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Chromatographic analysis of gases from the transformer

The process of creating and detecting gases in the transformers

ABSTRACT

Given the demands of today's power systems, the question of the transformer reliability is one of the top priorities. The need for monitoring the performance of transformers is imposed since the beginning of their use. This article aims to analyse the impact of the gases released during breakdowns and energy discharge within the transformer that could accelerate the degradation of the insulation system and gradually lead to major faults and incidents.

KEYWORDS

transformer, analysis, oil, gas, insulation

1. Introduction

Since the beginning of production of oil for transformers it has been shown that during their work, due to various phenomena, certain gases may appear [1]. In 1928, Buchholz relay was first used to collect gas bubbles passing through the oil to the conservator. Due to the occurrence of gas in the transformer, the oil is gradually being displaced, which in a certain amount pulls down the float and turns on a warning signal. In larger amounts of gas, Buchholz relay trips the transformer.

Consequently, there was a need for a quality analysis of the situation inside the transformer in order to detect and eliminate potential failures. In the early sixties gas chromatograph appeared, a device used to identify gases dissolved in transformer oil. Since the seventies, this analysis is used to detect a number of different

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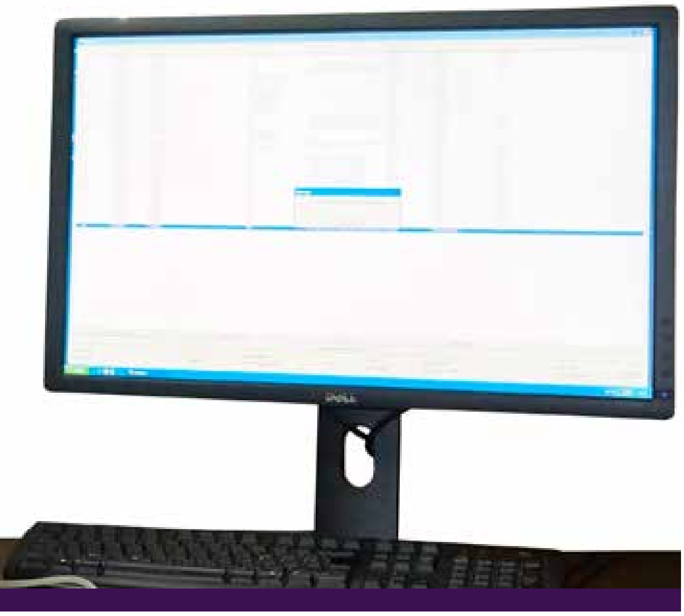

gases. Seven of them are characteristic for degradation of transformer oil-paper insulation: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), carbon monoxide (CO) and carbon dioxide (CO_2). In addition, some gases (C_3H_y) can also appear but they do not affect the work of the transformer much.

Today chromatographic analysis of the transformer's gases is one of the most important and the most sensitive methods for the early detection of changes in state of oil-paper insulation and thus represents an excellent indicator of the existence of potential failure [2].

Chromatography (derived from the Greek words chroma - colour and grafein - write) is the collective name for a group of techniques used for separating mixtures. It is a physical separation method in which the tested components are separated and isolated in two phases: stationary (fixed) and mobile (movable). Chromatography as a laboratory technique can be: analytical (works with small samples and attempts to assess the contribution of individual components in the mixture) and preparative (separation of components from the mixture and a kind of purification).

2. Occurrence of gases in the transformer

During the work transformers are exposed to electrical, thermal and mechanical stresses, leading to degradation of the insulation. The consequences are rapid chemical reactions and degradation of materials (out of which many are forming gases in the oil and above), damage to the insulation, reduction of operational safety, and ultimately failure or breakdown.

Mineral transformer oil and cellulosic materials (paper) are usually used for the transformer insulation. Cellulose insulation gives the transformer dielectric strength and spacing between windings as well as the space between windings which are at a different potential. Mineral transformer oil, due to the impregnation in paper, increases its dielectric strength.

The oil is mainly composed of saturated hydrocarbons linked by C-C and C-H bonds which crack as a result of faults with the formation of unstable parts, radicals or ions as well as other compounds. They are easily recombined in gas molecules, like in order by energy activation: hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2).

