Paper ID – 10609 Session 2022
D1 - MATERIALS AND EMERGING TEST TECHNIQUES
PS2 – Materials for Electro Technical Purposes

Universal method for assessing oil-filled equipment based on the results of DGA

Irina DAVIDENKO *[1], Konstantin OVCHINNIKOV [2], Marina VLADIMIROVA [3]
[*1] Ural Federal University, Russia
[2] "Energo-Diagnostics and Analytics" LLC, Russia
[3] "Massa LLC", Russia
i.v.davidenko@urfu.ru

SUMMARY

The article proposes a new method for identifying the type of defect based on the results of DGA, developed by I. Davidenko and K. Ovchinnikov in 2016 using machine learning methods. This diagnostic method can be used not only for power transformers (PT) and shunt reactors (SHR), but also for current transformers (CT) and voltage transformers (VT), as well as for high-voltage bushings of power transformers (BPT) and high-voltage bushings of oil circuit breakers (BCB). In addition, the method takes into account the design features of various types of oil-filled equipment, as well as changes (growth) of gas concentrations occurring as a result of aging of equipment insulation. Moreover, different rates of aging of equipment insulation are taken into account, associated with the features of its design.

KEYWORDS:

Analysis of dissolved gases (DGA), transformer oil, power transformers, shunt reactors, current transformers, voltage transformers, high-voltage bushings of power transformers, high-voltage bushings of oil circuit breakers, expert-diagnostic information system.

INTRODUCTION

Despite the fact that the analysis of gases dissolved in transformer oil (DGA) has been used for a long time and reveals up to 80% of defects in oil-filled power transformers, the accurate interpretation of the DGA results is still considered a non-trivial task. Assessment of the technical condition of transformers based on the results of the DGA consists of two stages: detecting the development of a defect and determining its nature and type. To identify the fact of the occurrence of a defect, the criteria for exceeding the concentrations of gases and the rates of their growth of their permissible and maximum permissible values are used. The regulated values, as a rule, are found by the integral distribution function of the results of preventive control of the DGA of the transformer park at the level of 0.9 and higher. Methods for identifying the type of defect determine its nature (electrical or thermal), as well as the degree of its manifestation. The degree of manifestation of a thermal defect is determined by the temperature in the defect zone. The degree of manifestation of electrical defects is related to the power, lifetime, and spatial characteristics of the discharge.

1. BUILDING A SYSTEM FOR ASSESSING THE DGA, TAKING INTO ACCOUNT THE AGING RATE OF INSULATION AND DESIGN FEATURES OF THE ELECTRICAL EQUIPMENT (EE)

In the method developed by us for diagnosing oil-filled equipment, the relative concentrations of gases a^i H_2 (hydrogen), CH_4 (methane), C_2H_6 (ethane), C_2H_4 (ethylene), C_2H_2 (acetylene) are used, calculated by the formula:

$$a^i = A^i_t / A^i_{PV}, \qquad (1)$$

where:
A^i_t - the value of the concentration of the *i*-th gas, measured on the date t, ppm;
A^i_{PV} - permissible value of the *i*-th gas concentration, ppm.

The permissible value of gas concentrations A^i_{PV} should be considered as a threshold above which the increased rate of gas formation makes it possible to detect the development of a defect in the equipment, provided that the influence of operating factors is excluded.

In order for the Davidenko-Ovchinnikov method to be universal (it could be used for different types of equipment), then for each type of equipment, its own values A^i_{PV} should be applied.

A^i_{PV} values were calculated according to the method [1] for each type of oil-filled equipment (for power transformers (PT), shunt reactors (SHR), current transformers (CT), voltage transformers (VT), high-voltage bushings of power transformers (BPT), high-voltage bushings of oil circuit breakers (BCB)), taking into account its design features and service life. The strength of the influence of the design features and the service life of the equipment on the gas concentration was determined using variance analysis.

The following influencing factors were investigated:

- voltage class (for all types of equipment);
- method of oil protection (for all types of equipment);
- brand of oil (for all types of equipment);
- service life (for all types of equipment);
- power (for PT);
- type of cooling system (for PT);
- type of on-load tap-changer (for PT);
- type of insulation (for CT, VT).

