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ANALYSIS OF GAS CONTENT DYNAMICS IN POWER TRANSFORMERS DURING DEVELOPMENT OF SPARK DISCHARGE

The results of analysis of the dynamics of change in the values of diagnostic criteria used to recognise the type of defect based on the dissolved gas analysis results for five high-voltage transformers during the development of spark discharges are presented. In the course of the analysis the dynamics of changes in gas concentrations and defect nomograms were considered. There was also analysed the change of the defect type during the spark discharges development by means of diagnostic space determined by gas ratios values according to IEC 60599 and ETRA square, and by means of diagnostic space determined by gas percentage content according to Duval's triangle. According to the results of the analysis it was found that during the development of spark discharges in different transformers the values of diagnostic criteria correspond to the defects of different types, which makes it practically impossible to predict this defect based on the results of previous tests. At the same time the values of both gas ratios and gas percentage as well as defect nomograms obtained by dissolved gas analysis before the moment when gas concentrations exceeded their limit values correspond to the defects of different types, which enables to recognise spark discharges at an early stage. Analysis of correlation relations between values of concentrations and percentages of gases and the operation time as well as between the values of concentrations and percentages of individual gases shows that the development of spark discharges is accompanied not only by the growth of gas concentrations, which is known and widely used, but there is also a significant positive correlation between the values of concentrations of dissolved gases in oil and the operation time as well as between concentrations of individual gases. At the same time, the gases between which a significant correlation has been detected during the development of spark discharges in different transformers differ significantly. The analysis showed that the standards and criteria of IEC 60599, the ETRA square and the Duval triangle do not allow any spark discharges to be detected. The maximum recognition reliability was obtained using the nomogram method. The results show that an early detection of spark discharges is possible, which increases the reliability of nondestructive diagnostics and prolongs the service life of transformers.

Keywords: power transformers, diagnostics, dissolved gas analysis (DGA), spark discharges, defect type dynamics, correlation, gas concentrations, gas percentages, gas ratios, ETRA square, Duval triangle, defect nomograms.

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АНАЛІЗ ДИНАМІКИ ЗМІНИ ГАЗОВМІСТУ МАСЕЛ У СИЛОВИХ ТРАНСФОРМАТОРАХ У ПРОЦЕСІ РОЗВИТКУ ІСКРОВИХ РОЗРЯДІВ

Наведено результати аналізу динаміки зміни значень діагностичних критеріїв, використовуваних для розпізнавання типу дефекту за результатами аналізу розчинених в маслі газів, для п'яти високовольтних трансформаторів в процесі розвитку іскрових розрядів. У процесі аналізу розглянуто динаміку зміни концентрацій газів, відсоткового вмісту газів, а також номограм дефектів. Також аналізувалася зміна типу дефекту в процесі розвитку іскрових розрядів з використанням діагностичного простору, що визначався значеннями відношень газів, регламентованих стандартом IEC 60599 і квадратом ЕТРА, та з використанням діагностичного простору, що визначався відсотковим вмістом газів, регламентованих трикутником Дюваля. За результатами аналізу встановлено, що при розвитку іскрових розрядів в різних трансформаторах значення діагностичних критеріїв відповідають дефектам різного типу, що практично не дозволяє прогнозувати даний дефект за результатами попередніх випробувань. У той же час значення і відношень газів, і їх відсотковий вміст, а також номограми дефектів, отримані за результатами аналізу розчинених в маслі ще до того моменту, коли концентрації газів перевищили свої граничні значення, відповідають дефектам різного типу, що дозволяє розпізнавати іскрові розряди на ранній стадії. За результатами аналізу кореляційних зв'язків між значеннями концентрацій і відсоткового вмісту газів та тривалістю експлуатації, а також між значеннями концентрацій і відсоткового вмісту окремих газів встановлено, що розвиток іскрових розрядів супроводжується не тільки зростанням концентрацій газів, що відомо і широко використовується, але і появою значущої позитивної кореляції між значеннями концентрацій розчинених у маслі газів і тривалістю експлуатації, а також між концентраціями окремих газів. При цьому гази, між якими виявлена значуща кореляція, в процесі розвитку іскрових розрядів в різних трансформаторах істотно розрізняються. Виконаний аналіз показав, що норми і критерії, регламентовані стандартом IEC 60599, квадратом ETRA і трикутником Дюваля не дозволяють розпізнавати іскрові розряди. Максимальна достовірність розпізнавання була отримана з використанням методу номограм. Отримані результати демонструють можливість раннього виявлення іскрових розрядів, що дозволяє підвищити достовірність неруйнівної діагностики і продовжити ресурс трансформаторів.

Ключові слова: силові трансформатори, діагностика, аналіз розчинених в маслі газів, іскрові розряди, динаміка зміни типу дефекту, кореляція, концентрації газів, відсотковий вміст газів, відношення газів, квадрат ETRA, трикутник Дюваля, номограми дефекту.

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АНАЛИЗ ДИНАМИКИ ИЗМЕНЕНИЯ ГАЗОСОДЕРЖАНИЯ МАСЕЛ В СИЛОВЫХ ТРАНСФОРМАТОРАХ В ПРОЦЕССЕ РАЗВИТИЯ ИСКРОВЫХ РАЗРЯДОВ

Приведены результаты анализа динамики изменения значений диагностических критериев, используемых для распознавания типа дефекта по результатам анализа растворенных в масле газов, для пяти высоковольтных трансформаторов в процессе развития искровых разрядов. В процессе анализа рассмотрена динамика изменения концентраций газов процентного содержания газов, а также номограмм дефектов. Также анализировалось изменение типа дефекта в процессе развития искровых разрядов с использованием диагностического пространства, определяемого значениями отношений газов, регламентируемых стандартом IEC 60599 и квадратом ETRA, и с использованием диагностического пространства, определяемого процентным содержанием газов, регламентируемых треугольником Дюваля. По результатам анализа установлено, что при развитии искровых разрядов в разных трансформаторах значения диагностических критериев соответствует дефектам разного типа, что практически не позволяет прогнозировать данный дефект по результатам предыдущих испытаний. В тоже время значения и отношений газов, и их процентного содержания, а также номограммы дефектов, полученные по результатам анализа растворенных в масле газов еще до того момента, когда концентрации газов превысили свои граничные значения, соответствуют дефектам разного типа, что позволяет распознавать искровые разряды на ранней стадии. По результатам анализа корреляционных связей между значениями концентраций и процентного содержания газов и длительностью эксплуатации, а также между значениями концентраций и процентного содержания отдельных газов установлено, что развитие искровых разрядов сопровождается не только ростом концентраций газов, что известно и широко используется, но и появлением значимой положительной корреляции между значениями концентраций растворенных в масле газов и длительностью эксплуатации, а также между концентрациями отдельных газов. При этом газы, между которыми выявлена значимая корреляция, в процессе развития искровых разрядов в разных трансформаторах существенно различаются. Выполненный анализ показал, что нормы и критерии, регламентируемые стандартом IEC 60599, квадратом ETRA и треугольником Дюваля, не позволяют распознавать искровые разряды. Максимальная достоверность распознавания была получена с использованием метода номограмм. Полученные результаты демонстрируют наличие возможности раннего обнаружения искровых разрядов, что позволяет повысить достоверность неразрушающей диагностики и продлить ресурс трансформаторов.

Ключевые слова: силовые трансформаторы, диагностика, анализ растворенных в масле газов**,** искровые разряды, динамика изменения типа дефекта, корреляция, концентрации газов, процентное содержание газов, отношения газов, квадрат ETRA, треугольник Дюваля, номограммы дефекта.

Statement of the problem. Deterioration of insulation properties of high-voltage power transformers during long-term operation occurs not only under the influence of processes of hydrolysis and pyrolysis of cellulose and oxidation of transformer oil, but also due to processes of ionization aging and thermal degradation, which are called developing defects. Just as in the case of medical diagnosis, untimely detected disease in the human body can lead to death, so the developing defects, if not detected in time, can lead to accidental damage to equipment, which is accompanied by serious economic losses. There is therefore an objective need for early detection and recognition of such defects. One of the most widespread methods of non-destructive diagnostics allowing to recognise developing defects of oil-filled equipment is the dissolved gases analysis (DGA). However, the use of traditional norms and criteria regulated in the majority of international and national standards and author's methods on interpretation of DGA results [1–10] allows to detect defects only if concentration of at least one of gases exceeds the limit values, which does not allow timely detection of fast-developing defects.

