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Effectiveness assessment of selected graphical techniques for the interpretation of measured concentrations of gases dissolved in transformer oil

Abstract. *The article describes selected graphical methods (Duval triangle, Duval pentagon and Mansour pentagon), which may be used for the analysis of gases dissolved in oil of power transformers. The effectiveness of recognizing the basic types of defects by these methods was assessed. This is of significant importance for the services responsible for maintaining transformers in operation.*

Streszczenie*. W artykule opisano wybrane metody graficzne (trójkąta i pięciokąta Duvala oraz pięciokąta Mansoura), które można stosować do analizy gazów rozpuszczonych w oleju transformatorów energetycznych. Oceniono skuteczność rozpoznawania przez te metody podstawowych typów defektów. Ma to istotne znaczenie dla służb odpowiedzialnych za utrzymanie transformatorów w ruchu. (****Ocena skuteczności wybranych technik graficznych do interpretacji zmierzonych stężeń gazów rozpuszczonych w oleju transformatorowym****).*

Keywords: power transformer, oil-paper insulation, diagnostics, DGA
Słowa kluczowe: transformator energetyczny, izolacja papierowo-olejowa, diagnostyka, DGA.

Introduction

Oil-paper insulation, typically used in the power transformer, both during normal operation and during electrical or thermal disturbances decomposes. During this process, gases are generated (H_2 - hydrogen, CH_4 - methane, C_2H_6 - ethane, C_2H_4 - ethylene, C_2H_2 - acetylene, CO - carbon monoxide and CO_2 - carbon dioxide) which partially remain dissolved in the oil.

Experience shows that the amount and composition of gases dissolved in oil allows to conclude about the occurrence of a defect in the transformer and its type. General information on the decomposition product of the oil insulation formed during different types of fault are given in Table 1. If the defect comprises the cellulose insulation carbon monoxide and carbon dioxide are also appear. Since taking an oil sample from a working transformer and then determining the type and amount of dissolved gases is a simple and cheap procedure, their analysis (marked with the acronym DGA) is the basic method of diagnosing the technical condition of the transformer.

Tab. 1. Decomposition product of the oil insulation formed during different types of fault [1, 2]

Fault type	Gases
Partial discharges	H_2, CH_4 (C_2H_4, C_2H_6)
Discharges	H_2, C_2H_2 (CH_4, C_2H_4)
Thermal faults	CH_4, C_2H_6, C_2H_4, H_2
In parentheses are given the gases associated in small quantities.	

On the occurrence of a defect, one concludes by comparing the currently measured values of gas concentrations with typical values. Typical values are determined on the basis of statistical analysis of gases dissolved in oil of transformer groups with common characteristics (e.g. on-load tap-changer). The intensity of the defect can be assessed to a certain extent by comparing the changes in gas concentration values between consecutive measurements with the typical values of such changes. Typical values of changes in gas concentrations over time are also determined for similar groups of transformers using statistical analysis. An attempt to identify the source (type) of a defect, understood as, for example, overheating in a certain temperature range, or partial discharges, is a more complicated task.

Currently many methods exist to identify the nature of potentially developing defects. Traditional methods used for this purpose include the key gas method [1], ratio methods (e.g. Rogers [1], Doernenburg [1], IEC [2]) and graphical methods (e.g. Duval triangle [3], Duval pentagon [4], Mansour pentagon [5, 6]). In addition, there is a whole group of techniques using computational intelligence methods. These methods utilize, among others: artificial neural networks, Bayesian networks, fuzzy sets, Dempster-Shafer theory, artificial immune systems, particle swarm optimization [7-11].

Among the traditional DGA methods, graphical methods are worth special attention, because one of the basic disadvantages of the ratios methods has been eliminated - no diagnosis, for special, not rare, mutual relations between the measured gas concentrations. The article presents three of the previously mentioned methods, namely the method: Duval triangle, Duval pentagon and Mansour pentagon. Next, the results of the estimation of the effectiveness of recognizing the basic types of defects by them were presented. For the latter purpose was used data came from several hundred transformers in which the defect was found and its type was recognized.