Further, on the basis of the analysis of the impact of the service life and design features specific for each type of electrical equipment on the results of the DGA, it was necessary to choose how the criteria for assessing the concentrations of gases and their growth trends would be differentiated (divided). On the one hand, the more the system being developed takes into account the criteria for assessing the results of the DGA, which affect the level of gases in the equipment, the more accurate the assessment of its technical condition. On the other hand, such a detailed specification of the system of criteria for assessing DGA complicates the diagnostic procedure in the future.

In this regard, we made a compromise solution, which involves taking into account the most significant factors determined by the analysis of variance, which was carried out for each type of equipment. As a result, for power transformers (PT), it was decided to take into account:

• voltage class and method of oil protection of the transformer - for all gases;

• the peculiarity of gas evolution of oils obtained by hydrocracking technology with a service life of up to 5 years for gases - H_2, CH_4;

• availability of an on-load tap-changer with a communicating volume with the transformer tank - for C_2H_2;

• power and service life of transformers, as two independent factors - for CO, CO_2.

For high-voltage oil-filled bushings, the evaluation criteria are divided according to the following criteria:

- voltage class and method of oil protection - for all gases;
- service life - for H_2, CH_4, CO, CO_2;
- peculiarity of gas evolution of oils obtained by hydrocracking technology - for H_2, CH_4;
- purpose \ place of installation \ use of high-voltage oil-filled bushings (oil circuit breakers \ power transformers) - for CO, CO_2.

For current transformers (CT), the developed system of criteria for evaluating the DGA takes into account:

- voltage class, method of oil protection - for all gases;
- service life - for CO, CO_2;
- type \ type of solid insulation CT - for all gases;
- the peculiarity of gas evolution of oils obtained by hydrocracking technology, with a service life of up to 4 years - for H_2, CH_4.

For voltage transformers (VT), the developed system of DGA evaluation criteria takes into account:

- type \ type of solid insulation VT - for all gases;
- service life - for H_2, CH_4, CO, CO_2.

If the excess of the permissible values (PV) of gas concentrations indicates the detection of the development of a defect in the equipment, then the excess of the maximum permissible values (MPV) of gas concentrations indicates the transition of the equipment from an operable state to a state with a high probability of failure. PV and MPV of gas concentrations were determined by the integral distribution function for different types of equipment at different levels. According to the methodology described in [1], the levels were selected in accordance with the values of failure rate flow for equipment of different types and different service lives. More details about the obtained system of criteria for evaluating the DGA for power transformers are described in [2].

Thus, the developed A^i_{PV} criteria, and, consequently, ai and the method itself, take into account the design features of various types of oil-filled equipment, as well as changes (accumulation) of gas concentrations that occur as a result of aging of equipment insulation. Moreover, different rates of aging of equipment insulation are taken into account, associated with the features of its design.

2. THE ESSENCE OF THE NEW METHOD FOR INTERPRETING THE RESULTS OF DGA

The concentration ratio of gases dissolved in oil depends on the type and nature of the developing defect. The method uses the relative concentrations of gases ai (H_2, CH_4, C2H_6, C_2H_4, C_2H_2), calculated by formula 1.

Identification of the type of defect is based on coding the obtained values of the relative concentrations ai into an alphabetic code and the rules for assigning the received code to codes describing 8 types of defects (Table 1).

The coding of the obtained values of the relative gas concentrations a^i is carried out in accordance with the following rules:

A - is the main gas for this defect, at the maximum relative concentration of a^i_{max} of hydrocarbon gases and H_2 and the condition of $a^i_{max} \geq 1$;

C - gas with a high content, its relative concentration a^i is the second largest among the gases under consideration and $a^i \geq 1$;

D - gas at a relative concentration a^i of the third largest or second largest, but $a^i < 1$;

G - all other gases.

Using the obtained five-digit code (set of letters), which describes the relative gas concentrations of the analyzed DGA sample, it is possible to determine the type of defect using Table 1.