Spark discharges are one of the faults which, if not detected in time, can cause accidental damage to high-voltage transformers. Such defects include discharges caused by deposits of contaminants or products of oil degradation on the surfaces of insulating structures with subsequent growth of discharge channel (creeping discharges) and spark discharges between areas with different potentials, which are caused by sharp edges, violation of contact connections or appearance of "floating potential". The analysis [11–13] has shown that among all the known standards the surface or creeping discharges are singled out as a separate type of defect only in [3, 5, 7], which complicates the recognition of this defect significantly.

Publication analysis. In addition to the norms and criteria governed by known standards and author's methods, a rather large volume of publications is currently devoted to the issues of interpretation of DGA results. For example, in [14, 15] fuzzy logic apparatus is used to interpret DGA results. In [16, 17], support vector machine (SVM) is used for defect type recognition. Another direction to improve the reliability of defect type recognition is the use of neural networks [18, 19]. In [20, 21], Adaptive Neuro-Fuzzy Inference System is used to interpret the results of oil dissolved gas analysis. In [22], a deep belief network is developed for defect type recognition. In [23, 24], a Bayesian approach is used to interpret the DGA results. The Bayesian network developed in [23] uses the values of gas ratios regulated by the Dornenburg and Rogers methods, as well as the Duval triangle. In [25], the gene expression programming apparatus was used to interpret the DGA results. For the same purpose, deep transmission networks were used in [26] and fault interpretation matrices (FIM) were used in [27]. In [28], the use of statistical machine learning techniques and neural networks to generate a staircase model is proposed. In [29], two scenarios with different data transformation techniques are considered to improve the accuracy of the neural pattern recognition (NPR) method for predicting fault types and severity. In [30], a method for diagnosing transformer faults based on Stacked Contractive Auto-Encoder Net (SCAEN) is proposed. In [31], a multiple classifiers based information fusion (MCIF) method is proposed. In [32], a new method for power transformer fault diagnosis based on DGA using data transformation and six optimized machine learning (OML) techniques is presented.

The analysis has shown that most of the above papers recognised the defect using only one criterion, either the gas ratios or the gas percentages, and as a rule, the norms and criteria regulated in [1-10] were used. At the same time, the dynamics of changes in these criteria during the development of the defect were practically not investigated, which is the reason for preparing this article.

Purpose of the article. The aim of the article is to analyse the possibilities of early detection of spark discharges in power transformers. In order to achieve this goal, the dynamics of the criteria used for defect type recognition based on DGA results in power transformers during the development of spark discharges has been analysed.

Research method. The theoretical basis of the performed research is the use of technical genesis procedure ("genesis" is an origin, occurrence), that is, determination of technical condition of the object for the past moment of time. Given the diversity of diagnostic criteria for determining the condition of high-voltage oil-filled equipment based on DGA results, in the course of the research the dynamics of both gas concentration values and gas percentage values and the value of gas ratios were analysed.

At the first stage of research the values of gas concentrations were analysed for compliance with different levels characterising presence or absence of defect in oil-filled equipment, according to the normative document in force in Ukraine [3]. The gas concentration levels are shown in Table 1.

Table 1 – Condition levels of 110 kV power transformers and shunt reactors according to dissolved gas concentrations in oil

Concentration levels	**Gases**				
	H_2	**CH_4**	**C_2H_6**	**C_2H_4**	**C_2H_2**
Below the analytical recognition threshold	**0.005**	**0.0015**			**0.0003**
Level I	**<0.01**	**<0.005**		**<0.0015**	**<0.00005**
Level II	**0.01-0.015**	**0.005-0.012**	**0.0015-0.01**		**0.00005-0.001**
Level III	**>0.015**	**>0.012**	**>0.01**		**>0.001**

In contrast to the IEC 60599 methodology, the gas concentrations given in Table 1 are called limit and have three levels:

- Level 1 – no defect is suspected;
- when the lower limit of the gas concentration range corresponding to Level 2 is exceeded, a gas build-up rate is determined (a defect is considered "present" if this rate exceeds 30 ml/day);
- Level 3 (exceeding the upper limit of Level 2) – a defect is predicted without regard to the gas build-up rate.

The hydrogen and hydrocarbon gas percentages were then determined [33, 34]:

$$A_{i\%} = 100\frac{A_i}{\Sigma}, \qquad (1)$$

where $A_{i\%}$ is the percentage content of a given gas;

A_i is the concentration value of a given gas;

Σ is the sum of the concentrations of hydrogen and hydrocarbon gases in the oil sample.

For equipment with a sufficiently large sample size, the values of paired correlation coefficients between the values of concentrations and percentages of gases and the operation time as well as between the values of concentrations and percentages of individual gases were analysed. The value of the paired correlation coefficient [35] was used for this purpose:

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

where r_{smp} is the sample value of the paired correlation coefficient;

x_i and y_i are the current values of the indicators;

$\bar{x}$ and $\bar{y}$ are the values of the sample mean of the indicators;

n is the volume of sample values

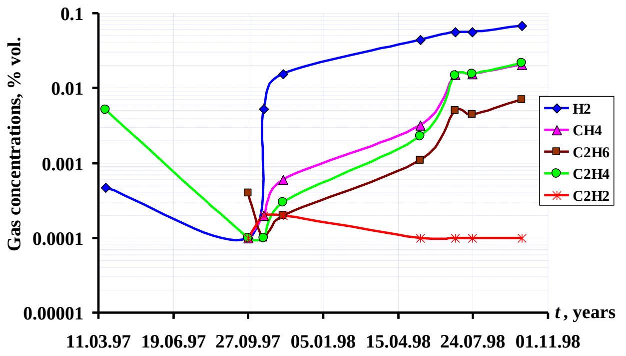
To test the main hypothesis, the absolute value of the sample paired correlation coefficient was compared with the critical value. If the value of the sample paired correlation coefficient does not exceed the critical value with the number of degrees of freedom $f = n–2$ and a given level of significance α (5% risk level was used), then the main hypothesis is not rejected, that is, the relationship is considered to be not significant.

The gas pair ratios were then calculated. To reduce the error, the calculation was only carried out if the gas concentrations in the ratio exceeded the values corresponding to the "limit of gases in oil". These values depend on both the sensitivity of the chromatograph and the measuring technique and according to [3] are H_2=50, CH_4=C_2H_6=C_2H_4=15 and C_2H_2=3 μl/l. The dynamics of the defect was evaluated using the ratios of gases regulated by the IEC 60599 standard and the ETRA square. The character of the defect type change during the defect development was also analysed using Duval triangle and Nomogram method.

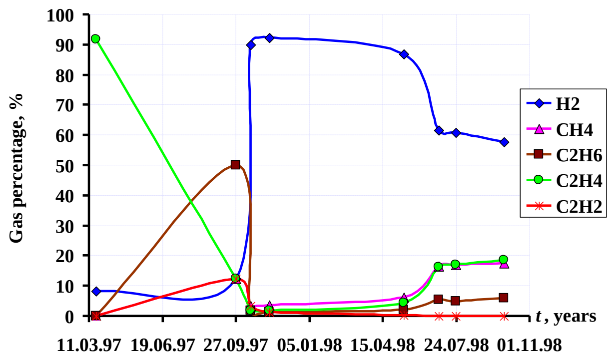
The proposed approach makes it possible not only to assess the nature of changes in defect types during its development, but also to analyse the possibilities of different methods for interpreting DGA results.

Research results. As an example, the following results show the dynamics of the gas content of high-voltage transformer oils during the development of spark discharges.