All calculations related to recognizing the nature of the defect on the basis of DGA were carried out using a computer program developed by the author.

Review of selected graphical methods

Duval triangle method

In the literature [3, 12], several versions of the Duval triangle are described. Due to the purpose of the study, only the basic version of the triangle will be recalled.

In the basic version of the Duval triangle, designed to recognize defects in transformers with oil - paper insulation, the concentrations of C_2H_2, CH_4, C_2H_4 are used.

The algorithm of the method requires determining the percentage participation of each of these gases in their sum according to equations set:

$$
\begin{aligned}
\%CH_4 &= \frac{100 \cdot CH_4}{CH_4 + C_2H_2 + C_2H_4} \\
\%C_2H_2 &= \frac{100 \cdot C_2H_2}{CH_4 + C_2H_2 + C_2H_4} \qquad (1) \\
\%C_2H_4 &= \frac{100 \cdot C_2H_4}{CH_4 + C_2H_2 + C_2H_4}
\end{aligned}
$$

The obtained values are coordinates that define the position of the point inside the Duval triangle. The method for determining the position of the point based on the knowledge of the coordinates is shown in Figure 1. It can be seen that the section: run from the value deposited on the side C_2H_4 must be parallel to the side CH_4, run from the value deposited on the side C_2H_2 must be parallel to the side C_2H_4 and finally, run from the value deposited on the side CH_4 must be parallel to the side of C_2H_2. All sections always intersect at one point.

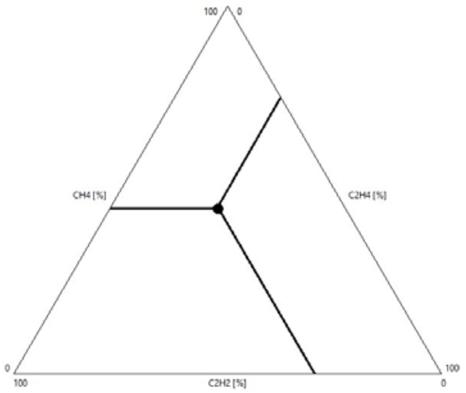

Fig. 1. The method of determining the position of a point inside a Duval triangle based on the coordinates $\%C_2H_2$, $\%CH_4$ and $\%C_2H_4$

The Duval triangle is divided into six zones that correspond to specific types of defects. The location of the point inside the triangle thus indicates a defect present in the transformer. The areas corresponding to different types of detected defects are shown in Figure 2. The names of the areas correspond to the following defects: PD - partial discharges, D1 and D2 - discharges of low and high energy respectively, DT - electrical and thermal defect, T1, T2 and T3 - thermal defect at a temperature: T<300°C, 300°C <T <700 °C and T>700°C respectively.

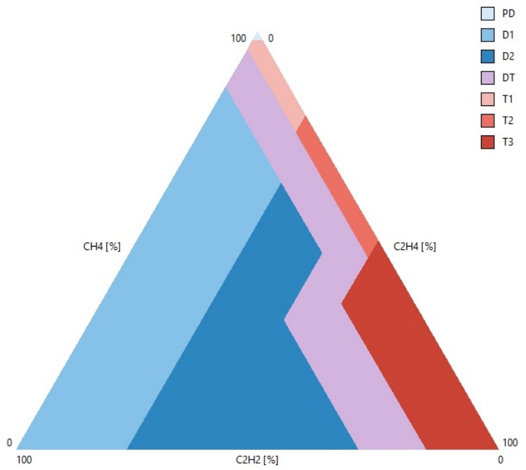

Fig. 2. Location of defect zones in the basic variant of the Duval triangle

Duval pentagon method

The method uses 5 gases: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2 [4, 12]. For each gas, the percentage participation of its concentration in the total concentration of all gases is determined.