Table 1 - Determination of the type of defect by the characteristic composition of gases

№	Predicted defect type	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
1	Thermal fault up to 300 °C	D, G	C	A	G, D	G
2	Thermal fault from 300 to 700 °C	G	A	D	C	G
3	Thermal fault more than 700 °C	G	C	D	A	G
4	PD	A	D	G	G	G
5	Discharges of low energy	A	D	G	G	C
6	Discharges of high energy, arc	C	D	G	G	A
		G	D	G	C	A
7	Composition of electrical and thermal faults with a predominance of electrical defect	G	C	G	D	A
8	Composition of electrical and thermal faults with a predominance of thermal defect	D, G	A	C	G	D, G

If the resulting five-digit alphabetic code does not completely coincide with any of those given in Table 1, you should find the most similar of the defect codes. To do this, first, defect codes are selected by the coincidence of the gas marked with the letter "A". If there are more than one such code, then a code is selected by concurrence of the gas marked with the letter "Б" (or "B" in the absence of the letter "Б" in the code).

The ratio of CO_2/CO gas concentrations is used additionally to clarify the localization of defects shown in Table 1. The interpretation of the CO_2/CO ratio is carried out according to [3].

The developed Davidenko-Ovchinnikov method is contained in the standard of a large state power grid enterprise [4]. Before its application in [4], it was tested for 2 years in the branches of this enterprise. In addition, the Davidenko-Ovchinnikov method was tested on cases of defects in oil-filled equipment, which has been confirmed by the type of defect by the results of an opening or other diagnostic method. Sample data for testing were provided by the branches of this enterprise. These are 139 cases of damage to power transformers, 22 cases of damage to CTs, 7 cases of damage to VTs, 30 cases of damage to high-voltage bushings of transformers and oil circuit breakers.

As mentioned above, the Davidenko-Ovchinnikov method can be used to identify the type of defect not only in power transformers, shunt reactors, but in high-voltage bushings, current transformers and voltage transformers.

The first example (given in table 2) demonstrates the assessment of the technical condition of the high-voltage nonhermetic bushing of the oil switch POSP/15-110/1000-U, which has been in operation for 22 years, filled with T-1500 oil.

Table 2 - An example of an assessment of the technical condition of a bushing

Gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Measured gas concentration A^i_t, ppm	2664.5	3393.9	801.7	20.49	2.94
Permissible value of gas concentration A^i_{PV}, ppm	180	90	40	16	1.5
The ratio of gas concentrations to its permissible value a^i	14.8	37.71	20.04	1.28	1.96
Gas presence in the sample	D	A	C	G	G
Type of defect - composition of electrical and thermal faults with a predominance of thermal defect	D, G	A	C	G	D, G
Result description of opening the equipment	Traces of breakdown of layers of paper insulation, a waxy substance were found.				

The opening results confirm the type of defect (Table 2), determined by the considered method.

The second example (given in Table 3) shows the identification of the type of defect according to the DGA results for a nonhermetic current transformer of the TFZM 110 kV type with a service life of 18 years, filled with GK oil.

Table 3 - An example of assessing the technical condition of CT

Gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Measured gas concentration A^i_t, ppm	1586.6	1724.0	428.0	1.4	0.2
Permissible value of gas concentration A^i_{PV}, ppm	1700	1100	400	6	1.5
The ratio of gas concentrations to its permissible value a^i	0.93	1.57	1.07	0.23	0.13
Gas presence in the sample	G	A	C	G	G
Type of defect - composition of electrical and thermal faults with a predominance of thermal defect	D, G	A	C	G	D, G
Result description of opening the equipment	The protruding part of the potential equalization conductor from the oil sight glass mounting bolt caused a breakdown of the insulating gap.				

The opening results confirm the type of defect (Table 3), determined by the considered method.

The third example (given in Table 4) demonstrates the assessment of the technical condition of the TM-1000/35 power transformer based on DGA. Transformer 35 kV, filled with T-1500 oil (oil protection type - free breathing), has been in operation for 36 years.