Causes for forming gases can be classified into three categories: *corona or partial discharge, pyrolysis (decomposition of substances under the influence of high temperatures), thermal decomposition and sparks*. Most of the energy is released during sparks, followed by overheating, and lastly due to the appearance of the corona. Gases that appear during fault are typical for degradation of the insulation system: hydrocarbons, carbon oxides and gases which do not come from failures [3]. Mentioned gases begin to form at certain temperatures as shown in Fig. 1.

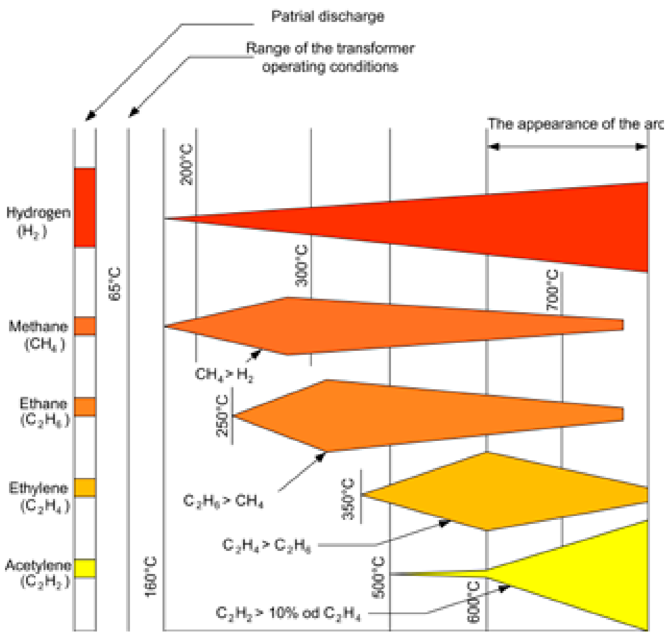

Figure 1: The appearance of flammable gases at average temperature of oil decomposition

Following the ratio of gases, it is important to consider the solubility of gases as a function of temperature. Fig. 2 shows that over the temperature range from 0 to 80 °C, solubility of some gases increases above 79 %, while the solubility of other decreases below 66 %.

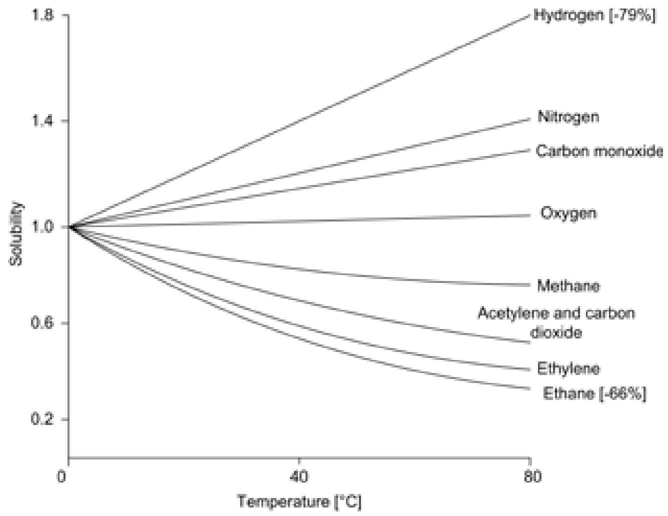

Figure 2: Solubility of gases as a function of temperature

3. Test methods

Oil swabs are conditioned by constructional features of the transformer. Well equipped devices have valves for sampling from three levels of tank height as well as from the Buchholz relay and the tap changer tank. It is important to emphasise that gases from the oil develop only when it is in operation, thus a quality representative sample should be taken while it is working, or soon after it has been shut down from service.

In case of sudden gas evolution, depending on the location and intensity of appearance, their distribution is uneven at first, but equalises after a while. Therefore, in some cases it is necessary to take more samples of oil from different places immediately after the observed phenomena and again after a certain time. For continuous monitoring of results from the same transformer, it is important that samples are taken in the same way at the same place and examined with the same test method. To examine and analyse the gas composition, the sample must be taken from Buchholz Relay or must be extracted from the oil.

Testing is carried out using gas separation or chromatography. Chromatography principle is based on equilibrium distribution of the two phases: fixed immobilised in a column or on a flat surface and movable, carrying the ingredients of the mixture through the system. Different travel speed of individual components will lead to separation (Fig. 3). In the initial phase the tested sample is introduced to a stream of inert carrier gas into a chromatography column filled with solid or liquid stationary phase. Liquid stationary phase may be absorbed on an inert solid support or can be immobilised on the walls of the capillary (capillary column). The separation of mixtures will be carried out provided that they have different solubility in the liquid stationary phase. The first component that comes out is the one that is the least soluble in the stationary phase.

