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Proposal of a new method for interpreting the concentrations of gases dissolved in mineral transformer oil

***Abstract**. The measurement and subsequent interpretation of the concentrations of gases dissolved in mineral oil is one of the basic procedures allowing the assessment of the technical condition of power transformers with oil-paper insulation. The article proposes a new method for interpreting measured gas concentrations. The achieved fault recognition efficiency is comparable to other classical methods and, in the case of partial discharges (PD), significantly exceeds them.*

***Streszczenie.** Pomiar, a później interpretacja stężeń gazów rozpuszczonych w oleju mineralnym jest jedną z podstawowych procedur pozwalających ocenić stan techniczny transformatorów energetycznych o izolacji papierowo-olejowej. W artykule zaproponowano nową metodę interpretacji pomierzonych stężeń gazów. Uzyskana skuteczność rozpoznawania defektów jest porównywalna z innymi klasycznymi metodami, a w przypadku wyładowań niezupełnych (wnz), istotnie je przewyższa.(**Propozycja nowej metody interpretacji stężeń gazów rozpuszczonych w mineralnym oleju transformatorowym**)*

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

Introduction

The measurement and subsequent interpretation of the concentrations of gases dissolved in mineral oil (hereinafter simply referred as oil) is one of the basic procedures allowing the assessment of the technical condition of power transformers with oil-paper insulation. This is because thermal and electrical stresses and aging processes lead to the degradation of oil and cellulose insulation. Degradation products include, among others, gases that dissolve in oil: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2). Based on the measured concentrations of the aforementioned gases, conclusions can be drawn about the presence of the potential fault and its nature [1-3].

A number of conventional [4-6] and utilising artificial intelligence algorithms [7] methods have been developed to recognize the nature of the faults based on the knowledge of the concentrations of gases dissolved in the oil. Among the conventional ones, the most well-known include the key gas method, Rogers method, Doernenburg method, ratio method according to IEC 60599, Duval triangle and Duval pentagon methods. Unfortunately, none of the methods developed to date, both conventional and using artificial intelligence algorithms, identify defects with 100% efficiency [8, 9]. Therefore, there is still a need for further attempts to create methods with easy implementation, clear inference rules and significant efficiency.

General idea of the proposed method

The method uses information about the concentrations of the five gases: H_2, CH_4, C_2H_6, C_2H_4 and C_2H_2. The listed gases should be pre-processed by determining their relative concentrations RC. For example, the relative concentration of hydrogen – RC(H_2) – is the ratio of the H_2 concentration in ppm and the sum of the concentrations in ppm of all gases taken into account in the method, according to the formula:

$$RC(H_2) = \frac{H_2}{H_2 + CH_4 + C_2H_6 + C_2H_4 + C_2H_2} \quad (1)$$

The method consists of two stages. In the first stage, a distinction is made between electrical and thermal type fault; in the second stage – depending on the result of the first one, PD/D1/D2 or T1/T2/T3 faults are distinguished, respectively. The fault designations used mean: PD – partial discharges, D1 – low-energy discharges, D2 – high-energy discharges, T1 – thermal fault with a temperature < 300°C, T2 – thermal fault with a temperature in the range of 300°C÷700°C, T3 – thermal fault with temperature > 700°C.

Determining the general nature of the defect in the first stage involves comparing the sum of the relative concentrations of H_2 and C_2H_2 with the criterion value, which, will be given in one of the following sections.

One may observe that the relative concentrations of individual gases or its combinations for recognised faults of the same type (same class) are close to each other – in other words, they form more or less coherent clusters. The above observation, for faults of thermal nature (i.e. T1, T2, T3) is illustrated in Figure 1, using as the example the C_2H_6 and C_2H_4 gas pair

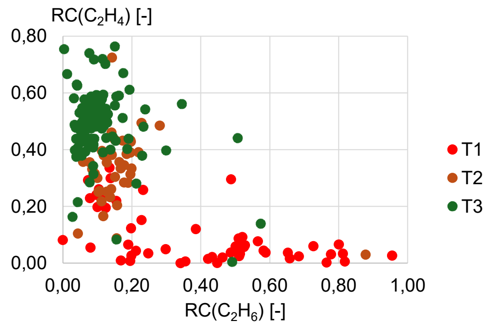

Fig.1. Relative concentration (RC) values observed for C_2H_6 – C_2H_4 gas pair in the case of thermal faults (T1/T2/T3)

Analysis of Figure 1 suggests the idea of replacing each cluster of points associated with a specific fault type with a single point. A natural candidate for such a point is the cluster's centre of gravity (centroid).