Each of the calculated percentages of concentrations should then be placed on the appropriate axis drawn from the center of the pentagon to one of the vertices. The axes are calibrated in such a way that the point in the middle of the pentagon corresponds to 0%, and in the vertex to 100% of the concentration of a given gas in the total concentration of all gases. After marking all the values on the axes, the points are connected with sections. As a result, a polygon for which the center of gravity should be determined (Figure 3a) is obtained. The "center of gravity" always lies within the smaller pentagon defined by the points corresponding to the 40% of the relative concentration of each gas. Inside this smaller pentagon, zones corresponding to various types of defects are marked, so the position of the designated center of gravity points to one of them (Figure 3b).

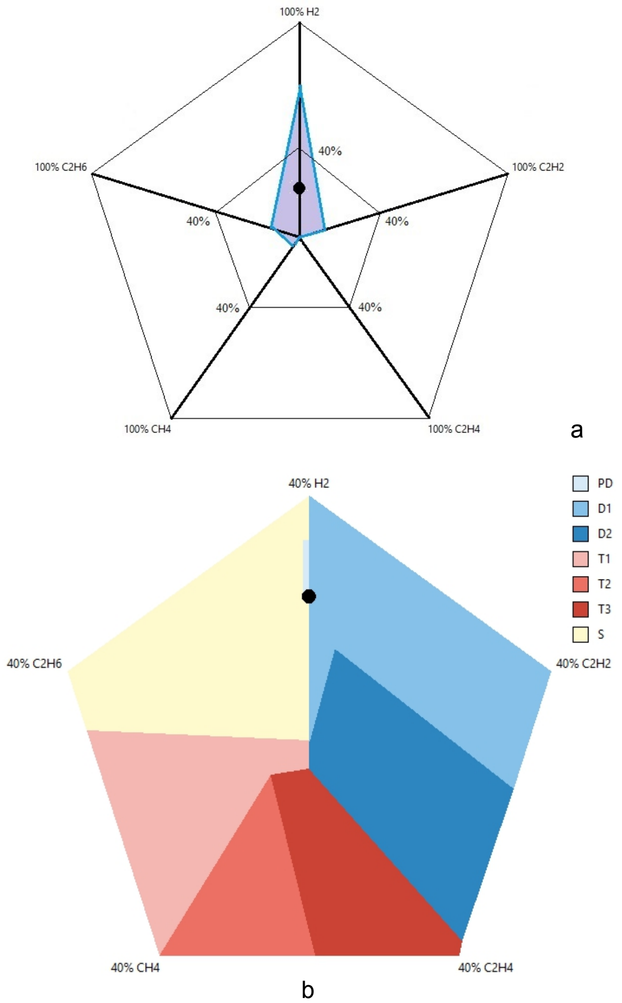

Fig. 3. Location of the defect in the Duval pentagon method

Designations of individual zones and defects are corresponding to those found in the Duval triangle method. There is also a new area marked with the symbol S associated with "parasitic gases".

Mansour pentagon method

In this method [6] the same gases are used as in the Duval pentagon method. For each of them, the percentage participation of its concentration in the total concentration of all gases is determined.

Each of the gases used in the method is associated with one of the vertices of the pentagon. Starting from the highest apex and moving in a clockwise direction, they are successively H_2, CH_4, C_2H_4, C_2H_6 and C_2H_2. In order to determine the nature of the defect, a calculated percentage of the gas represented by it in a total concentration of all gases is assigned to each of the vertices. Then the point corresponding to the "center of gravity" of the pentagon is determined. Because the pentagon is divided into the zones associated with defects of different character (Figure 4), the position of the "center of gravity" allows to determine what defect occurs in the transformer.

The designations of individual zones and the corresponding defects are consistent with those of the Duval triangle method.