Example No. 1. A 330 MVA autotransformer was damaged by a spark discharge [33]. Dependences of gas concentrations and percentage of gases on the operation time during the development of the defect in this autotransformer are shown in Fig. 1.



a



b

Figure 1 – Dependences of gas concentrations (*a*) and gas percentage (*b*) on operating time in a 330 kV autotransformer damaged by a spark discharge

As can be seen from the figure, during the development of the defect the gases with the maximum content were ethylene, ethane and hydrogen. The first excess of gas concentrations was recorded on 12.11.1997 for hydrogen. Then, a successive increase was observed in the concentrations of almost all gases, except for acetylene.

Table 2 shows the results of the correlation analysis between the values of concentrations and gas percentages and the operation time, as well as between the values of concentrations and percentages of individual gases.

Table 2 – Results of correlation analysis between values of concentrations and gas percentages and operation time, as well as between values of concentrations and percentages of individual gases in a 330 kV autotransformer damaged by a spark discharge

Gas	Operation time	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Gas concentrations						
H_2	**0.952**	**1.000**	**0.917**	**0.906**	**0.847**	–0.083
CH_4	**0.858**	**0.917**	**1.000**	**0.995**	**0.974**	–0.158
C_2H_6	**0.854**	**0.906**	**0.995**	**1.000**	**0.969**	–0.160
C_2H_4	**0.733**	**0.847**	**0.974**	**0.969**	**1.000**	–0.320
C_2H_2	0.148	–0.083	–0.158	–0.160	–0.320	**1.000**
Gas percentages						
H_2	0.441	**1.000**	–0.067	**–0.555**	**–0.719**	–0.429
CH_4	**0.812**	–0.067	**1.000**	0.292	–0.336	0.046
C_2H_6	–0.160	**–0.555**	0.292	**1.000**	–0.156	**0.943**
C_2H_4	–0.543	**–0.719**	–0.336	–0.156	**1.000**	–0.213
C_2H_2	–0.353	–0.429	0.046	**0.943**	–0.213	**1.000**

Table 2 shows that the results of the correlation analysis for the gas concentrations and percentage content differ significantly. A significant positive correlation between operation time and gas concentration values is found for all gases except acetylene. At the same time, a significant positive correlation between the gas percentage and the operation time was found only for methane. Hydrogen has the highest value of the paired correlation coefficient between gas concentrations and operation time. Methane has the highest value of the paired correlation coefficient between the gas percentage and the operation time. Despite increasing concentration values, the percentage of ethane, ethylene and acetylene decreases as the defect progresses. A significant correlation between the individual gases was found between all gases except acetylene. A significant correlation between the gas percentage contents was found between acetylene and ethane and between hydrogen and ethane as well as hydrogen and ethylene. At the same time with increasing of hydrogen percentage the ethane and ethylene percentage decreases, which is proved by the negative values of pair correlation coefficients. The results obtained are in good agreement with the findings given in [36], according to which the presence of a significant correlation between the concentrations of gases dissolved in oil and the operation time, as well as between individual gases, is one of the first indications of the presence of a defect. The dynamics of the defect type derived from the values of gas ratios recommended by IEC 60599 [1] in the analysed autotransformer is shown in Fig. 2.

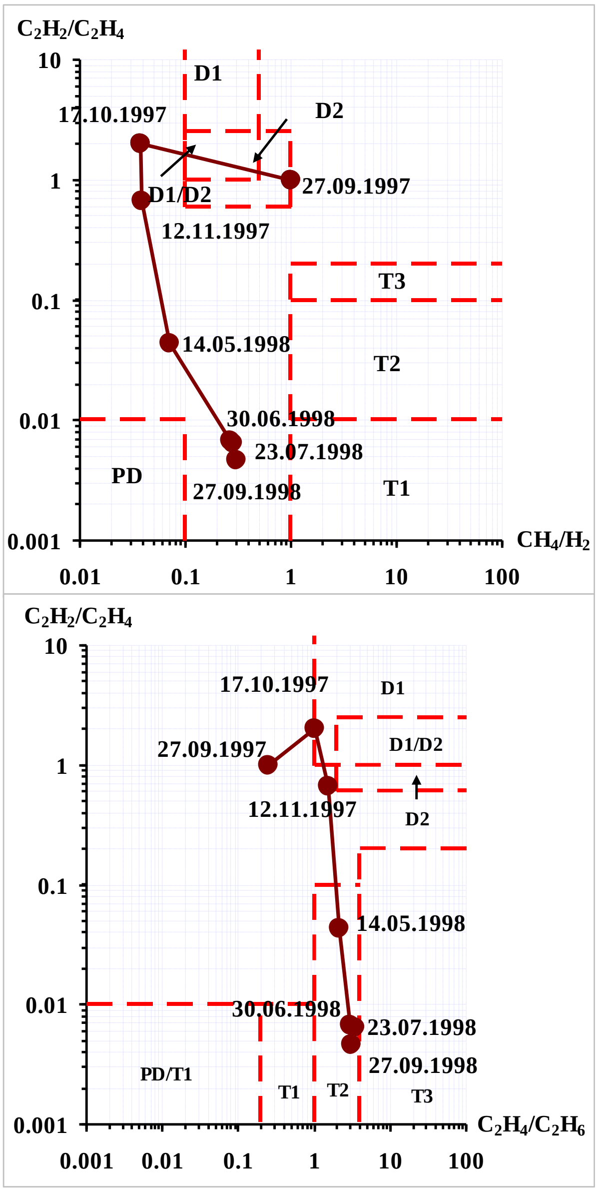


Figure 2 – Dynamics of the defect type in a 330 kV autotransformer damaged by spark discharge according to the values of the gas ratios recommended by IEC 60599

Figure 2 shows that during the development of the defect, the point values showing the diagnosis of the autotransformer shifted from one area to another. At the same time, practically for none of the measurements the diagnosis was established. According to the ETRA square [9] (Fig. 3) the defect started as partial discharges, then transformed into discharges with low energy density, after which it turned into high-temperature overheating accompanied by discharges.

However, during diagnostics of this autotransformer using Duval triangle [8] (see Fig.4) the dynamics of defect type changing was as follows: discharges with high energy density (27.09.1997), discharges with low energy density (17.10.1997), discharges with high energy density (12.11.1997), overheating with temperature 300–700 °C (from 14.05.1998 to 23.07.1998) and high-temperature overheating (27.091998).

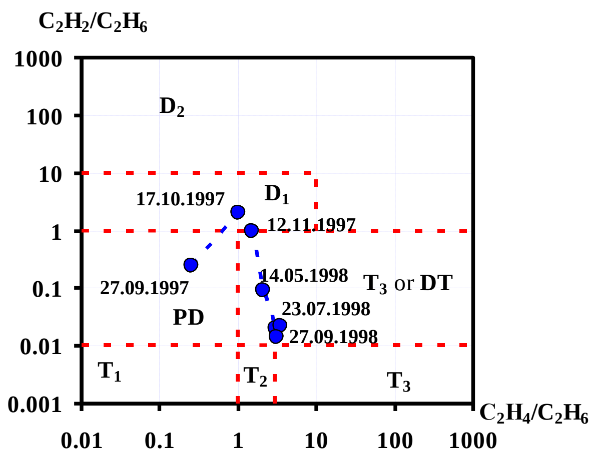


Figure 3 – Dynamics of the defect type in a 330 kV autotransformer damaged by spark discharge according to the values of the gas ratios recommended by the ETRA square

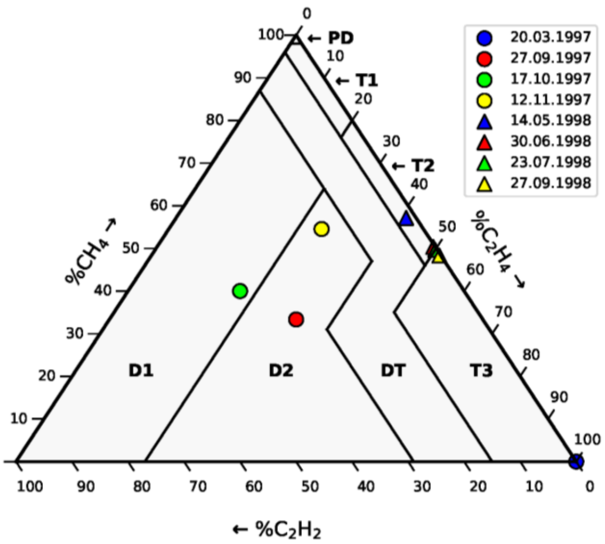


Figure 4 – Dynamics of defect type change in a 330 kV autotransformer damaged by spark discharge during diagnosis using Duval triangle