Determining the coordinates of the centroid in a multidimensional space requires calculating the sum of the coordinates of all points in a given dimension and dividing it by the number of points. To put it simply, in order to calculate the coordinates of the centre of gravity of the point cluster corresponding to defect T3 in Figure 1, one needs to calculate the average of the relative concentrations of ethane RC(C_2H_6) and the average of the relative concentrations of ethylene RC(C_2H_4). The effect of replacing the clusters from

Figure 1, observed for the C_2H_6 and C_2H_2 gas pair by the appropriate centroids is presented in Figure 2.

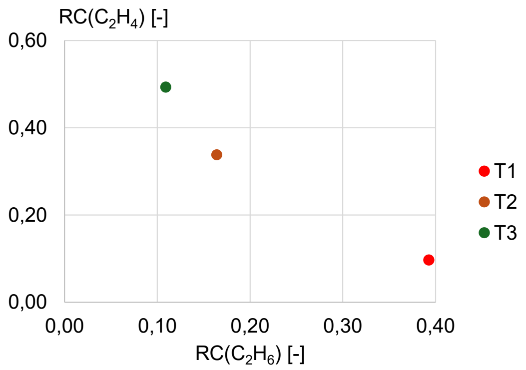

Fig.2. Centroids determined on the basis of the relative concentration of C_2H_6 – C_2H_4 gas pair observed for thermal faults

It seems reasonable to assume that for new measurement data obtained from a transformer in which a fault is suspected, the relative concentrations of individual gases or its combination will also be located closest to the centre of gravity corresponding to the fault potentially existing in that transformer. Therefore, for the analysed dataset, the determination of a detailed fault in the second stage of the proposed method involves evaluating the distance in multidimensional space of the relative concentrations of selected gases from previously determined centroids representing specific types of faults. The fault for which the distance is the smallest is assigned to the analysed data set. The measure of distance is the Euclidean distance. As one may notice, this is an adaptation of a classification algorithm known in machine learning, based on the assessment of the distance from the nearest centroid (NCC - Nearest Centroid Classifier).

The main problem of adapting the presented idea to the needs of diagnostics using DGA is the selection of such a combination of gases that their relative concentrations form the most coherent clusters possible, and their centres of gravity (centroids) are well separated.

Characteristics of the collected measurement data

To determine the parameters of the proposed method, the number of measurement sets given in Table 1 was used. Each set contained information about the concentrations of five gases (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2) and an assigned defect. The data came from literature sources, transformer manufacturers and utilities performing transformer diagnostics.

The data marked in Table 1 with the symbols T (thermal fault) and E (electrical fault) were used only to determine the criterion value used in the first stage of the method, i.e. to determine the general nature of the fault (thermal or electrical). The remaining measurement sets were used in the development of both stages of the methods.

Table 1. The number of measurement sets associated with a specific fault type utilised during method development.

T1	T2	T3	T	PD	D1	D2	E
56	46	120	158	80	61	130	62

In order to verify the developed method's performance and compare its effectiveness with other conventional methods, measurement datasets with the counts listed in Table 2 were used. It is worth noting that none of the datasets used to validate the method were used at the method development stage.

Table 2. The number of measurement sets associated with a specific types of faults utilised for assessing the effectiveness of the developed method.

T1	T2	T3	PD	D1	D2
16	16	37	24	22	47

Determination of criterion values

During the development of the first stage of the proposed method, it was noticed that the best way to distinguish a thermal fault from an electrical fault is based on the analysis of the sum of the relative concentrations of hydrogen – $RC(H_2)$ and acetylene – $RC(C_2H_2)$. Figure 3 shows the values of these sums for the collected measurement data.

