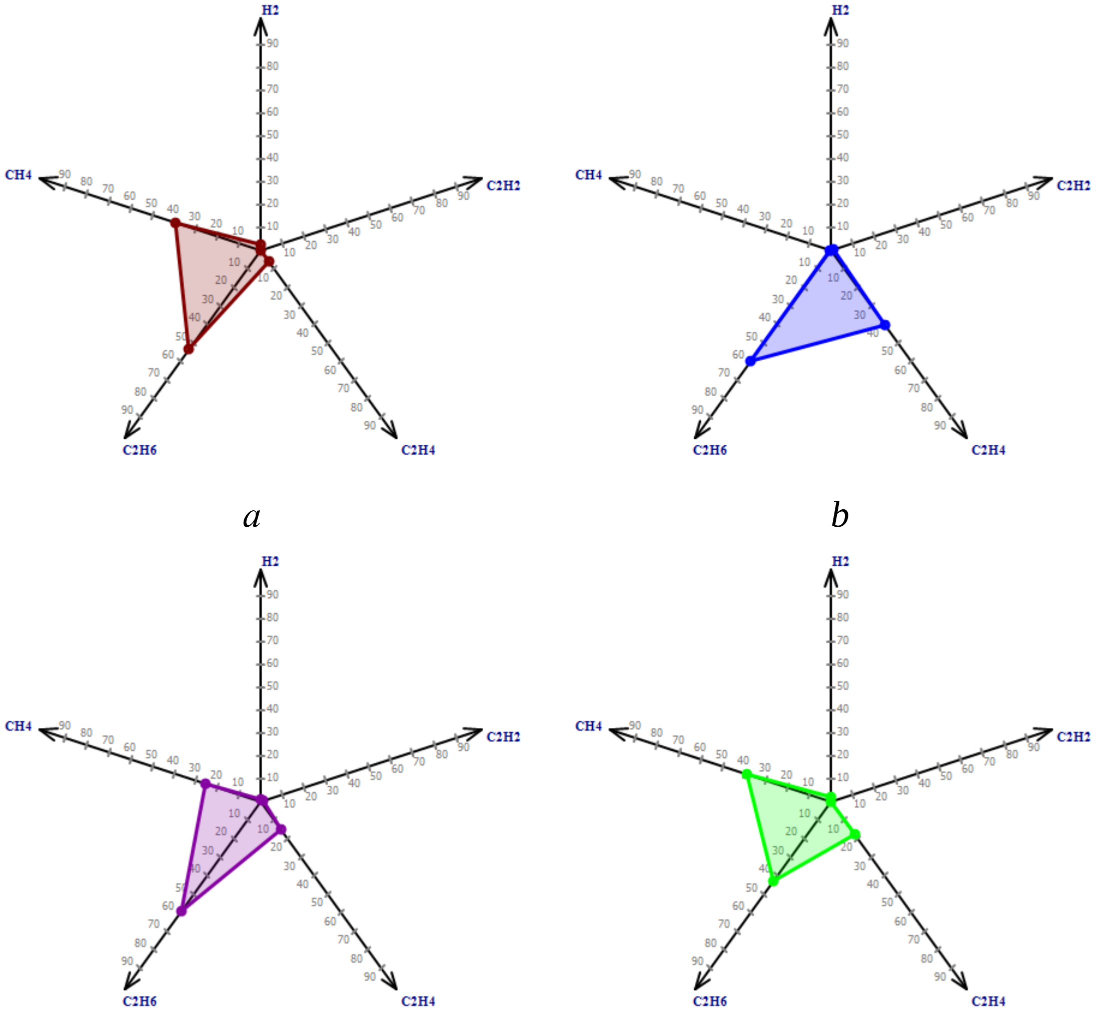
a *b*

c *d*

Figure 6 – Typical percentage composition of gases in oil samples with the highest methane content

In oil samples with the highest concentration of ethane, the percentage of hydrogen ranges from 0 to 25 %, methane from 0 to 46 %, ethylene from 0 to 50 %, ethane from 30 to 100 %, and acetylene from 0 to 40 %. As in previous cases, the probabilities of different gas percentage contents occurring vary. For hydrogen and acetylene, the most likely outcome is the absence of these gases in the oil sample. For methane, both low and high percentage concentrations are most likely. The probability of the ethylene percentage concentration decreases almost exponentially and increases slightly at the 46–48 % level. The highest probability for the ethane percentage concentration is at 50–55 %.

Fig. 7 shows the most typical diagrams of the percentage composition of gases in samples with the highest ethane content.



a *b*

c *d*

Figure 7 – Typical percentage composition of gases in oil samples with the highest ethane content

The gas composition shown in Fig. 7 a is the most likely (24.07%), accounting for 39 out of 162 samples. As can be seen from the diagram, in addition to ethane, the samples contain significant amounts of methane and ethylene.

In the oil samples with the highest concentration of ethylene (Fig. 4), the percentage content of hydrogen ranges from 0 to 38 %, methane from 0 to 48 %, ethylene from 30 to 100 %, ethane from 0 to 48 %, and acetylene from 0 to 50 %. As in previous cases, the percentage contents of individual gases have varying probabilities of occurrence. Thus, with a probability of just over 80 %, acetylene will be absent in oil samples with the maximum concentration of ethylene. As the percentage content of acetylene increases in oil samples with the maximum concentration of ethylene, the probability of its occurrence will decrease. The percentage of hydrogen follows a similar distribution, except that the probability of its absence in an oil sample is 65%. As the percentage of methane increases in oil samples with the maximum concentration of ethylene, the probability of its occurrence decreases according to a law close to an exponential one. In this case, the probability of the absence of methane in oil samples with the maximum concentration of ethylene is 21 %. The distribution of the percentage of ethylene has two distinct peaks, the first of which corresponds to a percentage of ethylene of 65–75 %, and the second to 97.5 %. In oil samples with the maximum concentration of ethylene, ethane will be absent with a probability of 36 %. As the percentage of ethane increases, the probability of its occurrence decreases according to a law close to an exponential one.

For the 1,962 oil samples with an ethylene concentration exceeding the analytical detection limit, several dozen possible gas composition profiles were identified. Fig. 8 shows the four most likely diagrams.