By analogy with [37, 38], analysis of the dynamics of changes in defect nomograms was also carried out (Fig. 5). Only 5 nomograms out of 8 shown in the figure were regulated by the normative document, valid in Ukraine (based on results of tests of 12.11.1997, 30.06.1998, 23.07.1998 and 23.07.1998). To determine the type of defect based on the results of tests of 23.03.1997 and 27.09.1997 the results of studies given in papers [39–42] were used. Nomogram based on the DGA results of 20.03.1997 corresponds to the combined defect – high-temperature overheating and partial discharges [39]. Nomogram based on the DGA results of 27.09.1997 corresponds to the combined defect – overheating with temperature 150-300 °C and discharges [40–42]. Nomograms made according to DGA results of 17.10.1997 and 12.11.1997 correspond to partial discharges [3, 39]. The nomogram based on the DGA results of 14.05.1998 corresponds to the combined defect of partial discharge and high-temperature overheating [39]. The last three nomograms correspond to spark discharges [3, 34, 39].

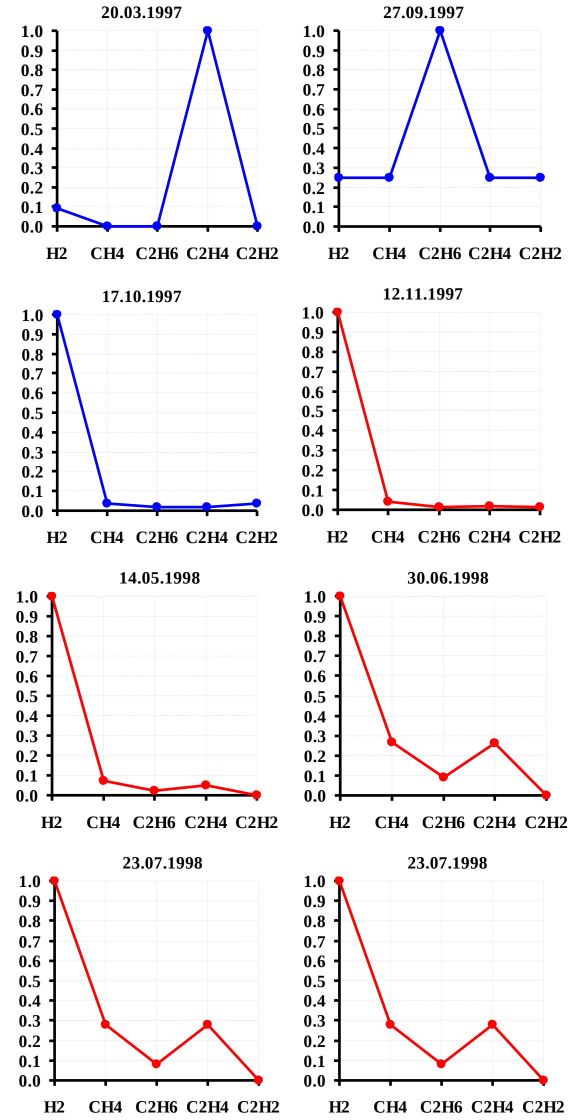


Figure 5 – Dynamics of defect nomograms in a 330 kV autotransformer damaged by spark discharge

Thus, the defect type changed several times during the development of the spark discharges. But the damage to the autotransformer could have been prevented as early as the results of the DGA of 12.11.1997.

Example No. 2. Spark discharges were also detected in the 220 kV autotransformer of Buran substation [37], but this autotransformer was timely taken out for repair. Fig. 6 shows the dependences of gas concentrations and gas percentage on the operation time during the defect development. The first analysis of 04.05.1999 showed that the concentration of acetylene exceeded nearly 40 times the limit value regulated in [3], the concentration of ethylene was 0.0084 % vol. that corresponded to Level 2 in accordance with [3], but the concentration of other gases did not exceed the detection limit of the chromatograph. The next analysis, dated 19.12.1999, showed a decrease in concentrations of acetylene and ethylene, but an increase in concentrations of hydrogen and methane (Fig. 6). This trend was observed until the autotransformer was taken out of service, but the ethane concentration never exceeded the detection limit of the chromatograph.

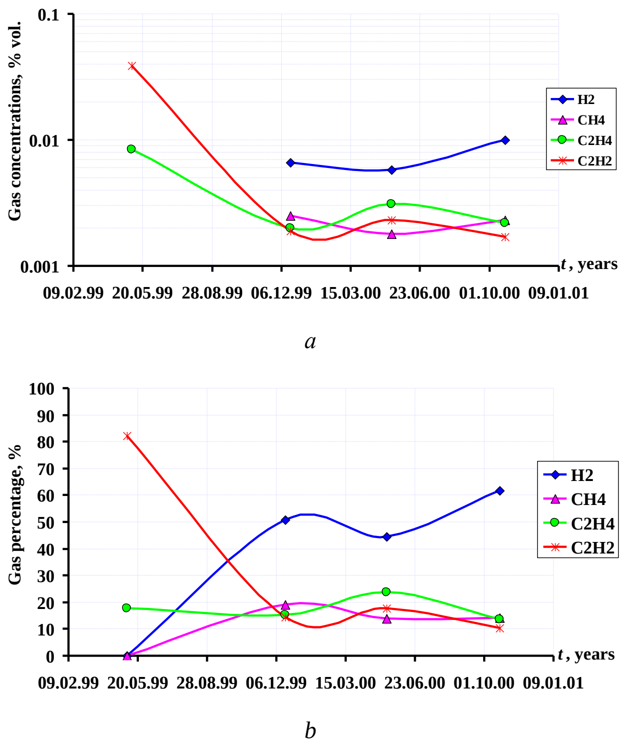


Figure 6 – Dependences of gas concentrations (*a*) and gas percentage (*b*) on operation time in the 220 kV autotransformer of Buran substation during spark discharge development

The results of the correlation analysis shown in Table 3 between the values of concentrations and percentages of gases and the operation duration, as well as between the values of concentrations and percentages of individual gases in the 220 kV autotransformer of Buran substation, differ from the similar results from Table 2. In particular, a significant positive correlation between the operation duration and the values of gas concentrations is found only for hydrogen and methane, for ethylene and acetylene the values of pair correlation coefficients are negative. A significant correlation is detected between the concentrations of all four gases, with a positive correlation (with increasing concentration of one gas, the concentration of the other increases) detected between methane and hydrogen as well as ethylene and acetylene, for all other gas combinations the correlation is negative. Table 3 shows that a significant positive correlation is found between the percentage of hydrogen and operation time, the percentage of acetylene decreases significantly as the defect progresses, and the percentage of methane and ethylene increases but not significantly. It is noteworthy that even though the decrease in ethylene concentration decreases during the defect development its percentage content increases insignificantly. A significant positive correlation was found between the percentage of hydrogen and methane, and a significant negative correlation between the percentage of acetylene and hydrogen as well as acetylene and methane.