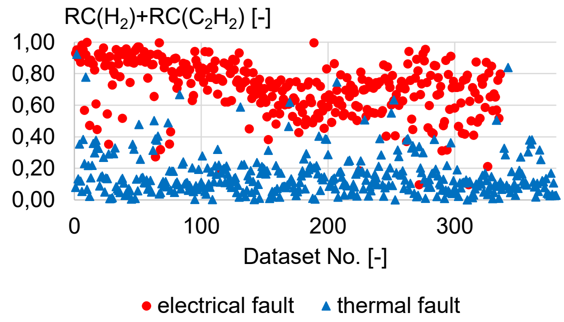

Fig.3. Distribution of the sums of the relative concentration of hydrogen $RC(H_2)$ and acetylene $RC(C_2H_2)$ for the collected data

It can be observed that the sums of the relative gas concentrations shown in Figure 3 in the case of thermal faults are located in the lower part of the graph area, and in the case of electrical faults in the upper part of the area.

In order to determine the limit value of the sum of the relative concentrations of hydrogen and acetylene, which will maximize the number of correct fault qualifications, the charts shown in Figure 2 was prepared.

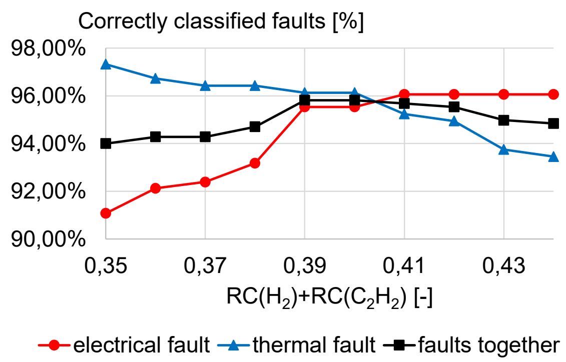

Fig.4. Correctly classified faults in % as a function of the limit value of the sum of the relative concentrations of hydrogen and acetylene.

Analysis of Figure 4, allows to formulate a criterion for the optimal qualification of measurement data in the first stage of method as follows: if $RC(H_2) + RC(C_2H_2) \leq 0{,}4$, then measurement data indicate a thermal fault, otherwise an electrical fault. It can be expected that incorrect classification of faults in the first stage of the proposed method will be approximately 4%.

Determination of the criteria for distinguishing PD/D1/D2 (or T1/T2/T3) defects in the second stage of the method was carried out in 5 identical iterations.

In the first step, the data assigned to each defect was divided randomly into two groups: the first group was used to determine the criterion values (i.e. centroids of relative concentrations of individual gases or its combination), the second group was used to assess the effectiveness of distinguishing defects for the designated criteria – this group always consisted of 25 datasets.

In the second step, criterion values (e.g. centroid coordinates) were determined, assuming that one gas, a combination of two, three, four and finally five gases can be used to recognize the fault. As a result, 31 gas combinations had to be considered (for example: H_2, H_2-CH_4, H_2-CH_4-C_2H_6, H_2-CH_4-C_2H_6-C_2H_4, H_2-CH_4-C_2H_6-C_2H_4-C_2H_2).

In the third step, the distances from the centroids were determined for each set of validation data, which made it possible to assign a recognized type of fault to these sets and finally assess the effectiveness of faults recognition.

After completing 5 iterations, the average defect recognition efficiency and standard deviation were determined for each gas sequence considered. On this basis, the final set of centroid coordinates was selected. The winning set should be characterized by the highest fault recognition efficiency, the smallest dispersion of results and similar efficiency in recognizing each type of faults.

The best results in recognizing thermal faults was achieved for the combination of C_2H_6, C_2H_4 and C_2H_2 gases, while in the case of electrical faults it was the combination of CH_4, C_2H_4 and C_2H_2 gases. Appropriate coordinates of centroids representing in 3-dimensional space thermal and electrical faults are given in table 3 and table 4 respectively.