The highest probability (12.18 %) corresponds to the percentage composition of gases shown in Fig. 8 a, which accounts for 239 samples out of 1,962. The probability of the percentage composition of gases shown in Fig. 8 b is 9.48 % – 186 samples out of 1,962. It should be noted that the probability of oil samples with a predominant ethylene content is also quite high: diagram 8c – 100 % ethylene content has a probability of

6.67 % (131 samples out of 1962), the diagram in Fig. 8 d – 95.47 % ethylene and 4.53 % methane has a probability of occurrence of 1.58 % (31 samples out of 1962). This trend is characteristic both of oil samples in which ethylene concentrations do not exceed Level II, and of those samples in which ethylene concentrations correspond to Level III. As can be seen from Fig. 8, the most common gas, apart from ethylene, is methane (20–30 %), followed by ethane (5–20 %). Hydrogen and acetylene occur much less frequently, and their percentage content does not exceed 10–15 %.

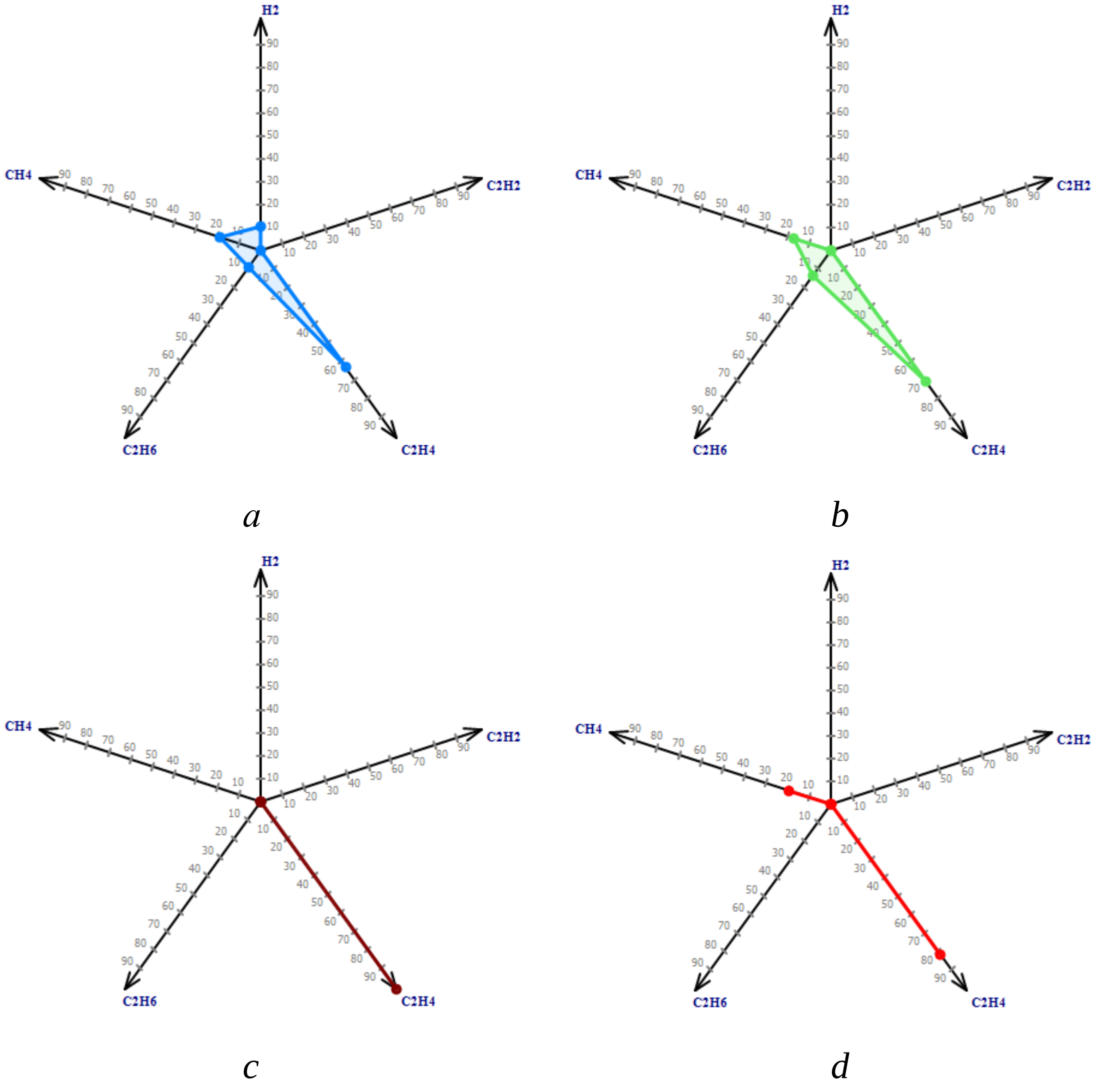


Figure 8 – Typical percentage composition of gases in oil samples with the highest ethylene content