Table 3 – Results of correlation analysis between values of concentrations and gas percentages and operation time, as well as between values of concentrations and percentages of individual gases in a 220 kV autotransformer of Buran substation

Gas	Operation time	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Gas concentrations						
H_2	0.939	1.000	0.915	–	–0.923	–0.904
CH_4	0.770	0.915	1.000	–	–0.995	–0.969
C_2H_6	–	–	–	1.000	–	–
C_2H_4	–0.811	–0.923	–0.995	–	1.000	0.989
C_2H_2	–0.836	–0.904	–0.969	–	0.989	1.000
Gas percentages						
H_2	0.833	1.000	0.929	–	0.457	–0.968
CH_4	0.571	0.929	1.000	–	0.523	–0.848
C_2H_6	–	–	–	1.000	–	–
C_2H_4	0.240	0.457	0.523	–	1.000	–0.228
C_2H_2	–0.883	–0.968	–0.848	–	–0.228	1.000

Since during the development of the defect the values of ethane concentrations did not exceed the detection limit of the chromatograph, it is not possible to determine the values of C_2H_4/C_2H_6 ratio, which does not allow to analyse the dynamics of the defect character change using gas ratios regulated by IEC 60599 and the ETRA square. Dynamics of change of defect nature in 220 kV autotransformer of Buran substation using Duval triangle is shown in Fig. 7. The figure shows that the use of Duval triangle for DGA results of the analysed autotransformer, at different stages of defect development, allowed to establish the diagnosis of discharges with high energy density (D2).

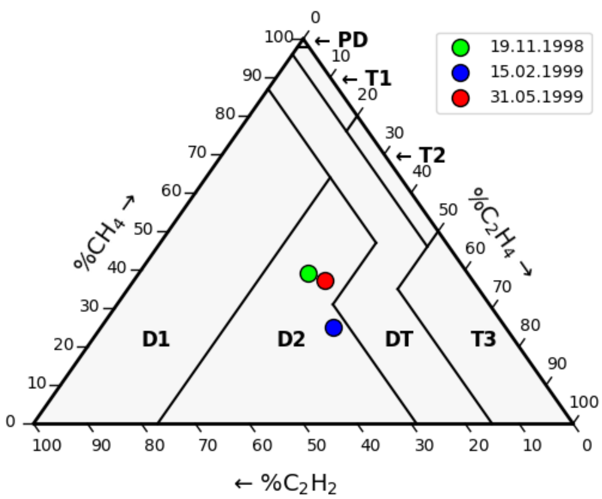


Figure 7 – Dynamics of defect type change in 220 kV autotransformer of Buran substation during diagnostics using Duval triangle

Dynamics of changes of defect nomograms in 220 kV autotransformer of Buran substation is shown in Fig. 8. The nomogram plotted by the DGA results dated 04.05.1999 is not regulated in [3]; however, according to [34, 38, 39], such a nomogram corresponds to discharges with high energy density. The last three nomograms are regulated in [3] and correspond to spark discharges.

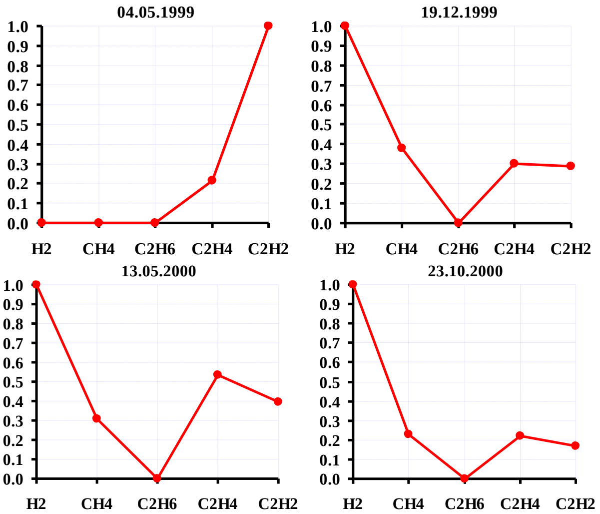


Figure 8 – Dynamics of defect nomograms change in 220 kV autotransformer of Buran substation during spark discharge development

Analysis of the results shows that in the above example, the content of saturated hydrocarbons and hydrogen increased while the content of unsaturated hydrocarbons decreased during the development of the defect. In this case, the presence of the defect could be judged from the test results of 04.05.1999.

Example No. 3. The 40 MVA 110/10/6 kV TDTN (three-phase three-winding transformer with Oil Natural Air Forced cooling and on-load tap-changer) transformer was taken out of service due to "fire in the magnetic core" caused by spark discharges. Of all 5 gases analysed, only acetylene exceeded the concentration limit values and that at the time of the last test. The dependences of gas concentrations and percentage of gases on the operation time in a 40 MVA TDTN transformer are shown in Fig. 9. Table 4 shows the results of the correlation analysis between the values of concentrations and percentages of gases and the operation time, as well as between the values of concentrations and percentages of individual gases.

Comparison of the results shown in Table 4 with the similar results from Tables 2 and 3 shows that in the development of defects of the same type, the dynamics of changes in both gas concentrations and the percentage content are significantly different. In a 40 MVA TDTN transformer the values of the pair correlation coefficients between operation time and gas concentrations are lower than the values of the pair correlation coefficients between operation time and gas percentage content. In contrast, the situation in the 330 kV autotransformer (see Table 2) is reversed. Table 4 shows that acetylene, ethylene and hydrogen have the most significant correlation with operation time. A significant correlation is found between the concentrations of all gases, and a significant correlation between the gases percentage is found for all gases except methane.

The dynamics of changing the defect type in a 40 MVA TDTN transformer according to the gas ratios recommended by IEC 60599 [1] is shown in Fig. 10.

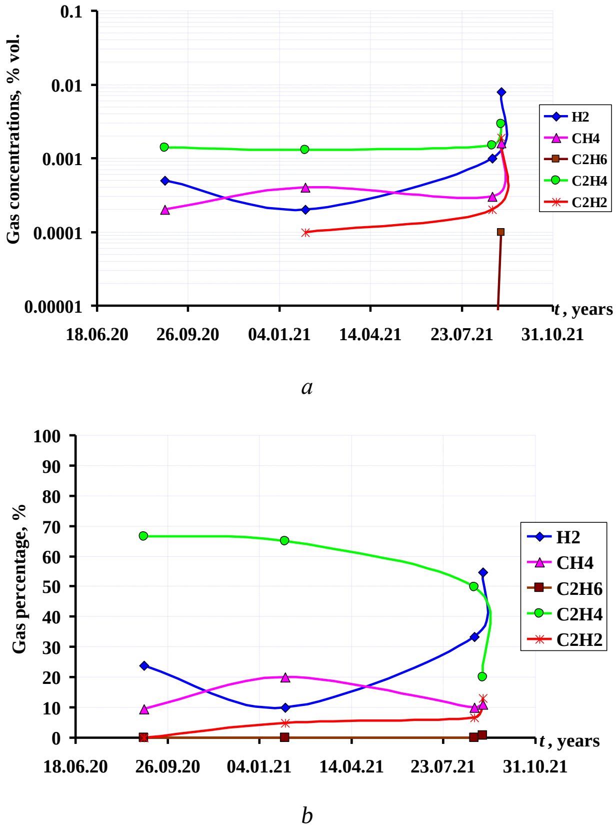


Figure 9 – Dependences of gas concentrations (*a*) and gas percentage (*b*) on operation time in a 40 MVA 110/10/6 kV TDTN transformer during spark discharge development

Table 4 – Results of correlation analysis between values of concentrations and gas percentages and operation time, as well as between values of concentrations and percentages of individual gases in 40 MVA and 110/10/6 kV transformer

Gas	Operation time	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Gas concentrations						
H_2	0.607	**1.000**	**0.984**	**0.996**	**1.000**	**0.997**
CH_4	0.598	**0.984**	**1.000**	**0.992**	**0.980**	**0.994**
C_2H_6	0.559	**0.996**	**0.992**	**1.000**	**0.994**	**0.996**
C_2H_4	0.606	**1.000**	**0.980**	**0.994**	**1.000**	**0.995**
C_2H_2	**0.631**	**0.997**	**0.994**	**0.996**	**0.995**	**1.000**
Gas percentages						
H_2	**0.891**	**1.000**	–0.626	**0.863**	**–0.940**	**0.772**
CH_4	–0.248	–0.626	**1.000**	–0.211	0.326	–0.018
C_2H_6	**0.998**	**0.863**	–0.211	**1.000**	**–0.939**	**0.856**
C_2H_4	**–0.960**	**–0.940**	0.326	**–0.939**	**1.000**	**–0.938**
C_2H_2	**0.876**	**0.772**	–0.018	**0.856**	**–0.938**	**1.000**