Table 3. A set of centroids coordinates adopted to distinguish thermal faults T1/T2/T3.

	$RC(C_2H_6)$	$RC(C_2H_4)$	$RC(C_2H_2)$
T1	0,3859	0,0967	0,0042
T2	0,1578	0,3376	0,0053
T3	0,1116	0,4969	0,0107

Table 4. A set of centroids coordinates adopted to distinguish electrical faults DP/D1/D2.

	$RC(CH_4)$	$RC(C_2H_4)$	$RC(C_2H_2)$
PD	0,0870	0,0260	0,0294
D1	0,0994	0,0853	0,2997
D2	0,1372	0,1767	0,2656

Implementation of the proposed method – an example

In order to present the practical use of the method, the case of a transformer suspected T1 fault will be considered [10]. The measured gas concentrations are given in Table 5.

Table 5. Measured concentrations of gases dissolved in the transformer oil [ppm]

H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
240	560	165	21	27

According to the method's algorithm, relative concentrations of the gases were calculated at the beginning. The obtained values are given in table 6.

Table 6 Calculated relative gas concentrations [-]

$RC(H_2)$	$RC(CH_4)$	$RC(C_2H_6)$	$RC(C_2H_4)$	$RC(C_2H_2)$
0,2369	0,5528	0,1629	0,0207	0,0267

In the first stage of the proposed method, was determined what general type of defect (thermal or electrical) the data indicates. For this purpose, the sum of the relative concentrations of hydrogen and acetylene was calculated and compared with the criterion given in the previous section. In our case: $RC(H_2)+RC(C_2H_2)=0,2369+0,0267=0,2636$. The obtained value is less than 0,4 and this means that the suspected defect is of a thermal nature.

In the second stage of the method, the Euclidean distances of the point (hereinafter referred to as F) defined by the relative concentrations of C_2H_6, C_2H_4 and C_2H_2 given in Table 6 from centroids representing T1, T2 and T3 faults were calculated and given in Table 7.

Table 7. Data and the calculated distances of point F from the centroids representing T1, T2 and T3 faults.

	$x=RC(C_2H_6)$	$y=RC(C_2H_4)$	$z=RC(C_2H_2)$	Distance
T1	0,3859	0,0967	0,0042	**0,2367**
T2	0,1578	0,3376	0,0053	0,3176
T3	0,1116	0,4969	0,0107	0,4792
F	0,1629	0,0207	0,0267	⤴

The formula for calculating the Euclidean distance between point F and for example centroid T1, is as follows:

$$(2)\quad D_{F-T1}=\sqrt{(x_F-x_{T1})^2+(y_F-y_{T1})^2+(z_F-z_{T1})^2}$$

The location of the point F and the centroids corresponding to thermal faults in three-dimensional space are also shown in Figure 5.

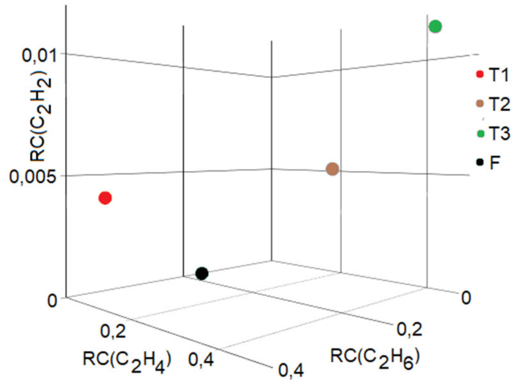

Fig.5. The location of the centroids corresponding to thermal faults T1/T2/T3 and the point F representing the measurement set for which the diagnostic procedure is carried out.

The smallest calculated distance, equal to 0,2367, occurred between point F representing the tested measurement set and the centroid corresponding to the thermal fault with a temperature <300°C (T1). So this is the final diagnosis that is consistent with the actual fault.

Evaluation of the effectiveness of the proposed method

Analysing the concentration of gases dissolved in transformer oil and drawing conclusions on the nature of a potentially occurring faults is a classification task. The classes here are the accepted types of faults. The effectiveness of faults recognition will be presented in the form of a confusion matrix.