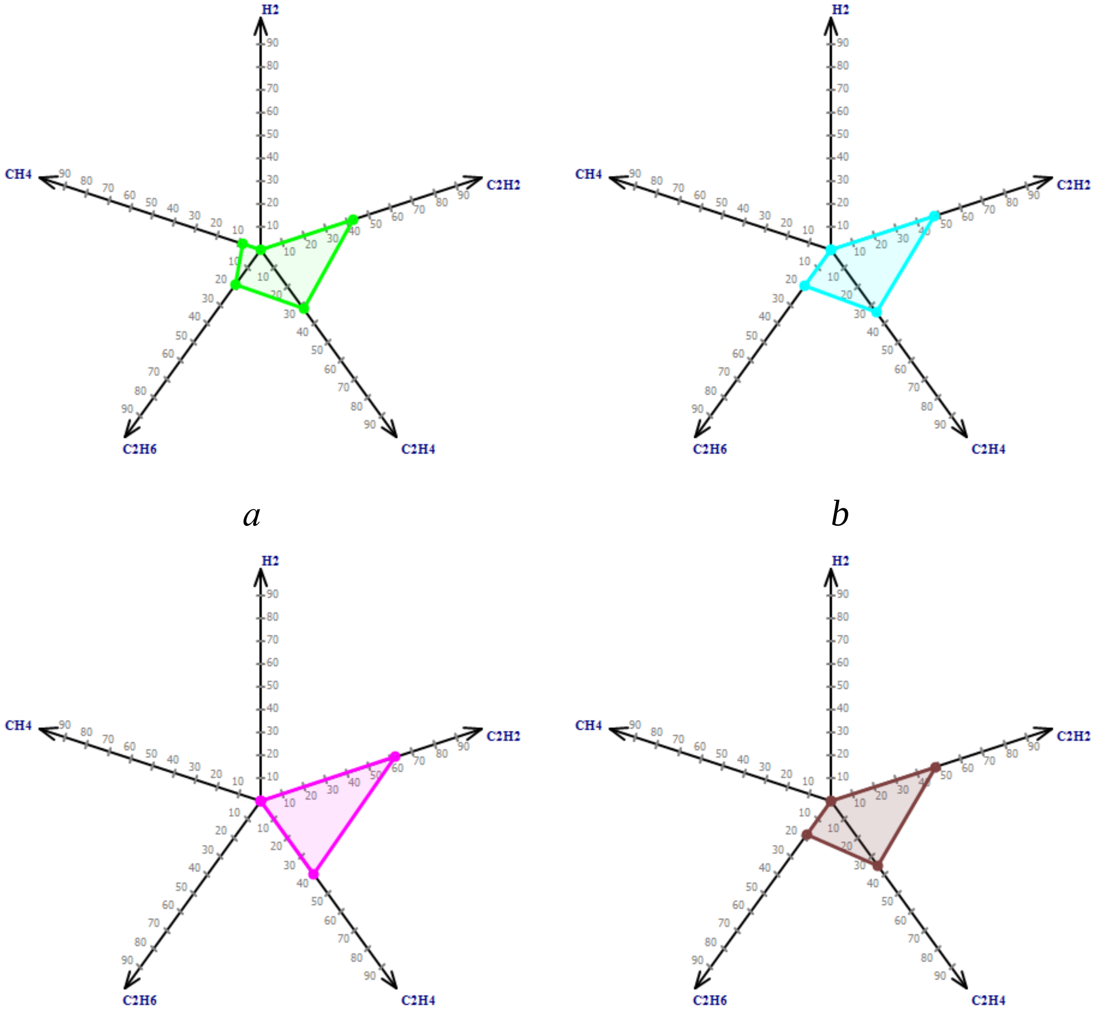
It should be noted that there is a fairly high likelihood of obtaining oil samples in which ethylene is the predominant component.

In oil samples with the highest acetylene concentration, the percentage of hydrogen ranges from 0 to 34 %, methane from 0 to 42 %, ethylene from 0 to 50 %, ethane from 0 to 46 %, and acetylene from 30 to 100 %. However, the probabilities of different gas concentrations occurring vary. For hydrogen and methane, the most likely scenario is the absence of these gases in the oil sample (90 % for hydrogen and 50 % for methane). For ethane, the probability of this gas being absent from the oil sample is around 40 %, whilst the percentage content has a slight peak at 12–24 %. The probability of ethylene concentration has a pronounced peak in the 24–40 % range, whilst the probability of this gas being absent from the oil sample is 17 %. The highest probability of acetylene concentration is 40–50 %. It is important to note that in oil samples with the maximum acetylene concentration, a qualitative difference is observed compared to the cases considered previously. Whereas, apart from the gas with the maximum concentration, methane had the highest probability of occurring in the range of relatively high values, in oil samples with the maximum acetylene concentration, ethylene has taken its place.

For 293 oil samples with acetylene concentrations exceeding the analytical detection limit, 30 diagrams of the percentage composition of gases were plotted. The most likely of these are shown in Fig. 9.

The gas composition shown in Fig. 9 a has the highest probability of 15.4 % (45 samples). Analysis shows that in such samples, ethylene is the second most significant component (up to 40 %). The methane content usually does not exceed 10–20 %, although in isolated cases it may reach 40 %, but with a very low probability. The ethane content usually does not exceed 20 %, and hydrogen is generally absent. A hydrogen content of around 20 % was detected in 24 out of 292 samples, accounting for 8.21 % of the total number of all samples with the maximum acetylene concentration.

A general analysis has shown that in oil samples from serviceable non-hermetic transformers, the percentage of gases varies across a wide range of values. At the same time, there is no ‘reference’ gas composition that is characteristic specifically of a defect-free (serviceable) state. Furthermore, it has been established that even for the same transformer, the gas composition of the oil can vary significantly from sample to sample, indicating the stochastic nature of gas processes in non-sealed equipment.



a *b*

c *d*

Figure 9 – Typical percentage composition of gases in oil samples with the highest acetylene content

Analysis of correlations between gases. To identify interdependencies between the concentrations of individual gases, a correlation analysis was carried out on oil samples with the highest concentrations of various gases. To reduce the margin of error, only those sample fragments were used in which the concentration of the gas with the highest concentration exceeded the analytical threshold but did not exceed Level II.

The strength of the correlation between two gases was assessed using Pearson's pairwise correlation coefficient:

$$r = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\cdot\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \cdot \sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}}, \qquad (2)$$

where r is the pairwise correlation coefficient; x_i, y_i are the current gas concentration values; $\bar{x}$, $\bar{y}$ – are the mean gas concentration values; n is the number of sample values.

The values of the pairwise correlation coefficients between the gases are given in Table 5; an analysis of the table reveals the following:

- in samples with the highest hydrogen concentration, no significant correlations between the gases were found;

- in samples with the highest methane concentration, a moderate correlation was observed between methane, ethane and ethylene;

- in samples with the highest concentration of ethylene, the correlation between methane, ethane and hydrogen is more pronounced than between ethylene and these gases;

- in samples with the highest concentration of ethane, significant correlations are observed only for certain pairs of gases;

- in samples with the highest acetylene concentration, functional correlations are virtually absent.

An interesting feature is that, for all samples except those with the highest acetylene content, a weak correlation is observed between hydrogen, methane and ethane – gases typically found in properly functioning sealed equipment. At the same time, acetylene shows a weak correlation with other gases only in the sample where it is the gas with the highest concentration.

Thus, in the absence of defects in non-leaky transformers, functional correlations between gases are practically non-existent. In contrast, in defective equipment, pronounced correlations arise between gases. This allows the presence of statistically significant correlations to be considered as an additional diagnostic indicator of a defective condition.

