Practical experience condition diagnosis gained from oil-immersed power transformers voltage class 10 kV

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Abstract. Dissolved Gas Analysis (DGA) for oil samples has been the most widely used diagnosis tool for transformer condition assessment for many years. However, DGA use to oil-filled transformers with a voltage class up to 10 kV. The aim of this paper is to address the issue of DGA interpretation to oil-filled transformers with a voltage class of 10 kV. This paper will present DGA tests results from 57 power transformers and will propose a maintenance decision making procedure using the IEC 60599-2015 Ratio Method, IEEE Std C57.104-2008 include Dornenberg Ratio Method and Rogers Ratio Method, and Russian Std CTO 56947007-29.180.010.094-2011 and Russian Std RD 153-34.0-46.302-00.

1. Introduction
Currently, the electric power industry offers a wide range of innovative technologies for the modernization of existing energy facilities to improve their reliability. In this regard, an important role in planning modernization costs is played by information on the residual resource of electrical equipment, which determines the priority and need for replacement. One of the main elements of such an object is a power transformer voltage class 10 kV, the depreciation cost of which is an important indicator in the current market.

At the same time, to assess the residual life, the transformer must be diagnosed without taking it out of operation, so as not to reduce the reliability of the power supply. It will also create conditions for the transition to maintenance based on the technical condition and will reduce the funds for depreciation deductions. An analysis of the experience of power grid companies shows that the residual life of a power transformer practically coincides with the residual life of its insulation. At the same time, traditional methods for diagnosing its condition, carried out according to the principle of planned preventive maintenance, are either economically ineffective, time consuming and, often, belated, or assess the general condition of the insulation without identifying local defects, in which, as a rule, short circuits occur.

The Dissolved Gas Analysis (DGA) has found the most widespread use in the electric power industry, since it has a number of advantages: high availability – it has the ability to carry out on operating equipment; low cost, as it is implemented by one specialist in a short time; versatility – it can be applied to any oil-filled transformer equipment and high-voltage bushings; good information content - it has the ability to identify a wide range of diagnosed defects; reproducibility of results.

The equipment required for carrying out the DGA, although relatively expensive, is used, as a rule, for a large number of facilities, which makes its use certainly cost-effective for almost any electric power company.
This article discusses practical experience using algorithm DGA, described below, to get answers to the following questions:

- Is there a defect in the power transformer voltage class 10 kV?
- If there is a defect, what is its nature?
- Which method will reveal the most defects?
- Will the interpretations contradict each other?

2. Algorithm DGA

The idea with dissolved gas analysis is based on the fact that during its lifetime the transformer, under the influence of various stresses, both normal and abnormal, generates decomposition gases, essentially from the organic insulation. Dissolved gas analysis (DGA) of transformers, reviewed in [1], can provide insights into thermal and electrical stresses sustained by oil-immersed power transformers.

The gases that are of interest for the DGA analysis are the following:

- \( H_2 \) – hydrogen;
- \( CH_4 \) – methane;
- \( C_2H_4 \) – ethylene;
- \( C_2H_6 \) – ethane;
- \( C_2H_2 \) – acetylene;
- \( C_3H_6 \) – propene;
- \( CO \) – carbon monoxide;
- \( CO_2 \) – carbon dioxide;
- \( O_2 \) – oxygen;
- \( N_2 \) – nitrogen.

Today three types of DGA methods are well defined: Key Gas method, Ratio methods, Total Dissolved Combustible Gas (TDCG) method. Each type of DGA method may evaluate different types of gas for analysis and are applied for supporting operational decisions on each level workflow. We made the following algorithm, which can be used to identify defects. It carried out as follows:

1) Use the Key Gas method for event thresholds.
   a. Determination of the main and characteristic gases for hydrocarbon gases and \( H_2 \):
      - main gas at \( a_{max} \);
      - typical gas with a high content at \( a > 1 \);
      - a characteristic gas with a low content at \( 0.1 < a < 1 \);
      - uncharacteristic gas at \( a < 0.1 \).
   b. Determination of the main and characteristic gases for \( CO \) and \( CO_2 \):
      - \( a_{max} \) the value corresponds to the main gas;
      - \( a > 1 \) the value corresponds to the characteristic gas.