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Modern gas chromatographs consist of the gas supply unit, the sampling unit with automatic injector, the column and the oven. It is equipped with temperature controllers and microprocessor systems

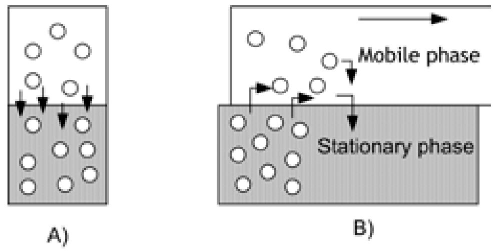

Figure 3: Distribution between the two phases:
A) equilibrium of molecules between stationary phases
B) model of chromatographic process

Modern gas chromatographs consist of four units supported by temperature controllers and microprocessor systems [4]. The first unit (gas supply unit) provides all the necessary gas supplies which may involve a number of different gases, depending on the chosen detector. Some detectors require hydrogen, air or oxygen to support combustion and a mobile phase supply that could be helium, nitrogen or some other inert gas. The second unit is the sampling unit with automatic injector with its own oven. The column represents the third unit, the important device that achieves separation and an oven to control process temperature. Oven is used to maintain the temperature of the process at the optimum level and to improve separation of components. It should operate over a wide temperature range (5 °C - 400 °C), but in practice the maximum oven temperature needed is usually less than 250 °C. The oven often has air circulation driven by a powerful fan to ensure even temperature throughout the oven. The temperature in all parts should be stable at ± 0.5 °C.The fourth part of chromatograph is the detector with wide range of available types. The output from the detector is usually electronically modified with data processing computer which processes the data and prints out report.

After insertion of the components (mixed only with inert gas – mobile phase) and their separation at the exit of the column, they are placed in the detector. Detectors help visualising the components eluted from the column. The obtained result after processing represents an input signal to the printer. The detector registers a series of symmetric peak evaluations whose response depends on the concentration of ingredients in the sample which is recorded as a function of time. The position of the peak on time axis helps identifying the ingredients, and in areas under the peaks, the exact amount of each separate ingredient can be calculated. Fig. 4 shows the output of the two component gas chromatographic analysis.

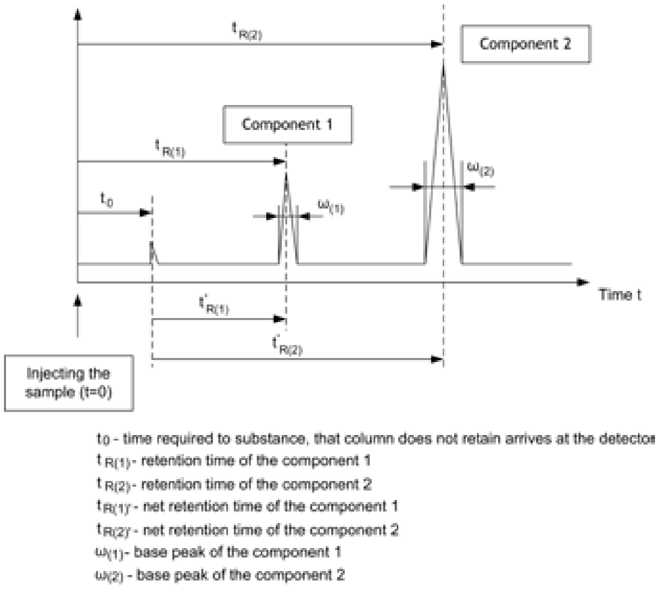

Figure 4: Output of the chromatographic tests with 2 components

Results of this method on a power transformer are shown in Fig. 5. Key information about the gases that appeared during the tests are shown in Table. 1. The flame ionisation detector (FID) is used as a detector. The sample gas is introduced into a hydrogen flame inside the detector. Any hydrocarbons in the sample will produce ions when they are burnt. The generation of these ions is proportional to the concentration of organic species in the sample gas stream.