Table 5 – Values of the pairwise correlation coefficients between gases in oil samples with the highest concentrations of various gases

Sample size	**Gas**	**H_2**	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**
Maximum H_2 concentration						
N=67 $\rho_{critical, 65, 0,95}=0,265$ [24]	**H_2**	**1,00**	0,200	**0,284**	0,0652	-0,0563
	CH_4	0,200	**1,00**	**0,505**	0,0333	-0,186
	C_2H_6	**0,284**	**0,505**	**1,00**	0,0168	-0,1168
	C_2H_4	0,0652	0,0333	0,0168	**1,00**	0,132
	C_2H_2	-0,0563	-0,186	-0,1168	0,132	**1,00**
Maximum CH_4 concentration						
N=781 $\rho_{critical, 100, 0,95}=0,195$ [24]	**H_2**	**1,00**	**0,237**	0,0780	0,219	-0,0792
	CH_4	**0,237**	**1,00**	**0,635**	**0,611**	0,0940
	C_2H_6	0,0780	**0,635**	**1,00**	**0,417**	-0,108
	C_2H_4	**0,219**	**0,611**	**0,417**	**1,00**	0,0938
	C_2H_2	-0,0792	0,0940	-0,108	0,0938	**1,00**
Maximum C_2H_4 concentration						
N=1432 $\rho_{critical, 100, 0,95}=0,195$ [24]	**H_2**	**1,00**	**0,407**	0,080	0,135	0,097
	CH_4	**0,407**	**1,00**	**0,454**	**0,347**	0,051
	C_2H_6	0,080	**0,454**	**1,00**	**0,274**	-0,036
	C_2H_4	0,135	**0,347**	**0,274**	**1,00**	0,065
	C_2H_2	0,097	0,051	-0,036	0,065	**1,00**
Maximum C_2H_6 concentration						
N=128 $\rho_{critical, 126, 0,95}=0,195$ [24]	**H_2**	**1,00**	**0,415**	**0,434**	-0,024	0,024
	CH_4	**0,415**	**1,00**	**0,540**	-0,250	-0,268
	C_2H_6	**0,434**	**0,540**	**1,00**	**0,262**	-0,254
	C_2H_4	-0,024	-0,250	**0,262**	**1,00**	0,042
	C_2H_2	0,024	-0,268	-0,254	0,042	**1,00**
Maximum C_2H_2 concentration						
N=205 $\rho_{critical, 126, 0,95}=0,195$ [24]	**H_2**	**1,00**	0,028	-0,129	-0,076	0,0503
	CH_4	0,028	**1,00**	0,134	0,158	0,139
	C_2H_6	-0,129	0,134	**1,00**	**0,505**	**0,241**
	C_2H_4	-0,076	0,158	**0,505**	**1,00**	**0,532**
	C_2H_2	0,0503	0,139	**0,241**	**0,532**	**1,00**

Conclusions.

In serviceable transformers of non-hermetic construction, gas concentrations may exceed the limits specified by current standards and proprietary methods, which may lead to an incorrect interpretation of the equipment's condition. The main causes of short-term increases in gas concentrations in serviceable transformers are fault conditions in the electrical network (short circuits, overvoltages), as well as increased load. Furthermore, abnormally high gas concentration values may result from methodological errors during gas analysis, particularly if the chromatograph is not correctly calibrated.

Based on the results of the study of the distribution of gas concentration levels for serviceable transformers of non-hermetic construction, it was established that the highest probability of exceeding the limit values is associated with concentrations of ethylene, acetylene and methane, and the lowest with hydrogen.

Based on the criterion of the gas with the highest concentration, it was established that in transformers of non-hermetic construction, the key gases in the absence of defects are ethylene and methane, whilst hydrogen has the lowest concentrations.

The values of gas rise rates and gas vapour ratios in non-airtight equipment may correspond to ranges characteristic of severe thermal defects, even in the absence of such defects.

The percentage content of gases in oil samples is characterised by significant variability and does not have the constant values typical of defect-free electrical equipment.

In the absence of defects in transformers of non-hermetic construction, there are no functional correlations between gases; the emergence of a statistically significant correlation may indicate the development of a defect.

The results obtained confirm the existence of significant quantitative and qualitative differences in the gas composition of oils in sealed and non-sealed equipment and justify the need to adjust the standard diagnostic criteria for transformers of non-hermetic construction.

BIBLIOGRAPHIC LIST:

1. IEC 60599:2022. Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis. Geneva, Switzerland: International Electrotechnical Commission, 2022. 80 p.
2. IEEE Std C57.104-2019. IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers. IEEE, 2019. 98 p. DOI: 10.1109/IEEESTD.2019.8890040.
3. СОУ-Н ЕЕ 46.501:2006. Діагностика маслонаповненого трансформаторного обладнання за результатами хроматографічного аналізу вільних газів, відібраних із газового реле, і газів, розчинених у ізоляційному маслі. Чинний від 01.03.2007. Київ : Міністерство палива та енергетики України, Об’єднання енергетичних підприємств «Галузевий резервно-інвестиційний фонд розвитку енергетики», 2007. 91 с.
4. Rogers R. R. IEEE and IEC Codes to Interpret Incipient faults in Transformers, Using Gas in Oil Analysis // *IEEE Transactions on Electrical Insulation*. 1978. Vol. EI-13, no. 5. P. 349–354. DOI: https://doi.org/10.1109/TEI.1978.298141.