In the first stage of the proposed method, rough classification took place. One of the two general types of defects was recognized: thermal (T) or electrical (E). The effect of this classification is presented in Table 8.

Table 8. Confusion matrix for the general classification of faults (T/E) in the proposed method.

Faults		actual	
		T	E
predicted	T	69	1
	E	0	92

Based on the contents of Table 8, it can be concluded that in only one case there was an incorrect diagnosis of the general nature of the fault – a fault that was actually electrical in nature was considered as thermal fault. The effectiveness of defect classification in the first stage exceeded 99%.

In the second stage of the proposed method, T1/T2/T3 or PD/D1/D2 faults were recognized. The results are presented in Table 9 and 10, respectively.

Table 9. Confusion matrix for detailed classification of thermal type faults (T1/T2/T3).

Faults		actual		
		T1	T2	T3
predicted	T1	14	0	1
	T2	2	12	3
	T3	0	4	33

Based on the contents of Table 9, it can be concluded that the classification efficiency for the analysed cases of thermal faults exceeded 85%.

Table 10. Confusion matrix for detailed classification of electrical type faults (PD/D1/D2).

Faults		actual		
		PD	D1	D2
predicted	PD	20	5	4
	D1	4	14	11
	D2	0	2	32

The results in Table 10 apply only to those cases that were correctly classified as electrical faults in first stage of the method. The classification efficiency exceeded 71%.

A final assessment of the suitability of the proposed method is possible only if it can be compared with other methods. The following tables therefore compare the number of correctly identified faults with three widely used classical methods. These are the Duval triangle and pentagon methods and the ratio method taken from IEC 60599 std.

The number of recognized thermal faults (T1, T2, T3) is given in Table 11 and the number of recognized electrical faults (PD, D1, D2) in Table 12 for each considered method.

Table 11. Number of correctly identified thermal faults – T1, T2 and T3. The number of analysed cases is given in parentheses.

	T1 (16)	T2 (16)	T3 (37)
Duval triangle method	11	8	34
Duval pentagon method	13	9	32
Ratio method acc. to IEC	14	11	24
Proposed method	14	12	33

The proposed method, for the analysed cases, recognizes T1 and T2 defects as well as the other classical methods. The T3 defect is recognized with the same efficiency as for the graphical methods, i.e. Duvals triangle and pentagon, and much better than for the ratio method.

In Table 12, for the ratio method, the criteria for recognizing D1 and D2 defects are determined so that they overlap to some extent. For this reason, two values indicating the number of correctly recognized faults were given. The number given after the slash sign (/) takes into account the ambiguous recognition of a defect as D1/D2.

Table 12. Number of correctly identified electrical faults – PD, D1 and D2. The number of analysed cases is given in parentheses.

	PD (24)	D1 (22)	D2 (47)
Duval triangle method	12	16	36
Duval pentagon method	10	17	37
Ratio method acc. to IEC	5	6/10	13/30
Proposed method	20	14	32

For the analysed cases, the proposed method recognizes D1 and D2 defects slightly worse than the Duval triangle and Duval pentagon methods. Comparison with the ratio method is in favour of the proposed method. Partial discharges of the corona type are best recognized by the proposed method and the difference is very significant. The PD defect is recognized 4 times better than in the case of the ratio method and 2 times better than in the case of other considered methods.

Conclusions

The article proposes a new method for identifying defects developing in a transformer based on the analysis of gases dissolved in mineral oil.

In the author's opinion, this is a method that uses simple inference rules and is easy to implement, e.g. in a spreadsheet.

Proposed method, like other classic methods and those using artificial intelligence algorithms, does not recognize defects with 100% effectiveness.

Based on the analyses carried out so far, the effectiveness of proposed method is comparable to that of Duval's triangle and pentagon methods, and in the case of a PD type defect, it is significantly higher.

Unlike the ratio methods, including the one proposed in the IEC 60599 standard, there is no problem of inability to recognize the defect.

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