2) Calculate the concentration ratio of gases, use Equation 1:

\[
 a^i = \frac{A^i}{A^i_{av}} \tag{1}
\]

Where \( A^i \) is the value of the concentration of the \( i \)-th gas, measured on the DGA [ppm];
\( A^i_{av} \) is the acceptable value of the \( i \)-th gas [ppm].

3) Check both following conditions are met:
   - the concentration of at least one gas (out of listed) was greater than the corresponding permissible value \( A > A_{lim} \). Use Table 2 assumes that no previous tests on the transformer for dissolved gas analysis have been made or that no recent history exists;
   - the concentration of \( A^i \) gases included in the ratio of gas vapor was 3 times higher than the detection limit \( A^i > 3 \cdot M^i \). The calculation is made according to the Equation 2:

\[
 M^i = \frac{Z h_{mn} A^i_{c}}{h_i} \left( B_i + \frac{V_g}{V_m} \right) \tag{2}
\]

where, \( h_{mn} \) is the chromatograph noise value;
\( h_i \) is the height of the \( i \)-th gas peak in the chromatogram in the calibration mixture;
\( A^i_{c} \) is the concentration of the \( i \)-th gas in the calibration mixture, ppm, calculate by the Equation 3;
$B_i$ is the solubility coefficient of the i-th gas in transformer oil, tacked from table 1, measured at t = 20-25° C. and pressure 1 × 104 Pa (760 mm Hg);

$V_g$ is the volume of the gas phase in the syringe when the i-th gas is extracted from the oil [cm³];

$V_m$ is the volume of oil in the syringe when extracting the i-th gas from the oil [cm³].

$$A'_c = b_i \cdot S_i / \left( B_i + \frac{V_g}{V_m} \right)$$

(3)

where $b_i$ is the calibration factor for determination of combustible gas, g, dissolved in oil;

$S_i$ is the area of the peak of oxygen or nitrogen in the chromatogram.

| Table 1. Coefficients of solubility $B_i$ of gases in oil. |
|---------------------------------------------|
| Gas     | $H_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | CO | $O_2$ | $N_2$ |
|---------|-------|--------|----------|----------|----------|----|-------|-------|
| $B_i$   | 0.05  | 0.40   | 1.20     | 1.75     | 2.78     | 0.12| 1.08  | 0.15  |

According to standards, described in this, the detection limit concentrations of dissolved gas ($M^d_i$) should be no higher than table 2. The permissible value of the parameter value is the boundary that separates the serviceable equipment from the non-serviceable equipment that has the likelihood of damage development and makes it possible to detect the development of a defect in the equipment.

| Table 2. Dissolved key gas concentration limits. |
|---------------------------------------------|
| Standard | Gas | $H_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | CO | $O_2$ | $N_2$ |
|----------|-----|-------|--------|----------|----------|----------|----|-------|-------|
| IEEE Std C57.104 – 2019 [2]   | H2  | 100   | 120    | 1        | 50       | 65       | 350| 2500  | 720   |
| IEC 60599-2015 [3]            |     | 50-   | 30-    | 2-20     | 60-      | 20-90    | 400-600| 3800- | -     |
| CIGRE [4]                     |     | 150   | 130    | 280      |          |          |        | 14000 | -     |
| Russian Std CTO 34.01-23-003-2019 [5] |     | 20-   | 7-30   | 10       | 30       | 10       | 150– | 1700– | 80-   |
| Russian Std RD 153-34.0-46.302-00 [6] | | 50    |        |          |          |          | 180  | 2600  | 200   |
| | | | | | | | | | |
| | | | | | | | | | |

If at least one of the gases in each ratio between gases exceeds the limit, the ratio key gases procedure is valid, otherwise, if it is not significant d the unit should be resample and investigated by alternative procedures.

4) Interpretation of the results, using to one of the ratio methods. There are two approaches to interpreting DGA results: logical-computational and graphical methods. The definition of the main logical-computational methods are given below.