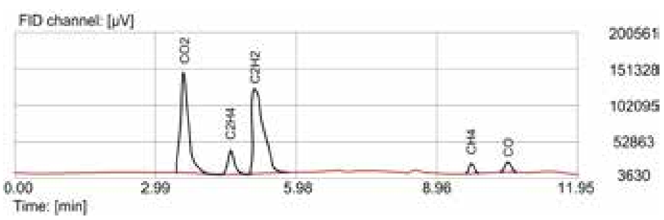

Figure 5: Graphic result of gas chromatographic analysis

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4. Interpretation of results

Based on the results of gas analysis it is possible to diagnose three fundamental causes of the insulation degradation which are divided into six typical problems [5] with following observable consequences:

(1) Partial discharge – PD [6]
(2) Discharge with low energy – D1
(3) Discharge with high energy – D2
(4) Thermal fault (up to 300 °C) – T1
(5) Thermal fault (above 300 °C) – T2
(6) Thermal fault (above 700 °C) – T3

It often happens that one phenomenon steps into another or that two things occur simultaneously. Once we know the concentrations of certain gases, we can proceed with choosing the method by which they will be interpreted. Interpretive methods use several ratios of gases to qualify a few different states of the transformer.

The ratios of gases used by interpretive methods are: $R_1=CH_4/H_2$, $R_2=C_2H_2/C_2H_4$, $R_3=C_2H_2/CH_4$, $R_4=C_2H_6/C_2H_2$, $R_5=C_2H_4/C_2H_6$, $R_7=C_2H_6/CH_4$. Gas concentration is expressed in *ppm* or *µl/l* [7].

4.1. Roger's ratio method

This method utilises four gas ratios: R_1, R_2, R_5, and R_7. Combination of the coding of these ratios gives 12 different types of transformer faults (normal deterioration, partial discharge, overheating (<150 °C, 150 °C - 200 °C, 200 °C - 300 °C), general conductor overheating, winding circulating currents, core and tank circulating currents, flashover without power follow through, arc with power follow through, continuous sparking to floating potential and partial discharge with tracking. Roger's ratio method provides a wide range of results, but the consistency of the method is quite low.

4.2. IEC method

IEC method originated from the Roger's ratio method, except that the ratio R_7 is excluded if concentration of gases is above ty-

Table 1: Key information about gases that appeared during test

No.	Time [min]	Height [µV]	Area [min*µV]	Name	Concentration
1	3,60	129222	18988	CO2	6853 ppm
2	4,47	26792	2712	C2H4	468 ppm
3	4,90	109098	23541	C2H2	4580 ppm
4	9,85	12742	1149	CH4	329 ppm
5	10,37	14009	1278	CO	372 ppm

The problem in the monitored transformer was identified as low energy discharges by the Duval triangle method

pical values [6]. Acceptable values of gases in normal operation of a transformer are: (C_2H_2 without tap (2-20), with tap (60-280), H_2 (50-150), CH_4 (30-130), C_2H_4 (60-280), C_2H_6 (20-90), CO (400-600), and CO_2 (3800-14000) (*ppm*)).

4.3. Doernenburg ratio method

This method utilises the gas concentration from the following ratios: R_1, R_2, R_3, and R_5. In this method the gases must be present in significant amounts in order to guarantee proper results: (H_2>100, CH_4>150, CO>350, C_2H_2>35, C_2H_4>50, and C_2H_6>65). This method, being one of the oldest ones, is the least accurate and a significant disadvantage is the need for greater amount of gas to make it usable.

4.4. Duval triangle method

Mr. Duval developed this method in the 1960s. Three types of hydrocarbons are monitored: methane, ethylene and acetylene. This method classifies six types of errors [8]. If the coordinates are located in the PD field, it indicates that partial discharge occurred, as shown in Fig. 6.