5. Dörnenburg E., Strittmater W. Monitoring Oil-Cooled Transformers by Gas Analysis // *Brown Boveri Review*. 1974. Vol. 61. P. 238–274.
6. Müller R., Schliesing H., Soldner K. Die Beurteilung des Betriebszustandes von Transformatoren durch Gasanalyse // *Elektrizitätswirtschaft*. 1977. No. 76. P. 345–349.
7. Mollmann A., Pahlavanpour B. New guideline for interpretation of dissolved gas analysis in oil filled transformers // *Electra*. 1999. No. 186. P. 31–51.
8. Kawamura T., Kawada N., Ando K., Yamaoka M., Maeda T., Takatsu T. Analyzing gases dissolved in oil and its application to maintenance of transformers. International Conference on Large High Voltage Electric Systems: SIGRE Session Report 12–05. Paris, 1986. P. 1–5.
9. Committee on Special. Conservation and control of oil-insulated components by diagnosis of gas in oil // *Electric Technology Research Association*. 1980. Vol. 36. No. 1. (in Japanese)
10. Duval M. The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers // *IEEE Electrical Insulation Magazine*. 2008. Vol. 24. No. 6. P. 22–29. DOI: 10.1109/mei.2008.4665347.
11. Cheim L., Duval M., Haider S. Combined Duval Pentagons: A Simplified Approach// *Energies*. 2020. Vol. 13. No. 11. P. 2859.DOI: 10.3390/en13112859.
12. Gouda O. E., El-Hoshy S. H., E.L.-Tamaly H.H. Condition assessment of power transformers based on dissolved gas analysis // *IET Generation, Transmission & Distribution*. 2019. Vol. 13. No. 12. P. 2299–2310. DOI: 10.1049/iet-gtd.2018.6168.
13. Gouda O. E., El-Hoshy S. H., H E.L.-Tamaly H.H. Proposed three ratios technique for the interpretation of mineral oil transformers based dissolved gas analysis // *IET Generation, Transmission & Distribution*. 2018. Vol. 12. No. 11. P. 2650–2661. DOI: 10.1049/iet-gtd.2017.1927.
14. Emara M. M., Peppas G. D., Gonos I. F. Two graphical shapes based on DGA for power transformer fault types discrimination // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2021. Vol. 28. No. 3. P. 981–987. DOI: 10.1109/tdei.2021.009415.
15. Kim S.-w., Kim S.-j., Seo H.-d., Jung J.-r., Yang H.-j., Duval M. New methods of DGA diagnosis using IEC TC 10 and related databases Part 1: Application of gas-ratio combinations // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2013. Vol. 20. No. 2. P. 685–690. DOI: 10.1109/tdei.2013.6508773.
16. Lee S.-j., Kim Y.-m., Seo H.-d., Jung J.-r., Yang H.-j., Duval M. New methods of DGA diagnosis using IEC TC 10 and related databases Part 2: Application of relative content of fault gases // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2013. Vol. 20. No. 2. P. 691–696. DOI: 10.1109/tdei.2013.6508774.
17. Kim S.-J., Seo H.-D., Kim S.-W. Internal defect diagnosis method of an oil immersed transformer through a dissolved gas composition ratio. South Korean Patent 1020130074674, Jul. 4, 2013. (in Korean)
18. Mansour D.-E. A. Development of a new graphical technique for dissolved gas analysis in power transformers based on the five combustible gases // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2015. Vol. 22. No. 5. P. 2507–2512. DOI: 10.1109/TDEI.2015.004999.
19. Shutenko O., Kulyk O. Method of fault-type recognition based on the dissolved gas analysis using a set of diagnostic criteria. *IET Generation, Transmission & Distribution*. 2023. P. 1–13. DOI: 10.1049/gtd2.13068.
20. Duval M., Paulhiac L. New DGA interpretation method using specific gas limits vs type of faults in power transformers. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2026. DOI: 10.1109/tdei.2026.3657732.
21. Luo, L. et al. (2023). A Fault Diagnosis Method for Power Transformer Using Canonical Variate Analysis and Support Vector Machine. In: Liang, Q., Wang, W., Liu, X., Na, Z., Zhang, B. (eds) Communications, Signal Processing, and Systems. CSPS 2022. Lecture Notes in Electrical Engineering, vol 874. Springer, Singapore. DOI: 10.1007/978-981-99-2362-5_18.
22. Patel D., Chothani N. Relevance Vector Machine Based Transformer Protection // *Power Systems*. 2020. P. 107-131. DOI: 10.1007/978-981-15-6763-6_5.

23. Malik I. M., Sharma A., Naayagi R. T. A Comprehensive and Practical Method for Transformer Fault Analysis with Historical Data Trend using Fuzzy Logic // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2023. P. 1-1. DOI: 10.1109/TDEI.2023.3286795.
24. Chen H. C., Zhang Y., Chen M. Transformer Dissolved Gas Analysis for Highly-Imbalanced Dataset Using Multi-Class Sequential Ensembled ELM // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2025. P. 1–9. DOI: 10.1109/TDEI.2023.3280436.
25. Jan B., Rahman O., Parveen S., Khan S. A. Multi-Stage Binary Classification Technique for Incipient Fault Diagnosis of Oil Immersed Power Transformers Based on ANFIS. 2023 International Conference on Power, Instrumentation, Energy and Control (PIECON). Aligarh, India, 2023. P. 1–6. DOI: 10.1109/PIECON56912.2023.10085900.
26. Kherif O., Benmahamed Y., Teguar M., Boubakeur A., Ghoneim S. S. M. Accuracy Improvement of Power Transformer Faults Diagnostic Using KNN Classifier With Decision Tree Principle // *IEEE Access*. 2021. Vol. 9. P. 81693–81701. DOI: 10.1109/ACCESS.2021.3086135.
27. Majd M. K., Niasati M. Internal fault diagnosis in power transformers using dissolved gas analysis and deep learning technique // *Computational Intelligence in Electrical Engineering*. 2025. Vol. 16. No. 2. P. 83–100. DOI: 10.22108/isee.2025.145040.1734.
28. Dladla V. M. N., Thango B. A. Fault classification in power transformers using dissolved gas analysis and optimized machine learning algorithms // *Machines*. 2025. Vol. 13. No. 8. P. 742. DOI: 10.3390/machines13080742.
29. Saleh A. G. et al .Detecting incipient faults in power transformers through hybrid model of DGA and machine learning / *Electric Power Systems Research*. 2026. Vol. 256. P. 112877. DOI: 10.1016/j.epsr.2026.112877.
30. Kulyk O. S., Shutenko O. V. Analysis of gas content in oil-filled equipment with spark discharges and discharges with high energy density // *Transactions on Electrical and Electronic Materials*. 2019. Vol. 20. No. 5. P. 437–447. DOI: 10.1007/s42341-019-00124-8.
31. Shutenko O., Kulyk O. Analysis of Gas Content in Oil-Filled Equipment with Low Energy Density Discharges // *International Journal on Electrical Engineering and Informatics*. 2020. Vol. 12. No. 2. P. 258–277. DOI: 10.15676/ijeei.2020.12.2.6.
32. Shutenko O., Kulyk O. Diagnosis of oil-filled equipment with x-wax deposition based on dissolved gas analysis. 2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON). Lviv, Ukraine, 26–28 August 2021. P. 1–6. DOI: 10.1109/ukrcon53503.2021.9575623.
33. Shutenko O., Kulyk O. Recognition of low-temperature overheating in power transformers by dissolved gas analysis // *Electrical Engineering*. 2022. Vol. 104. No. 4. P. 2109–2121. DOI: 10.1007/s00202-021-01465-5.
34. Shutenko O., Kulyk O. Recognition of overheating with temperatures of 150-300°C by analysis of dissolved gases in oil. 2020 IEEE 4th International Conference on Intelligent Energy and Power Systems (IEPS). Istanbul, Turkey, Sep. 7–11, 2020. P. 71–76. DOI: 10.1109/ieps51250.2020.9263145.
35. Shutenko O., Kulyk O. Combined defects recognition in the low and medium temperature range by results of dissolved gas analysis. *2020 IEEE KhPI Week on Advanced Technology (KhPIWeek)*. Kharkiv, Ukraine, 5–10 October 2020. P. 65–70. DOI: 10.1109/khpiweek51551.2020.9250131.
36. Shutenko O., Kulyk O. Recognition of combined defects with high-temperature overheating based on the dissolved gas analysis // *Sādhanā*. 2022. Vol. 47. No. 3. P. 146. DOI: 10.1007/s12046-022-01919-x.
37. Shutenko O., Kulyk O. Recognition of discharges that are accompanied by low-temperature overheating based on the analysis of gases dissolved in the oil of high-voltage transformers // *Енергозбереження, Енергетика, Енергоаудит*. 2021. №. 3-4(157-158). P. 20–33. DOI: 10.20998/2313-8890.2021.03.02.
38. Duval M., Heizmann T. Identification of Stray Gassing of Inhibited and Uninhibited Mineral Oils in Transformers // *Energies*. 2020. Vol. 13. No. 15. P. 3886. DOI: 10.3390/en13153886.