5) Use the Total Dissolved Combustible Gas (TDCG) method to continuously assess the condition of the transformer after a fault has been identified. The definition of the TDCG method is given Equation (4) [2]:

$$TDCG_V = \frac{FG(V)}{1000000}$$

(4)

where $FG$ is the sum of $H_2, CH_4, C_2H_6, C_2H_4, C_3H_2$ and CO [microliters/liter (ppm)];

$V$ is the volume of oil in transformer [liters (gallons)];

$TDCG_v$ is the total dissolved combustible gas volume [liters (gallons)]. The TDCG value does not include $CO_2$, which is not a combustible gas.
3. Logical-computational methods for interpreting DGA

IEEE Std C57.104-2008 [2] provides practical guides in interpreting DGA results gives high diagnostic accuracy by using Dornenburg Ratio diagnostic method and Rogers Ratio Method.

Dornenburg Ratio Method [7]. Historically, this is one of the first methods to determine the type of defect by the ratio of gas concentrations. Apparently, therefore, the capabilities of the technique are very limited. Dornenburg introduced the differentiation between electrical and thermal failure mode and introduced ratios for fault gases with similar solubility. The Dornenburg Ratio method (table 3) identifies faults by analyzing gas concentration ratios such as which can be used to identify thermal faults, corona discharge and arcing.

| Code | Type of Fault                      | CH₄  | C₂H₂  | C₂H₆  | C₂H₄  |
|------|-----------------------------------|------|-------|-------|-------|
| TD   | Thermal Decomposition             | >1   | <0.75 | >0.4  | <0.3  |
| LE   | Partial Discharge (Low-Intensity) | <0.1 | Not Significant | >0.4  | <0.3  |
| HE   | Partial Discharge (High-Intensity)| <1 to >0.1 | >0.75  | <0.4  | >0.3  |

Doernenburg Method is not considered the normal state, but there are restrictive conditions for application of this method, as showed in the Table 2.

Rogers Ratio Method [8]. Rogers' method proposes a coded representation of gas ratios to determine the nature of a defect in a transformer. The method analyzes three ratios of five gases. To determine the nature of the defect, the following gas concentration ratios are used table 4.

| Type of Fault                      | C₂H₂   | C₂H₄   | C₂H₆   |
|-----------------------------------|--------|--------|--------|
| Normal State                      | >0.1 to <1.0 | <0.1  | <1.0  |
| Low-energy density arcing         | <0.1   | <0.1   | <1.0  |
| Arcing – High-energy discharge    | 0.1 to 1.0 | 0.1 to 3.0 | >3.0  |
| Low temperature thermal           | >0.1 to <1.0 | <0.1  | 1.0 to 3.0 |
| Thermal <700 °C                   | >1.0   | <0.1   | 1.0 to 3.0 |
| Thermal >700 °C                   | >1.0   | <0.1   | >3.0  |

Table 4 shows another one of the early gas ratio approaches the method according to Mueller, Schliesing & Soldner (MSS) [5]. The MSS technique differs from all previously considered in that other gas ratios were analyzed.

| Type of Fault                      | C₂H₂   | C₂H₄   | C₂H₆  | CO₂   | CO    |
|-----------------------------------|--------|--------|-------|-------|-------|
| Normal State                      | <0.3   | <0.3   | <0.3  | 3.0 to <10.0 |
| Discharge of high energy          | >3.0   | 1.0 to <3.0 | >1.0  | 0 to <3.0 |
| Discharge of low energy           | >3.0   | 3.0 to <10.0 | >1.0  | 0 to <3.0 |
| Partial discharge with high energy| 0.3 to <3.0 | >=10  | <1.0  | 3.0 to <10.0 |
| Partial discharge with low energy | <0.3   | >=10  | <1.0  | 3.0 to <10.0 |
| Local overheating up to 300 °C    | <0.3   | <1.0   | <1.0  | 0.3 to <1.0 | >=10 |
| Local overheating from 300 °C to 1000 °C | <0.3   | <1.0   | >1.0  | 1.0 to <3.0 | >=10 |
| Local overheating over 1000 °C    | 0.3 to <3.0 | <1.0  | >1.0  | >1.0  | >=10 |
| Local overheating and discharge   | 0.3 to <3.0 | 0.1 to 3.0 | >1.0  | 1.0 to <3.0 | >=10 |
| Local overheating and discharge   | <0.3   | >=10  | >1.0  | 1.0 to <3.0 | >=10 |