Table 4 - An example of assessing the technical condition of a power transformer

Gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2
Measured gas concentration A^i_t, ppm	149.0	162.1	119.0	589.1	255.2
Permissible value of gas concentration A^i_{PV}, ppm	20	7	10	30	10
The ratio of gas concentrations to its permissible value a^i	7.45	23.16	11.9	19.37	25.52
Gas presence in the sample	G	C	G	D	A
Type of defect - composition of electrical and thermal faults with a predominance of electrical defect	G	C	G	D	A
Result description of opening the equipment	The pressure screw between the upper yoke beam and the pressing ring of the LV winding of phase "C" has traces of discharges and heating with the formation of oil decomposition products.				

A photo of the transformer defect is shown in Figure 1.

Fig. 1. Defect of the TM-1000/35 transformer, discovered during its opening.

The method is adjusted to the design features and operating modes of various types of equipment, as well as to the rate of their aging, through the application of a system of criteria for assessing the PV of gas concentrations calculated for each type of equipment, divided into groups with different service life and design features.

In comparison with the methods of the source [3], the proposed method makes it possible to determine previously unidentified compositions of thermal and electrical defects for power and measuring transformers, taking into account the predominance of one or another character of the defect. In our opinion, knowledge of the prevailing nature of the defect is the basis for making correct decisions about the possibility of further operation of electrical equipment and the choice of maintenance operations. For oil-filled bushings, the number of types of recognized defects by the new method increases from 4 [3] to 8.

The history of the creation of the method is briefly explained below.

3. ALGORITHM FOR DEVELOPING THE DAVIDENKO-OVCHINNIKOV METHOD

When developing the method, its authors, I. Davidenko and K. Ovchinnikov (Davidenko-Ovchinnikov method), used real PT defects identified by the Expert Diagnostic System for Evaluating the Condition of Oil-Filled Equipment «Albatross». The system has accumulated 256 transformer defects over 25 years of operation at Russian power enterprises. Each defect case had the following data:

- passport characteristics of the transformer;
- a history of damage development reflected in the results of the DGA and other measurements;
- a description of the defect discovered when the transformer was opened.

The method development algorithm consisted of the following stages:

1. All cases were checked by the authors for the completeness and reliability of the data.

2. Third-party experts classified all cases based on the defect description made after opening the transformer according to the list of defects from Table 1.

3. For each case, the relative gas concentrations a^i (formula 1) were found for the results of the DGA before the transformer was taken out of operation.

4. The obtained relative concentrations a^i were coded by letters in accordance with some accepted rules.

5. By means of machine learning, typical letters for gases were identified for each of the 8 defects. In this study, machine learning was not a key tool, but only helped to solve one of the intermediate tasks - damage clustering using k-nearest neighbors method (kNN). Letter codes were used as a vector space, which were replaced by numbers from 4 to 1 for letters from A to G, respectively.

6. Then, the received letter codes were checked for each type of defect.

For each type of defect (cluster), the following was studied:

- absence of cases, which reference to several different defects;
- absence of unrecognizable cases;
- share of correctly identified defects (the expert's opinion was used as a ground truth).

In this study, the expert's opinion was used as ground truth.

7. If the result of checking item 6 is unsatisfactory, then repeating items 4 to 6 with a change in the rules for coding relative concentrations a_i. At the same time, the clusters could be additionally specified by the author's boundaries (corner cases) or additionally divided into smaller ones.

Below we consider the issue of the accuracy of identification by a new method of the type of defect in power transformers.

4. ALGORITHM FOR TESTING METHODS FOR INTERPRETING DGA RESULTS FOR THE ACCURACY OF IDENTIFICATION OF KINDS OF DEFECTS

The sample used to test the accuracy of DGA interpretation methods included 134 transformer faults. All cases had reliably known causes of defects and the nature of their manifestations expressed in the description of the result of opening the transformer. Third-party experts assigned defect type codes to each damage case according to Table 5 based on the studying results the nature of the defect manifestation. Statistics of various types of damage contained in the sample are given in Table 5.

We see that the test sample is unevenly distributed among the types of power transformer defects identified by the DGA results.