39. Buchacz T., Buchacz J., Duval M. Stray Gassing of Oil in HV Transformers // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2021. Vol. 28. No. 5. P. 1729–1734. October, DOI: 10.1109/TDEI.2021.009520.
40. Martin D., Lelekakis N., Wijaya J., Duval M., Saha T. Investigations Into the Stray Gassing of Oils in the Fault Diagnosis of Transformers // *Power Delivery, IEEE Transactions*. 2014. No. 29. P. 2369-2374. DOI: 10.1109/TPWRD.2014.2316501.
41. Thango B. A., Akumu A. O., Sikhosana L. S., Nnachi A. F., Jordaan J. A. Preventive Maintenance of Transformer Health Index Through Stray Gassing: A Case Study. 2021 IEEE PES/IAS PowerAfrica. Nairobi, Kenya, 2021. P. 1–5. DOI: 10.1109/PowerAfrica52236.2021.9543255.
42. Абрамов В. Б., Боярчуков Г. М., Яблонский Р. В. Отличительные особенности газообразования в трансформаторном масле герметичного и негерметичного высоковольтного оборудования // *Новини енергетики*. 2009. № 9. С. 17–32.
43. IET. Application of dissolved gas analysis for transformer condition assessment // *IET Generation, Transmission& Distribution*. 2016. Vol. 10. No. 2. P. 1–10.
44. Saranya S., Mageswari U., Roy N., Sudha R. Comparativestudyofvarious DGA methodstodiagnosetransformerfaults // *International Journal of Engineering Research and Applications*. 2013. Vol. 3. No. 3. P. 592–595.
45. Абрамов В. Б. Особенности контроля маслонаполненного оборудования по результатам хроматографического анализа растворенных в масле газов // *Электрические сети и системы*. 2012. № 4. С. 77–79.
46. Боярчуков Г. М. Диагностика состояния негерметичного высоковольтного оборудования по содержанию газов в трансформаторном масле // *Енергетика та електрифікація*. 2012. № 7. С. 24–28.
47. Абрамов В. Б., Боярчуков Г. М., Яблонский Р. В. Влияние пробоотборников на результаты хроматографического анализа газов, растворенных в масле высоковольтного оборудования // *Енергетика та електрифіація*. 2007. №7. С. 39–46.
48. Боярчуков Г. М. Практические проблемы оценки состояния высоковольтного оборудования по содержанию газов в трансформаторном масле // *Новини енергетики*. 2010. № 7. С. 23–33.
49. Shutenko O., Proskurnia O., Abramov V. Comparative analysis of risks which are accompanied by the use of typical and boundary gases concentrations for the diagnostics of high voltage transformers // *Energetika*. 2018. Vol. 64. No. 3. P. 137–145. DOI: 10.6001/energetika.v64i3.3806.
50. Shutenko O., Dovgalyuk V. Analysis of the Laws of Distribution of Gases Growth Rates in Serviceable Normally Operating 110-330 kV Transformers of Non-hermetic Construction.2025 IEEE 6th KhPI Week on Advanced Technology (KhPIWeek). Kharkiv, Ukraine, 2025. P. 1-6. DOI: 10.1109/KhPIWeek61436.2025.11288722.

REFERENCIS:

1. IEC 60599:2022. Mineral oil-filled electrical equipment in service – Guidance on the interpretation of dissolved and free gases analysis. Geneva, Switzerland: International Electrotechnical Commission, 2022. 80 p.
2. IEEE Std C57.104-2019. IEEE Guide for the Interpretation of Gases Generated in Mineral Oil-Immersed Transformers. IEEE, 2019. 98 p. DOI: 10.1109/IEEESTD.2019.8890040.
3. SOU-N EE 46.501:2006. Diahnostyka maslonapovnenoho transformatornoho obladnannia za rezultatamy khromatohrafichnoho analizu vilnykh haziv, vidibranykh iz hazovoho rele, i haziv, rozchynenykh u izoliatsiinomu masli. Chynnyi vid 01.03.2007. Kyiv : Ministerstvo palyva ta enerhetyky Ukrainy, Obiednannia enerhetychnykh pidpryiemstv «Haluzevyi rezervno-investytsiinyi fond rozvytku enerhetyky», 2007. 91 с.
4. Rogers R. R. IEEE and IEC Codes to Interpret Incipient faults in Transformers, Using Gas in Oil Analysis // *IEEE Transactions on Electrical Insulation*. 1978. Vol. EI-13, no. 5. P. 349–354. DOI: https://doi.org/10.1109/TEI.1978.298141.