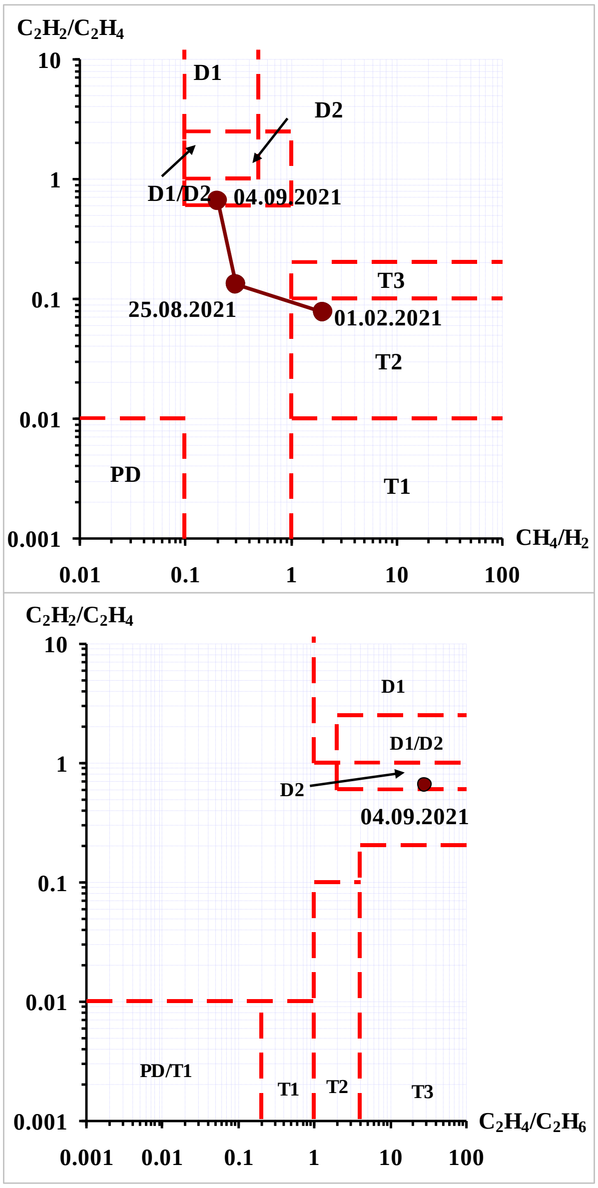


Figure 10 – Dynamics of defect type change in a TDTN 40 MVA transformer during spark discharge development according to the values of gas ratios recommended in IEC 60599

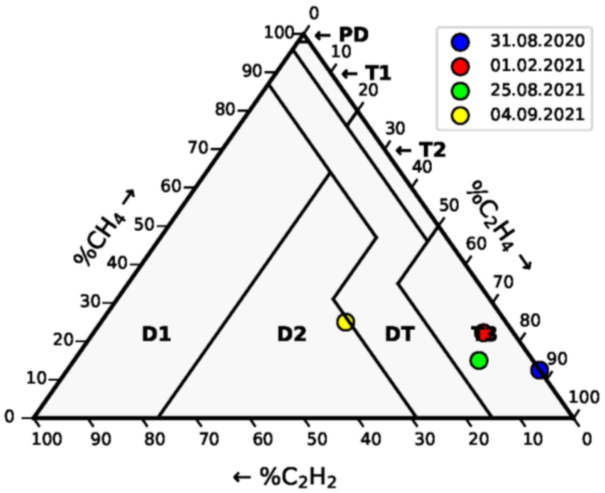


Figure 11 – Dynamics of defect type change in a 40 MVA TDTN transformer using Duval triangle diagnostics

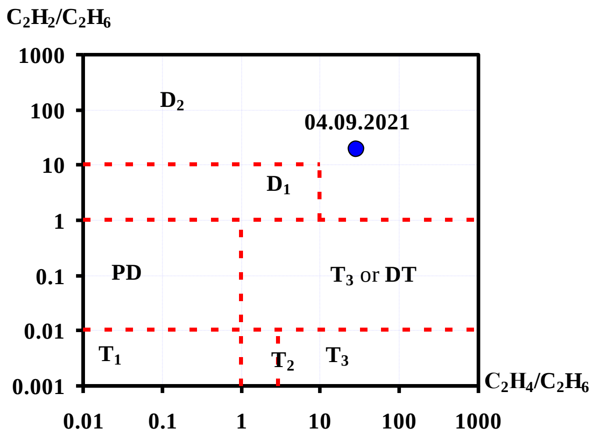


Figure 12 – Diagnostic results of the defect type in a 40 MVA TDTN transformer according to the values of the gas ratios recommended by the ETRA square

The figure shows that the values of gas ratios varied over a fairly wide range during the development of the defect, but it was not possible to establish a diagnosis for any of the measurements.

Using the Duval triangle (Fig. 11), the presence of high-temperature overheating was established for the DGA results of 31.08.2020, 01.02.2021 and 25.08.2021. However, for the test results of 04.09.2017, corresponded to a combined defect (DT) passing into high energy density discharges.

As the ethane content in the first three oil samples was below the detection limit of the chromatograph during the development of the defect, the use of the ETRA square did not allow analysing the dynamics of the defect type in a given diagnostic space. However, for the last test results of 04.09.2021, the diagnosis was high energy density discharges (Fig. 12).

The dynamics of changes in nomograms in the process of spark discharges development is shown in Fig. 13. According to the figure the nomograms plotted by DGA results of 31.08.2020 and 25.08.2021 correspond to the presence of high-temperature overheating and spark discharges [39], the nomogram of 01.02.2021 is typical for high-temperature overheating and the nomogram of 04.09.2021 corresponds to spark discharges [3, 26, 34].

It is noteworthy that in the DGA results of this transformer dated 31.08.2020 and 25.08.2021, the hydrogen content exceeds the methane content, which is not typical for non-sealed transformers. As shown in [43], the hydrogen content is usually lower than the methane content due to the diffusion of hydrogen into the atmosphere due to its low solubility in oil in non-sealed equipment. This circumstance (excess of hydrogen content over methane content) can be used as an initial indication of the presence of electrical discharges in non-sealed oil-filled equipment.

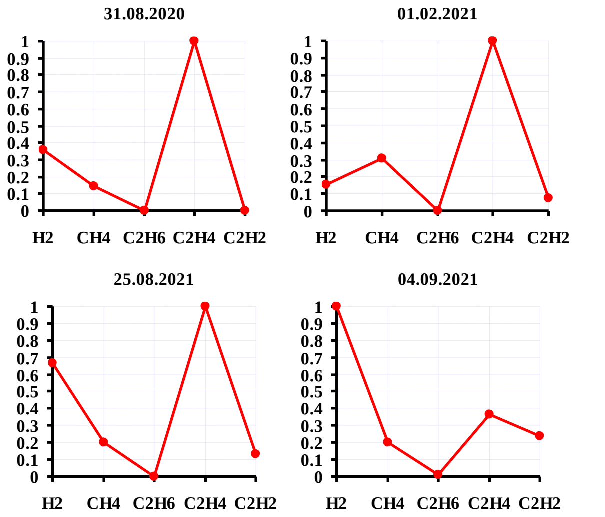


Figure 13 – Dynamics of defect nomograms in a 40 MVA TDTN transformer during spark discharge development

Example No. 4. The DGA results of an autotransformer 125 MVA 220/110 kV dated 17.03.2003 revealed spark discharges [44]. Since the authors have available DGA results only for the last three tests, no analysis of correlation relationships between values of concentrations and percentages of gases and operation time, as well as between values of concentrations and percentages of individual gases was performed for this autotransformer. The evolution of the type of defect in the analysed autotransformer in the diagnostic space regulated by the IEC 60599 standard is shown in Fig. 14. The figure shows that the use of the gas ratios recommended by IEC 60599 allowed a diagnosis to be made in only one case out of three. In particular, for the first analysis from 28.08.2002, the values of gas ratios corresponded to overheating with a temperature above 700 °C, while the value of ethylene concentration corresponded to Level 2, which, according to [3], indicates the possible presence of a defect. For measurements from 24.01.2003 and 17.03.2003 no diagnosis was established, because, according to the figure, the points representing transformer conditions do not fall into any of the diagnosis areas. In the oil sample from 24.01.2003 the concentration of ethylene exceeds the limit value of Level 2, and concentrations of other gases correspond to Level 1. In the oil sample from 17.03.2003 the concentration values of hydrogen and acetylene exceed the limit value of Level 2, concentrations of ethylene and methane correspond to Level 2 and concentrations of ethane correspond to Level 1.