Note that the most damaged transformer units are windings (39% of the total number of faults) and switching devices (31%) [5]. According to the statistics of damage [5], in these nodes of the transformer, the electrical nature of the defect is more common than the thermal one. Arc discharge prevails among defects with an electrical character. Accordingly, the sampling bias towards spark defects is natural and to a large extent reflects the real distribution of the types of defects in the power transformer fleet.

Table 5 - Statistics of the types of defects of the test sample transformers

№	Predicted defect type	Number of cases, %
1	Thermal fault up to 300 ℃	3.7
2	Thermal fault from 300 to 700 ℃	8.2
3	Thermal fault more than 700 ℃	3.7
4	PD	9.0
5	Discharges of low energy	12.0
6	Discharges of high energy, arc	38.0
7	Composition of electrical and thermal faults with a predominance of electrical defect	15.0
8	Composition of electrical and thermal faults with a predominance of thermal defect	10.4

Below is the algorithm for testing methods developed by the authors of the article for the accuracy of identifying the type of defects based on the results of DGA. When assessing the recognition accuracy of the class of the technical condition of the transformer, the following criteria were applied:

- correct definition: the nature of the defect (electrical, thermal, mixed);
- correct determination of the intensity of manifestation of the nature of the defect.

The degree of manifestation of a thermal defect is determined by the temperature in the defect zone. The degree of manifestation of electrical defects is related to the power, lifetime, and spatial characteristics of the discharge.

At the same time, the accuracy of the methods, in cases where they confused neighboring classes of technical condition, was considered higher than when the extreme classes of defects of the same nature were confused.

For example, the accuracy in the recognition error of "thermal fault up to 300 ° C " and "thermal fault from 300 to 700 ° C " was estimated higher than in the recognition error of "thermal fault up to 300 ° C" and "thermal fault more than 700 ° C". The accuracy of the method in the case of recognition error “Discharges of low energy” and “Discharges of high energy, arc” was estimated higher than in the case of recognition error “PD” and “Discharges of high energy, arc”. The crudest type of error was considered to be a mistake in the nature of the defect. For example, a thermal defect instead of an electrical one.

Testing consisted in comparing the type of defect, determined by the listed methods, with the type of defect, determined by third-party experts based on the results of opening (repair) of transformers.

5. ANALYSIS OF THE ACCURACY TESTING RESULTS OF DGA INTERPRETATION METHODS

For testing at the first stage, the Davidenko-Ovchinnikov method, the nomogram method [7], as well as all standard methods [3], including the Duval triangle, the Dornenburg method [6] were used. The nomogram method was developed by Japanese diagnosticians in the 1980s. The method is based on a comparison of the diagram of ratios of measured gas concentrations (H_2, CH_4, C2H_6, C_2H_4, C_2H_2) relative to the maximum concentration with nomograms of typical defects. Comparing the nomograms of defects - with the diagram of the gas ratios of the transformer under study, the closest image is distinguished and thus the nature of the defect is determined. The method offers 12 nomograms describing 8 types of defects: electrical and thermal character of varying intensity of manifestation, as well as mixed character (electrical and thermal).

At the second stage, for a deeper analysis, the 3 most accurate methods were selected: Duval's triangle, the Davidenko-Ovchinnikov method and the nomogram method. The advantages of the selected methods:

- a wide range of diagnosed types of defects;
- identification of defects of a mixed nature (electrical and thermal at the same time);
- absence or decrease in the number of undiagnosed cases;
- good recognition accuracy according to the method described above.

All of the methods under consideration determine rather well the nature of the defect - thermal or electrical. However, all methods were mistaken in identifying defects at the initial stage of their development: "thermal fault up to 300 ° C" and " PD ".

The Davidenko-Ovchinnikov method recognizes a "thermal fault up to 300 °C" better than other methods by 20%. Other methods confuse it with intense "thermal fault more than 700 °C" or a mixed defect.

Note that it is not uncommon for the methods to erroneously determine the serviceable state of the transformer when there is an actual "PD" defect. The methods of Davidenko-Ovchinnikov and nomograms identified correctly "PD" by 33% better than the Duval method.