5. Dörnenburg E., Strittmater W. Monitoring Oil-Cooled Transformers by Gas Analysis // *Brown Boveri Review*. 1974. Vol. 61. P. 238–274.
6. Müller R., Schliesing H., Soldner K. Die Beurteilung des Betriebszustandes von Transformatoren durch Gasanalyse // *Elektrizitätswirtschaft*. 1977. No. 76. P. 345–349.
7. Mollmann A., Pahlavanpour B. New guideline for interpretation of dissolved gas analysis in oil filled transformers // *Electra*. 1999. No. 186. P. 31–51.
8. Kawamura T., Kawada N., Ando K., Yamaoka M., Maeda T., Takatsu T. Analyzing gases dissolved in oil and its application to maintenance of transformers. International Conference on Large High Voltage Electric Systems: SIGRE Session Report 12–05. Paris, 1986. P. 1–5.
9. Committee on Special. Conservation and control of oil-insulated components by diagnosis of gas in oil // *Electric Technology Research Association*. 1980. Vol. 36. No. 1.
10. Duval M. The duval triangle for load tap changers, non-mineral oils and low temperature faults in transformers // *IEEE Electrical Insulation Magazine*. 2008. Vol. 24. No. 6. P. 22–29. DOI: 10.1109/mei.2008.4665347.
11. Cheim L., Duval M., Haider S. Combined Duval Pentagons: A Simplified Approach// *Energies*. 2020. Vol. 13. No. 11. P. 2859.DOI: 10.3390/en13112859.
12. Gouda O. E., El-Hoshy S. H., E.L.-Tamaly H.H. Condition assessment of power transformers based on dissolved gas analysis // *IET Generation, Transmission & Distribution*. 2019. Vol. 13. No. 12. P. 2299–2310. DOI: 10.1049/iet-gtd.2018.6168.
13. Gouda O. E., El-Hoshy S. H., H E.L.-Tamaly H.H. Proposed three ratios technique for the interpretation of mineral oil transformers based dissolved gas analysis // *IET Generation, Transmission & Distribution*. 2018. Vol. 12. No. 11. P. 2650–2661. DOI: 10.1049/iet-gtd.2017.1927.
14. Emara M. M., Peppas G. D., Gonos I. F. Two graphical shapes based on DGA for power transformer fault types discrimination // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2021. Vol. 28. No. 3. P. 981–987. DOI: 10.1109/tdei.2021.009415.
15. Kim S.-w., Kim S.-j., Seo H.-d., Jung J.-r., Yang H.-j., Duval M. New methods of DGA diagnosis using IEC TC 10 and related databases Part 1: Application of gas-ratio combinations // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2013. Vol. 20. No. 2. P. 685–690. DOI: 10.1109/tdei.2013.6508773.
16. Lee S.-j., Kim Y.-m., Seo H.-d., Jung J.-r., Yang H.-j., Duval M. New methods of DGA diagnosis using IEC TC 10 and related databases Part 2: Application of relative content of fault gases // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2013. Vol. 20. No. 2. P. 691–696. DOI: 10.1109/tdei.2013.6508774.
17. Kim S.-J., Seo H.-D., Kim S.-W. Internal defect diagnosis method of an oil immersed transformer through a dissolved gas composition ratio. South Korean Patent 1020130074674, Jul. 4, 2013.
18. Mansour D.-E. A. Development of a new graphical technique for dissolved gas analysis in power transformers based on the five combustible gases // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2015. Vol. 22. No. 5. P. 2507–2512. DOI: 10.1109/TDEI.2015.004999.
19. Shutenko O., Kulyk O. Method of fault-type recognition based on the dissolved gas analysis using a set of diagnostic criteria. *IET Generation, Transmission & Distribution*. 2023. P. 1–13. DOI: 10.1049/gtd2.13068.
20. Duval M., Paulhiac L. New DGA interpretation method using specific gas limits vs type of faults in power transformers. *IEEE Transactions on Dielectrics and Electrical Insulation*. 2026. DOI: 10.1109/tdei.2026.3657732.
21. Luo, L. et al. (2023). A Fault Diagnosis Method for Power Transformer Using Canonical Variate Analysis and Support Vector Machine. In: Liang, Q., Wang, W., Liu, X., Na, Z., Zhang, B. (eds) Communications, Signal Processing, and Systems. CSPS 2022. Lecture Notes in Electrical Engineering, vol 874. Springer, Singapore. DOI: 10.1007/978-981-99-2362-5_18.
22. Patel D., Chothani N. Relevance Vector Machine Based Transformer Protection // *Power Systems*. 2020. P. 107-131. DOI: 10.1007/978-981-15-6763-6_5.