The use of the ETRA square (Fig. 15) enabled a diagnosis to be made on the results of all three tests. So for the results of DGA of 28.08.2002 a diagnosis of overheating with temperature above 700 °Cwas given, and for the results of DGA of 24.01.2003 and 17.03.2003 a combined defect was diagnosed – overheating with temperature above 700 °Caccompanied by discharges.

The diagnosis of this autotransformer using Duval triangle (Fig. 16) produced opposite diagnoses. Thus, the DGA results of 28.08.2002 were interpreted as a combined defect, while the DGA results of 24.01.2003 and 17.03.2003 were interpreted as overheating with a temperature above 700 °C.

This example clearly illustrates that the use of different methods and criteria for interpreting DGA results for the same data can lead to different diagnoses.

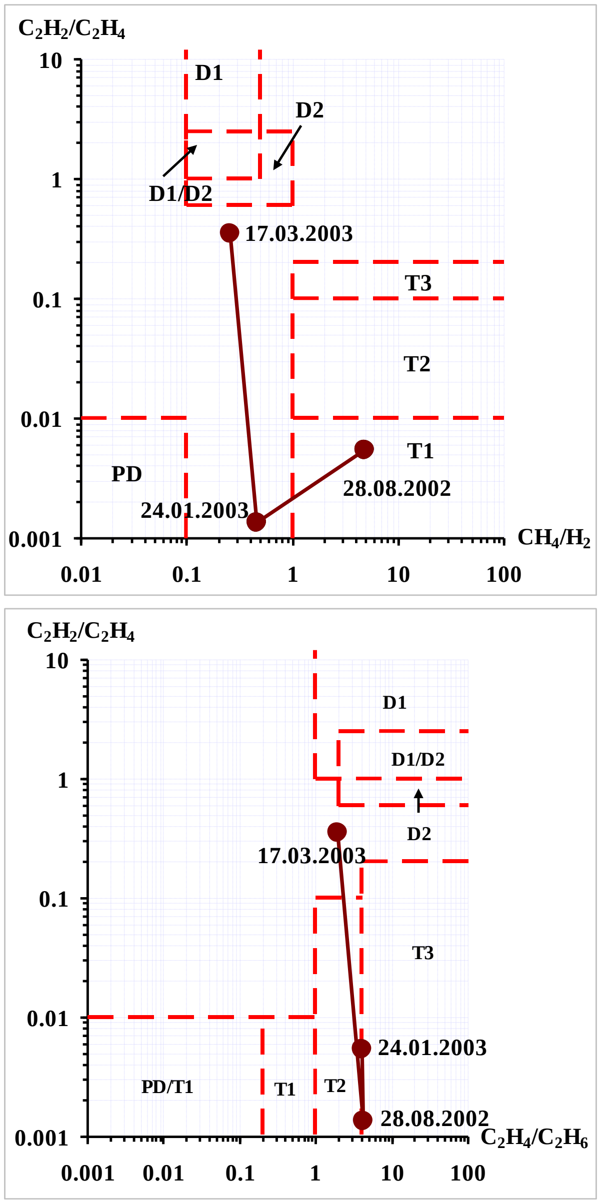


Figure 14 – Dynamics of change of defect type in a 125 MVA 220/110 kV autotransformer during spark discharge development according to the values of gas ratios recommended in IEC 60599

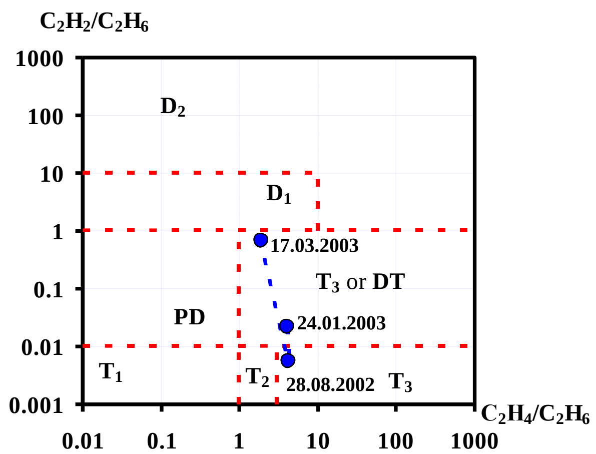


Figure 15 – Dynamics of change in defect type in a 125 MVA 220/110 kV autotransformer according to the values of the gas ratios recommended by the ETRA square

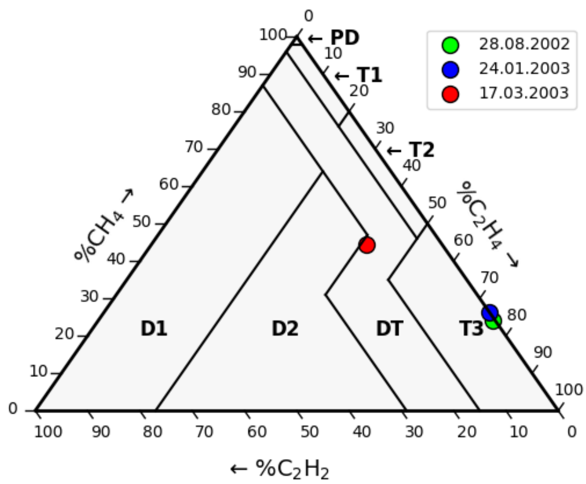


Figure 16 – Dynamics of change in defect type in a 125 MVA 220/110 kV autotransformer using Duval triangle diagnosis

Dynamics of nomogram change in autotransformer 125 MVA 220/110 kV is shown on Fig. 17. Nomogram based on DGA results from 28.08.2002 corresponds to overheating with temperature above 700 °C [3]. The nomogram based on DGA results from 24.01.2003 corresponds to overheating with temperature above 700 °C accompanied by spark discharges [39], and the nomogram based on DGA results from 17.03.2003 corresponds to spark discharges [3, 34, 39].

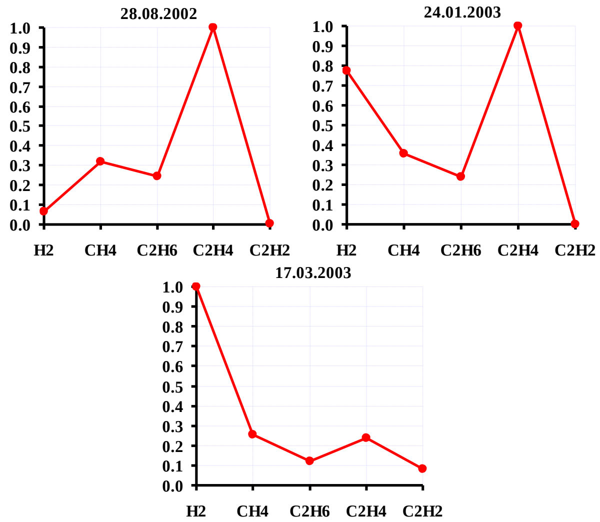


Figure 17 – Dynamics of defect nomograms in a 125 MVA 220/110 kV autotransformer during spark discharge development

Example No. 5. In the 35 kV transformer the spark discharge was detected by the DGA results of 31.05.1999, at that out of 5 analysed gases the limit value was exceeded only by acetylene concentration, ethylene concentration corresponded to Level 2, and concentration of other gases - to Level 1. It should be noted that in two previous oil samples dated 19.11.1998 and 15.02.1999 the gas concentration values corresponded to Level 1, that is, the serviceable condition. Due to the small sample size of this transformer, no correlation analysis was carried out between the values of concentrations and percentages of gases and the operation time as well as between the values of concentrations and percentages of individual gases.