The method of nomograms determines the defect "Discharges of low energy, creeping discharges" better. Duval's triangle confuses this defect with "Arc, discharges of high energy ", and the Davidenko-Ovchinnikov method with "PD".

The defect "Arc, discharges of high energy " is diagnosed by all methods quite well. The Duval's triangle and the nomogram method in half of the cases confuse the "composition of faults with a predominance of electrical defect" with the defect "thermal fault more than 700 °C". The accuracy of the Davidenko-Ovchinnikov method in determining this defect is 25% higher.

This article presents the result of comparing the accuracy (reliability) of determining the type of defect by various methods for a fleet of transformers in the Russian Federation. According to the test results, the most accurate determination of the type of defects in power transformers of the Russian Federation according to the results of the DGA is the method developed by I. Davidenko and K. Ovchinnikov. It should be noted that the park of transformers of the Russian Federation also contains transformers of foreign manufacturers. The authors believe that this method is applicable abroad, provided that the permissible value of gas concentration (A^i_{PV}) calculated for foreign transformers fleets is used. Using your own values (A^i_{PV}) will allow you to adjust the method to the defects of the transformer fleet of your country (region) for the design features of the equipment and the features of the used insulating materials.

In general, the accuracy of methods for identifying the type of defect with exact or partial coincidence in the sample under consideration does not exceed 70%. The obtained result does not contradict the generally known opinion that DGA allows to reveal more than 80% of defects in a power transformer, as well as M. Duval's opinion that DGA reveals 96% of damage. The fact is that the detection of developing defects according to the results of the DGA occurs according to the criteria for exceeding the regulated values by the gas concentrations and the rates of their growth. We tested the accuracy of identifying the type of defect.

CONCLUSIONS

1. The method developed by I. Davidenko and K. Ovchinnikov is easy to use, practically has no cases of unrecognizable defects in the state of transformers.

2. The method, developed by I. Davidenko and K. Ovchinnikov, takes into account the design features and the intensity of the aging processes of equipment of different types, since it uses the permissible values of gas concentrations A^{i}_{PV}, which, in turn, are calculated for different groups of equipment, taking into account the influence of design features and service life.

3. The accuracy of the proposed method in recognizing the fault types such as "PD" and "Low intensity heating" is higher than that of the Duval’s triangle and nomograms.

4. The method developed by I. Davidenko and K. Ovchinnikov includes the identification of two additional defects: a composition of electrical and thermal defects with a predominance of an electrical defect or a predominance of a thermal defect.

5. The proposed method is universal, since it can be used for PT, SHR, CT, VT and high-voltage bushings and, at the same time, is tuned to the characteristics of each type of equipment, due to the use of relative gas concentrations.

BIBLIOGRAPHY

[1] Davidenko I. «Obtaining of estimating criteria of controlled parameters and their trends via statistical analysis of operating data» (ISH 17-th International Symposium on Higt Voltage Engineering. Hannover, Germany, on August 22–26).

[2] Pelymskiy V.L., Buzaev V.V., Davidenko I.V., Moiseichenkov A.N., Ovchinnikov K.V. «Improvement of DGA estimation by the criterion of maximum permissible values» (D1_307_2018 SIGRE-2018 26 – 31 August 2018, Paris, 12 Pg. http : //www.cigre.org).

[3] IEC 60599:2015 «Mineral oil-filled electrical equipment in service - Guidance on the interpretation of dissolved and free gases analysis».

[4] Organization Standard of Rosseti PJSC 34.01-23-003-2019 "Guidelines for the technical diagnosis of developing defects in oil-filled high-voltage equipment according to the results of the analysis of gases dissolved in mineral transformer oil».

[5] Davidenko I.V., Ovchinnikov K.V. «Algorithm of analysis of power transformers damageability and examples of applying» (ELECTRO Magazine 2014. № 4. p.13-17)

[6] IEEE Std C57.104™-2008 «IEEE Guide for the Interpretation of Gases Generated in Oil Immersed Transformers».

[7] E. Mori et al., "Latest diagnostic methods of gas-in-oil analysis for oil-filled transformer in Japan" (Proceedings of 1999 IEEE 13th International Conference on Dielectric Liquids)