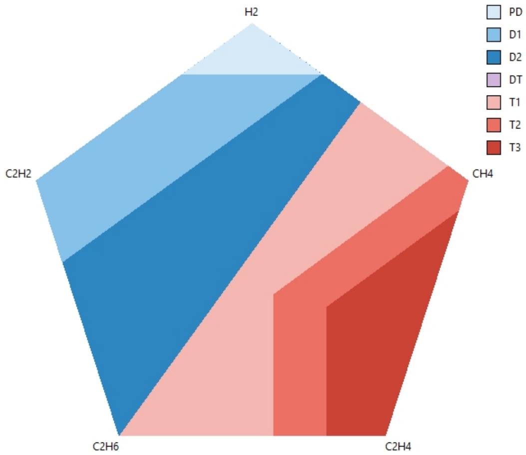

Fig. 4. Location of defect zones in the Mansour pentagon.

Materials and methods

In order to estimate the effectiveness of the described graphical methods, 411 sets of measured gas concentrations were analyzed. They came from transformers where fault was found and its type identified. Since the faults were described with varying accuracy, the collected data was divided into three categories of defects. As a result, 216 measurement sets represented thermal defects occurring in the transformer, 152 sets represented discharges and 43 sets represented partial discharges.

In order to evaluate the effectiveness of recognizing a given type of defect and overall effectiveness by the compared methods, the values of the S_{di} and S_d indicators defined by the formula (2) and (3) were calculated.

$$S_{di} = \frac{N_{pdi}}{N_{di}} \cdot 100\% \tag{2}$$

$$S_d = \frac{N_{pd}}{N_d} \cdot 100\% \tag{3}$$

where: N_{pdi} - number of correctly recognized defects of i-th type, N_{pd} - number of correctly recognized defects of all types, N_{di} - number of measurement sets representing the defect of i-th type, N_d - the number of all measurement sets.

The graphical methods selected for comparison recognize the same types of defects, so only minimal modification has been introduced, ignoring the indicated temperature range in the case of thermal defects and energy released in the case of discharges. In this way, the number and nature of defects recognized by the methods were consistent with the number and nature of defects represented by the measurement data.

Effectiveness of defects recognition by graphical methods

The results obtained using the Duval triangle method for analyzing data associated with the partial discharge faults are shown in Figure 5. Because this method definitely is the worst for detection partial discharges occurring in the transformer, Figure 6 shows the results obtained for the best one, namely Mansour pentagon method.

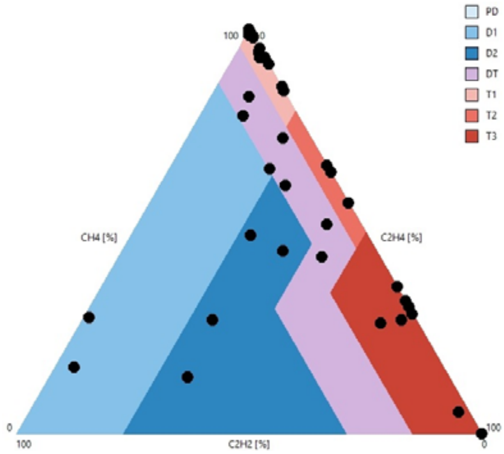

Fig. 5. Defects recognized by the Duval triangle method for data came from transformers in which partial discharges were found.

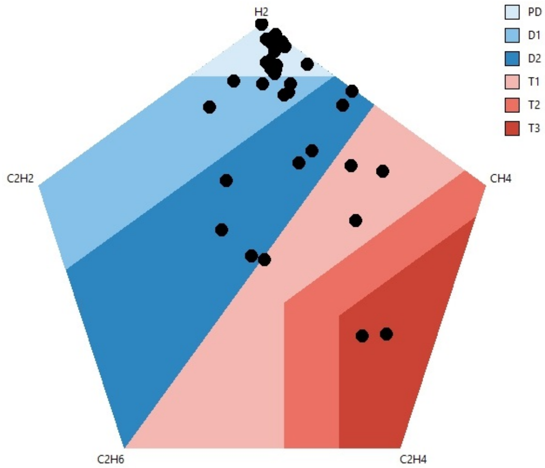

Fig. 6. Defects recognized by the Mansour pentagon method for data came from transformers in which partial discharges were found.