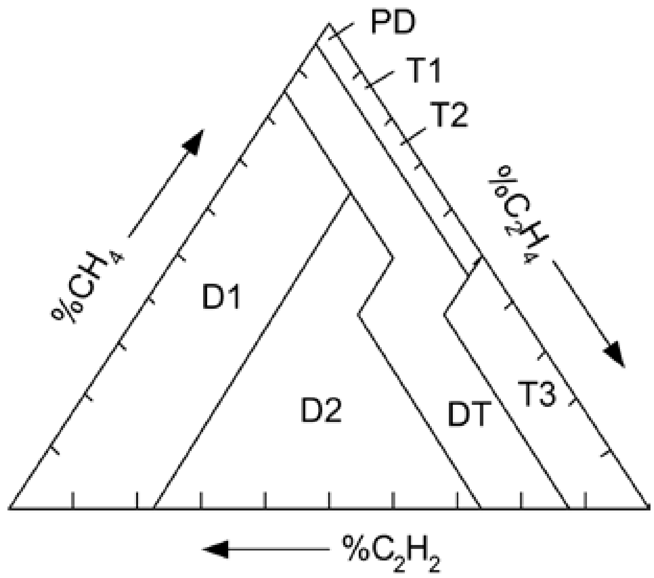
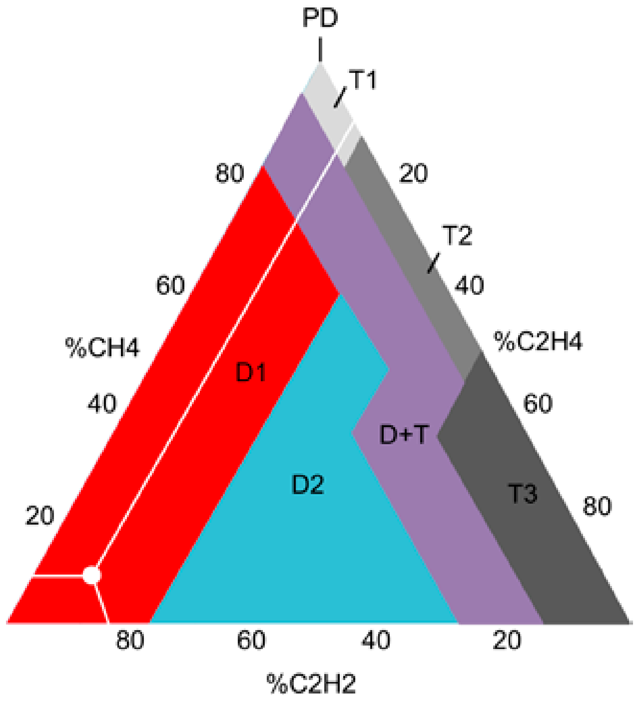


Figure 6: Duval triangle method

Boundaries within the triangle are defined on the basis of experience, from a large number of failures that have occurred in the transformer worldwide during the last sixty years. The problem in the transformer from Chapter 3 was discovered by this method, done after chromatographic analysis. As seen in Fig. 7 the problem is registered in the area of low energy discharges. Today, Duval triangle method is one of the most accurate ones to detect early failures in the transformers with best results for correct predictions.



Fault code	Fault
D1	Discharges of low energy

Figure 7: Interpretation of the result with Duval triangle method

4.5 Key gas method

Key gas method could present damage levels of the transformer and its cause by analysing the levels of combustible gases. The method defines the level of damage by taking into consideration all of the total combustible gases which can be classified in different ranges. The presence of the fault gases depends on the temperature or energy that will break the links of the insulation or oil chemical structure. This method uses the amount of the individual gases rather than gas ratios for fault detection. Principal gases for general faults types are: *ethylene* – overheated oil, *carbon monoxide* – overheated cellulose, *hydrogen* – corona in oil, *acetylene* – arcing in oil. Key gas method is very reliable and provides good results in the initial detection of problems within the transformer.

4.6 Nomograph method

Nomograph method combines the fault gas ratio concept with the Key gas threshold value in order to improve the accuracy of fault diagnosis. It has to provide both graphic presentation of fault-gas data and the means to interpret its significance. The nomograph consists of series of vertical logarithmic scales representing the concentrations of the individual gases [9].

5. Conclusion

It is very important to know the condition of the transformer, not only during the tests, but also in operating mode. With the methods of analysis (chromatography) of gases from the transformer, it is possible to quickly and easily get to the key results that will show partially the condition of the transformer. In the industry, due to dirt and very common failures and electrical stresses, it is necessary to arrange such tests and analysis of oil at least once a year. Timely detected faults are remedied easier, faster and cheaper, thanks to a lesser extent of the damage and the possibility of repairing certain faults on the spot, which eliminates the difficulties associated with transportation of transformers (especially large units) for repair. Further, the repairs can be planned and aligned with the needs of power system and consumers.

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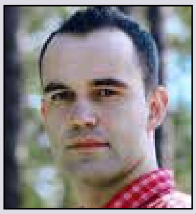

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