* - the value is not significant for this type of defect.
The next ratio method is using in officially valid regulatory document governing in the Russian Federation, and IEC 60599-2015 [3].

| Type of Fault | $CH_4$ | $C_2H_2$ | $C_2H_4$ |
|---------------|--------|----------|----------|
| Normal State  | 0.1 to 1.0 | < 0.1 | < 1.0 |
| Partial Discharge | < 0.1 | a | < 0.2 |
| Discharges of low energy | 0.1 to 0.5 | > 1 | > 1 |
| Discharges of High Energy | 0.1 to 1.0 | 0.6 to 2.5 | > 2.0 |
| Thermal Fault of Low < 300°C | > 1.0 but | a | < 1 |
| Thermal fault of Medium temperature range 300°C-700°C | > 1 | < 0.1 | 1.0 to 4.0 |
| Thermal fault of high temperature > 700°C | > 1.0 | < 0.2 | > 4.0 |

a - the value is not significant for this type of defect.

These Guidelines are based on the experience accumulated in Russia in the application of the diagnosis of developing defects based on the results of chromatographic analysis of gases dissolved in oil of power transformers.

The nature of the defects developing in transformers is determined according to Table 7 in relation to the concentration of pairs of five gases: H2, CH4, C2H2, C2H4 and C2H6.

| Type of Fault | $CH_4$ | $C_2H_2$ | $C_2H_4$ |
|---------------|--------|----------|----------|
| Normal State  | 0.1-1  | < 0.1   | ≤ 1      |
| Partial discharges with low energy density | < 0.1 | < 0.1 | ≤ 1 |
| Partial discharges with high energy density | < 0.1 | 0.1-3 | < 1 |
| Discharges of Low power | 0.1-1 | > 0.1 | 1-3 |
| Discharges of High power | 0.1-1 | 0.1-3 | ≥ 3 |
| Thermal fault of Low Temperature < 150°C | 0.1-1 | < 0.1 | 1-3 |
| Thermal Fault of Low Temperature range 150°C-300°C | ≥ 1 | < 0.1 | < 1 |
| Thermal fault of Medium temperature range 300°C-700°C | ≥ 1 | < 0.1 | 1-3 |
| Thermal fault of high temperature > 700°C | ≥ 1 | < 0.1 | ≥ 3 |

4. Results

In order to comparison between the results of the traditional methods were used in this study 170 samples of DGA and were selected and used data of 57 transformers for testing. An accompanying note was created for each oil sample, indicating the following information: company name; dispatching name of equipment; the name of the manufacturer’s enterprise; dispatching name of equipment; equipment brand; factory number; rated voltage; date of manufacture; date of commissioning; the brand of the filled oil; the reason for the sampling; oil temperature during selection; date of sampling; the types of analysis that need to be carried out in the laboratory; name of the specialist who took the sample.

In this study were used nine key gases, as inputs features: $O_2$; $H_2$; $CH_4$; $C_2H_4$; $C_2H_6$; $C_2H_2$; $CO$; $CO_2$; $N_2$. Concentrations of nine gases were measured, the detection threshold was 1 ppm, i.e. one
millionth volume fraction. For each transformer, in accordance with the methodology, three oil samples of DGA were taken, the standard deviation within each triple does not exceed 10% (if the measured concentration exceeds 3 ppm, i.e., there is no noticeable sampling error), which indicates good data reproducibility. For oxygen and nitrogen, the background can be detected, i.e. relatively narrow concentration range, which covers more than 50% of measurements. For oxygen background: 20 thousand ppm - 40 thousand ppm (70% of samples fell into this range) and for nitrogen background: 55 thousand ppm - 80 thousand ppm (80% of samples fell into this range). For CO and CO₂, samples are smoothly spread over a wide range, there is no narrow range where results are most concentrated. In this sense, one cannot speak of a background, but one can indicate a characteristic range of concentrations:

- For CO, the typical concentration range is 20-400 ppm (80% of the samples fell within this range);
- For CO₂, the typical concentration range is 700-10000 ppm (80% of the samples fell within this range).