Similarly the results obtained using the Duval pentagon method and Mansour pentagon method for data associated with the discharge faults and thermal faults are shown in Figure 7 and 8 respectively.

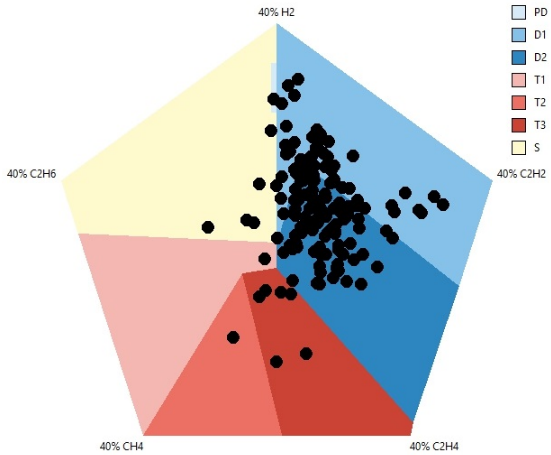

Fig. 7. Defects recognized by the Duval pentagon method for data came from transformers in which discharges were found.

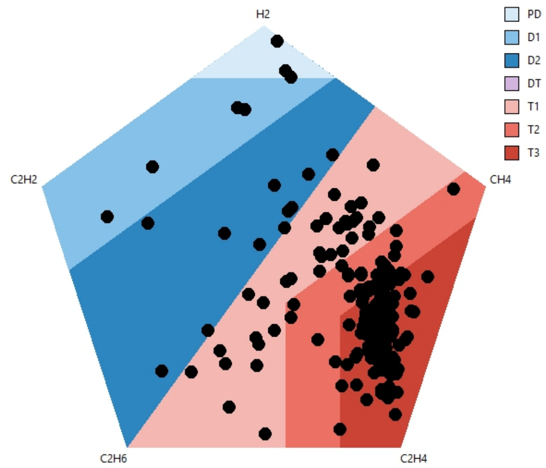

Fig. 8. Defects recognized by the Mansour pentagon method for data came from transformers in which thermal faults were found.

The results of estimation of the effectiveness of identifying basic defect types and overall effectiveness are presented in Table 2 and Table 3 respectively.

Tab. 2. Effectiveness [%] of recognizing basic defect types by analyzed graphical methods

	Duval triangle	Duval pentagon	Mansour pentagon
Partial discharges	16,28	27,91	**55,81**
Discharges	**93,42**	90.79	84,87
Thermal faults	**91,67**	87,50	90,74

Tab. 3. Overall effectiveness [%] of recognizing defect types by analyzed graphical methods

	Duval triangle	Duval pentagon	Mansour pentagon
All defect types	67,12	68,73	**77,14**

Summary

The paper presents three graphical DGA methods supporting recognition of defects of electrical or thermal nature, which may occur in power transformers.

The graphical methods, in contrast to other methods (key gas or ratio methods) [13] in all cases indicate the occurrence of a defect, but not always in the correct way.

The analysis carried out showed that all the presented methods are the least successful in recognizing defects such as partial discharges. The author's experience [14], as well as literature reports [13] show that this situation also applies to other, so called conventional methods. Among the methods presented in the paper, Mansour pentagon method was the best to perform this task (its effectiveness was 2-3 times higher than other ones).

It turns out that the referenced Mansour pentagon method, also very well recognizes other types of defects, so it is worth considering, after gaining more experience, to include it for the routine DGA methods.

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