23. Malik I. M., Sharma A., Naayagi R. T. A Comprehensive and Practical Method for Transformer Fault Analysis with Historical Data Trend using Fuzzy Logic // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2023. P. 1-1. DOI: 10.1109/TDEI.2023.3286795.
24. Chen H. C., Zhang Y., Chen M. Transformer Dissolved Gas Analysis for Highly-Imbalanced Dataset Using Multi-Class Sequential Ensembled ELM // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2025. P. 1–9. DOI: 10.1109/TDEI.2023.3280436.
25. Jan B., Rahman O., Parveen S., Khan S. A. Multi-Stage Binary Classification Technique for Incipient Fault Diagnosis of Oil Immersed Power Transformers Based on ANFIS. 2023 International Conference on Power, Instrumentation, Energy and Control (PIECON). Aligarh, India, 2023. P. 1–6. DOI: 10.1109/PIECON56912.2023.10085900.
26. Kherif O., Benmahamed Y., Teguar M., Boubakeur A., Ghoneim S. S. M. Accuracy Improvement of Power Transformer Faults Diagnostic Using KNN Classifier With Decision Tree Principle // *IEEE Access*. 2021. Vol. 9. P. 81693–81701. DOI: 10.1109/ACCESS.2021.3086135.
27. Majd M. K., Niasati M. Internal fault diagnosis in power transformers using dissolved gas analysis and deep learning technique // *Computational Intelligence in Electrical Engineering*. 2025. Vol. 16. No. 2. P. 83–100. DOI: 10.22108/isee.2025.145040.1734.
28. Dladla V. M. N., Thango B. A. Fault classification in power transformers using dissolved gas analysis and optimized machine learning algorithms // *Machines*. 2025. Vol. 13. No. 8. P. 742. DOI: 10.3390/machines13080742.
29. Saleh A. G. et al .Detecting incipient faults in power transformers through hybrid model of DGA and machine learning / *Electric Power Systems Research*. 2026. Vol. 256. P. 112877. DOI: 10.1016/j.epsr.2026.112877.
30. Kulyk O. S., Shutenko O. V. Analysis of gas content in oil-filled equipment with spark discharges and discharges with high energy density // *Transactions on Electrical and Electronic Materials*. 2019. Vol. 20. No. 5. P. 437–447. DOI: 10.1007/s42341-019-00124-8.
31. Shutenko O., Kulyk O. Analysis of Gas Content in Oil-Filled Equipment with Low Energy Density Discharges // *International Journal on Electrical Engineering and Informatics*. 2020. Vol. 12. No. 2. P. 258–277. DOI: 10.15676/ijeei.2020.12.2.6.
32. Shutenko O., Kulyk O. Diagnosis of oil-filled equipment with x-wax deposition based on dissolved gas analysis. 2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering (UKRCON). Lviv, Ukraine, 26–28 August 2021. P. 1–6. DOI: 10.1109/ukrcon53503.2021.9575623.
33. Shutenko O., Kulyk O. Recognition of low-temperature overheating in power transformers by dissolved gas analysis // *Electrical Engineering*. 2022. Vol. 104. No. 4. P. 2109–2121. DOI: 10.1007/s00202-021-01465-5.
34. Shutenko O., Kulyk O. Recognition of overheating with temperatures of 150-300°C by analysis of dissolved gases in oil. 2020 IEEE 4th International Conference on Intelligent Energy and Power Systems (IEPS). Istanbul, Turkey, Sep. 7–11, 2020. P. 71–76. DOI: 10.1109/ieps51250.2020.9263145.
35. Shutenko O., Kulyk O. Combined defects recognition in the low and medium temperature range by results of dissolved gas analysis. *2020 IEEE KhPI Week on Advanced Technology (KhPIWeek)*. Kharkiv, Ukraine, 5–10 October 2020. P. 65–70. DOI: 10.1109/khpiweek51551.2020.9250131.
36. Shutenko O., Kulyk O. Recognition of combined defects with high-temperature overheating based on the dissolved gas analysis // *Sādhanā*. 2022. Vol. 47. No. 3. P. 146. DOI: 10.1007/s12046-022-01919-x.
37. Shutenko O., Kulyk O. Recognition of discharges that are accompanied by low-temperature overheating based on the analysis of gases dissolved in the oil of high-voltage transformers // Enerhozberezhennia, Enerhetyka, Enerhoaudyt. 2021. No. 3-4(157-158). P. 20–33. DOI: 10.20998/2313-8890.2021.03.02.
38. Duval M., Heizmann T. Identification of Stray Gassing of Inhibited and Uninhibited Mineral Oils in Transformers // *Energies*. 2020. Vol. 13. No. 15. P. 3886. DOI: 10.3390/en13153886.
39. Buchacz T., Buchacz J., Duval M. Stray Gassing of Oil in HV Transformers // *IEEE Transactions on Dielectrics and Electrical Insulation*. 2021. Vol. 28. No. 5. P. 1729–1734. October, DOI: 10.1109/TDEI.2021.009520.

40. Martin D., Lelekakis N., Wijaya J., Duval M., Saha T. Investigations Into the Stray Gassing of Oils in the Fault Diagnosis of Transformers // *Power Delivery, IEEE Transactions*. 2014. No. 29. P. 2369-2374. DOI: 10.1109/TPWRD.2014.2316501.

41. Thango B. A., Akumu A. O., Sikhosana L. S., Nnachi A. F., Jordaan J. A. Preventive Maintenance of Transformer Health Index Through Stray Gassing: A Case Study. 2021 IEEE PES/IAS PowerAfrica. Nairobi, Kenya, 2021. P. 1–5. DOI: 10.1109/PowerAfrica52236.2021.9543255.

42. Abramov V. B., Boyarchukov G. M., Yablonskiy R. V. Otlichitel'nyye osobennosti gazoobrazovaniya v transformatornom masle germetichnogo i negermetichnogo vysokovol'tnogo oborudovaniya // *Novyny enerhetyky*. 2009. № 9. S. 17–32.

43. IET. Application of dissolved gas analysis for transformer condition assessment // *IET Generation, Transmission& Distribution*. 2016. Vol. 10. No. 2. P. 1–10.

44. Saranya S., Mageswari U., Roy N., Sudha R. Comparativestudyofvarious DGA methodstodiagnosetransformerfaults // *International Journal of Engineering Research and Applications*. 2013. Vol. 3. No. 3. P. 592–595.

45. Abramov V. B. Osobennosti kontrolya maslonapolnennogo oborudovaniya po rezul'tatam khromatograficheskogo analiza rastvorennykh v masle gazov // *Elektricheskiye seti i sistemy*. 2012. № 4. S. 77–79.

46. Boyarchukov G. M. Diagnostika sostoyaniya negermetichnogo vysokovol'tnogo oborudovaniya po soderzhaniyu gazov v transformatornom masle // *Enerhetyka ta elektryfikatsiia. 2012. № 7.* S. *24–28.*

47. Abramov V. B., Boyarchukov G. M., Yablonskiy R. V. Vliyaniye probootbornikov na rezul'taty khromatograficheskogo analiza gazov, rastvorennykh v masle vysokovol'tnogo oborudovaniya // *Enerhetyka ta elektryfikatsiia*. 2007. №7. S. 39–46.

48. Boyarchukov G. M. Prakticheskiye problemy otsenki sostoyaniya vysokovol'tnogo oborudovaniya po soderzhaniyu gazov v transformatornom masle // *Novyny enerhetyky*. 2010. № 7. S. 23–33.

49. Shutenko O., Proskurnia O., Abramov V. Comparative analysis of risks which are accompanied by the use of typical and boundary gases concentrations for the diagnostics of high voltage transformers // *Energetika*. 2018. Vol. 64. No. 3. P. 137–145. DOI: 10.6001/energetika.v64i3.3806.

50. Shutenko O., Dovgalyuk V. Analysis of the Laws of Distribution of Gases Growth Rates in Serviceable Normally Operating 110-330 kV Transformers of Non-hermetic Construction.2025 IEEE 6th KhPI Week on Advanced Technology (KhPIWeek). Kharkiv, Ukraine, 2025. P. 1-6. DOI: 10.1109/KhPIWeek61436.2025.11288722.

Стаття надійшла до редакції:14.01.2026; рецензування: 25.01.2026;
прийнята до публікації 05.02.2026. Автори прочитали и дали згоду рукопису.
The article was submitted on 14.01.2026; revised on 25.01.2026; and accepted for publication on 05.02.2026. The authors read and approved the final version of the manuscript.