For the following gases H₂, CH₄, C₂H₄, C₂H₆, C₂H₂, it is not possible to determine the lower limit of the characteristic range, since the measurement gave zero concentration for a significant number of samples. In this sense, it can be said that any significant deviation from zero in the concentrations of these gases indicates an abnormal process.

Nine types of failure are the output features. Those are:

1) PD1 – partial discharges with low energy density in gas-filled cavities due to incomplete impregnation or moisture in the insulation.
2) PD2 – partial discharges with low energy density in gas-filled cavities by reason of perforating solid insulation.
3) PD3 – partial discharges with high energy density in gas-filled cavities due to incomplete impregnation or moisture in the insulation. Leads to leaving a mark or breaking through solid insulation.
4) E1 – low power electrical discharges due to continuous sparking in oil between connections of different potentials or floating potential by reason of oil breakdown between solids.
5) E2 – high power electrical discharges as a result arc discharges; sparking, oil breakdown between windings or coils or between coils to ground.
6) T1 – thermal defect of low temperature (<150 °C) by reason of general overheating of the insulated wire.
7) T2 – thermal defect in the range of low temperatures (150–300 °C) by reason of local overheating of the core due to the concentration of the flux. Hot spot temperature rise.
8) T3 – thermal defect in the range of medium temperatures (300-700 °C).
9) T4 – high temperature thermal defect (> 700 °C) by reason of hot spot in the core; overheating of copper due to eddy currents, poor contacts; circulating currents in the core or tank.

The above review of approaches to diagnostics of oil-immersed power transformers based on the results of DGA shows that the considered methods differ from each other. We decided to compare the results that these methods give for the 170 samples of DGA. Defects T1, T2, T3, T4 were detected in the samples under study, some were determined to be normal and some were of an undetermined nature. Comparison of the results in Table 8.

The main differences in diagnostics:

1) Transformers identified as normal by the method Std RD 153-34.0-46.302-00, Rogers Ratio and partially Dornenberg Ratio in the methods Std STO 34.01-23-003-2019 and IEC 60599-2015 are classified as thermal defects of low temperature.
2) Five results of Rogers Ratio calculations contradict the rest of the methods. Namely, according to the Rogers Ratio method, defects belong to T2, and according to the rest, to T3.
3) Russian standards make it possible to more accurately differentiate between defects.

Table 8. Comparison of the defect detection sensitivity for different ratio methods.

| Norm                        | T1  | T2  | T3  | T4  | Unidentified |
|-----------------------------|-----|-----|-----|-----|--------------|
| Dornenberg Ratio Diagnosis  | 144 | -   | -   | -   | 27           |
| Rogers Ratio Diagnosis      | 27  | 5   | 52  | 87  |              |
| Mueller, Schliesing, Soldner Ratio Diagnosis | -  | 25  | 56  | 90  |              |
| IEC 60599-2015              | -   | 55  | 7   | 50  | 59           |
| Russian Std CTO 34.01-23-003-2019 | -  | 55  | 7   | 68  | 41           |
| Russian Std RD 153-34.0-46.302-00 | 27 | 28  | 5   | 75  | 36           |

5. Conclusion
Analysis of the physicochemical characteristics of the oil can provide information on the presence of insulation defects, accompanied by severe overheating of the oil (hundreds of degrees) or discharges. As suggested, we can detect in the power transformer voltage class 10 kV, using logical-computational methods for interpreting DGA. There is a correlation between the methods for diagnosing transformer faults proposed in this article, confirmed by large datasets collected from operating transformers and compared with data collected from failed transformers. The age of the investigated transformers ranged from 4 to 52 years. All detected defects are of a thermal nature. The greatest accuracy in diagnosing a defect is provided by Russian Std RD 153-34.0-46.302-00. Moreover, some of the identified defects are of a contradictory nature, cases T2 and T3. In conclusion, ratio-based methods, such as Doernenburg, Rogers, and IEC can only be used if there is a substantial amount of gas used with the ratio, otherwise the methods lead to ratio values outside the specific range and it will not be possible for the type of fault to be identified [2], [7], [8], [10]. Therefore, these methods can be used to identify faults, rather than detect them.

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