The results of diagnostics of this transformer using the values of gas ratios recommended by IEC 60599 at different stages of defect development are shown in Fig. 18. The figure shows that of the three DGA results the use of the IEC 60599 standard allowed to establish a diagnosis only for the results of the first analysis of 19.11.1998 with overheating with a temperature of 300-700 °C. For the DGA results of 15.02.1999 and 31.05.1999 no diagnosis was made, since the figure shows that the points representing the condition of the transformer do not fall into any of the diagnosis areas.

Using the ETRA square to diagnose this transformer allowed a diagnosis to be made for all three test results (Fig. 19).

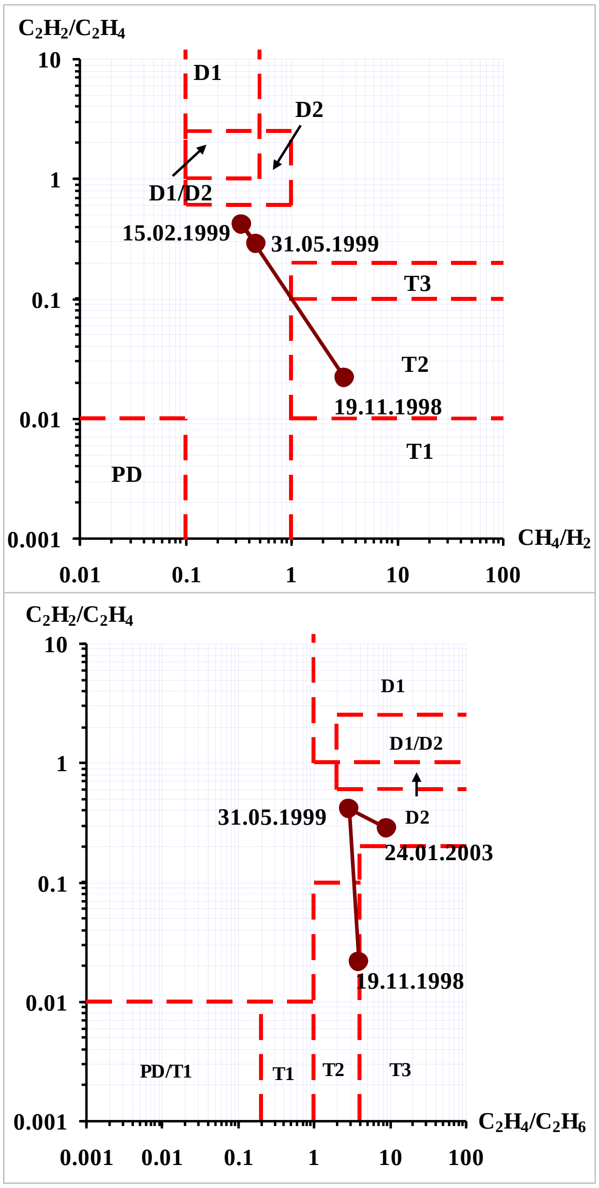


Figure 18 – Dynamics of change of defect type in a 35 kV transformer during spark discharge development according to the values of gas ratios recommended in IEC 60599

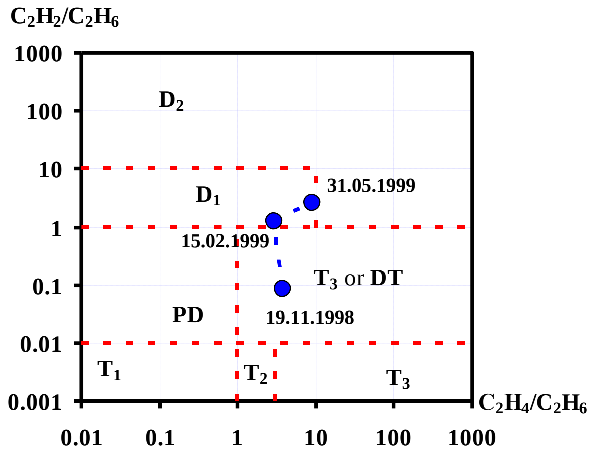


Figure 19 – Dynamics of the defect type in a 35 kV transformer, according to the values of the gas ratios recommended by the ETRA square

The figure shows that the DGA result of 19.11.98 diagnosed overheating with a temperature above 700 °C accompanied by discharges. The DGA results of 15.02.1999 and 31.05.1999 diagnosed low energy density discharges.

Diagnostics with Duval triangle (Fig. 20), DGA result of 19.11.98 were interpreted as overheating with temperature above 700 °C, and DGA results of 15.02.1999 and 31.05.1999 diagnosed a combined defect (discharges accompanied by heating).

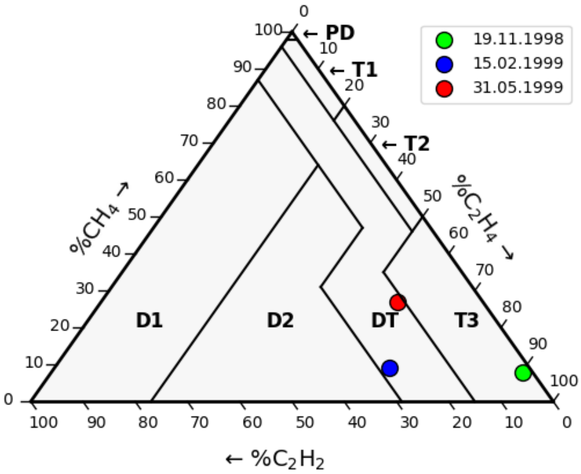


Figure 20 – Dynamics of change in defect type in a 35 kV transformer with Duval triangle diagnosis

According to the Nomogram method (Fig. 21) the DGA result of 19.11.98 correspond to a high-temperature overheating accompanied by discharges [3, 39].

The DGA result obtained on 15.02.99 also correspond to a combined defect, namely, high-temperature overheating accompanied by spark discharges [39]. The result of 31.05.1999 correspond to spark discharges [3, 34, 39].

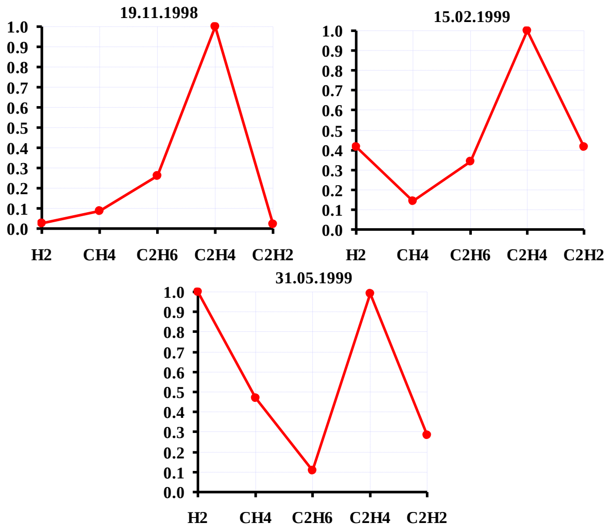


Figure 21 – Dynamics of defect nomograms in 35 kV autotransformer during spark discharge development

Conclusions. The analysis shows that in the five transformers analysed the values of diagnostic criteria at different stages of the defect development correspond to defects of different types, which does not allow predicting this defect based on the results of previous tests. At the same time the examples illustrate that the defect development takes place before the gas concentration values exceed their limit values, which enables early detection of spark discharges in high-voltage power transformers based on the DGA results. It was found that the standards and criteria regulated by IEC 60599, ETRA square and Duval triangle do not allow spark discharges to be detected as these methods do not have the areas characteristic for this type of defect and the highest number of correct diagnoses was made using the nomogram method. For all five examples given, the change of the defect type in the course of its development is observed, and consequently, when assessing the possibility of further operation of transformers, besides the degree of danger of the defect and the speed of its development, the possibility of transformation of the defect from less to more "dangerous" and fast-developing one must be taken into account. The obtained results demonstrate the possibility of early detection of spark discharges, which allows increasing the reliability of nondestructive diagnostics and prolonging the service life of transformers.

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