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Condition assessment of power transformer using gas detection methods

***Abstract**. This article deals with the gases dissolved in oil generated during the power transformer operation. The attention is paid to the production of gases typical for particular failures. The most powerful and widely used diagnostic tool for investigation faults and their root causes is dissolved gas-in-oil analysis DGA. Hydran sensor is one of the most used sensors applied for on-line monitoring of gas generation. The aim of this contribution is to compare the results and plausibility of the mentioned gas detection methods in medium-term period.*

***Streszczenie.** W artykule analizowano obecność gazu rozpuszczonego w oleju transformatora energetycznego oraz zależność tego gazu od różnego rodzaju uszkodzeń. Analizowano różne metody pomiarowe i do celów analizy wybrano czujnik Hydran. (**Badania stanu transformatora energetycznego na podstawie analizy obecności gazu w oleju**)*

Keywords: power transformer, condition monitoring, dissolved gas-in-oil analysis DGA, Hydran sensor.
Słowa kluczowe: transformator energetyczny, gaz roozpuszczony w oleju, czujnik Hydran

Introduction

Power transformers are the key elements of the state infrastructure. They ensure the continuous power supply through the transmission and distribution system to the end-customers. Electricity market liberalization as well as German nuclear power plants shut-down initiates to take into the consideration potential overloading of power transformers. These reasons result in the requirements of the uninterrupted, safe and reliable transformer operation.

The transformer technical life is particularly influenced by the lifetime of their weakest subsystem. As is generally known, insulation is the weakest part from material point of view. According to IEC 60076-7 [1] standard, insulation system lifespan is defined as total time between inception condition, when the insulation is considered as a new, and final condition that results in high risk of transformer failure. Insulation is thermally, electrically and mechanically stressed during transformer operation. Thermal stress is caused mainly by Joule's losses in windings and losses in magnetic core. Electrical life of insulation system is influenced primarily by partial discharges, result of electrical field impact. Short circuits can cause the movement of the windings that lead to the disruption of insulation mechanical integrity. Furthermore, moisture, solid particles, oxygen and oil aging products (organic acids, aldehydes, ketones and polymers of unsaturated hydrocarbons) reduces electro-insulation lifetime. Some of these aggressive aging products are absorbed by solid insulation that leads to accelerated aging and total decomposition. One of the key monitored parameters in systems with electrical insulation based on paper-oil is temperature, moisture and gases dissolved in oil. [1, 2]

Interaction of operating conditions and degradation factors with key subsystems of transformers can cause excessive degradation and has a significant impact on their overall lifespan. Furthermore, potential overloading can lead to the failure, end their serviceability and can create serious problems. Routine off-line diagnostics in connection with monitoring systems help to avoid their outages and shut-downs. In addition, they contribute to extend their technical life and to efficient application of these very expensive capital investments.

Nowadays, one of the biggest challenges of experts working in power transformer diagnostics is research of correlation between conventional widely used off-line diagnostic methods and on-line parameters. Furthermore, attention is paid to the determination of gradients, trends of on-line parameters after their exceeding the proper maintenance is carried out. This maintenance approach is in literature known as Condition Based Maintenance – CBM. [3, 4, 5]

Gas development within the power transformer

Gases dissolved in oil are generated even during routine operation because of the deterioration of electro-insulating system paper-oil. Each thermal, electrical and combined fault is accompanied by generation significant amount of distinctive combustible gases. Thus, gases dissolved in oil are key identifiers of fault incipient. Knowledge of the content and type of gases allows effective identification and recognition of faults in electrical equipments.

During failure corresponding gases are produced in dependence on the temperature and electric field within the transformer. The polymeric chains of solid insulation are less thermally stable than the hydrocarbon bonds in oil. Thus, the cellulosic chains are decomposed at lower temperatures. There is significant degradation of solid insulation even at 105 °C and total decomposition is at temperature 300 °C. Furthermore, the presence of oxygen significantly contributes to the faster decomposition. Thermal degradation of solid insulation is mainly accompanied by carbon monoxide, carbon dioxide and decomposition products – furans. [4, 5, 6]

Mineral oil is composed of the several hydrocarbons linked together by different carbon molecular bonds. The weakest bond is the C-H bond. Thus, hydrogen is generated through wide temperature range. More energy and higher temperature are needed to break particular carbon bonds. The degree of the bond also influences resistance to thermal decomposition of the oil. Single carbon bond is less resistance than the double bond. Carbon triple bond is the strongest bond within the mineral insulation oil. Ethylene, ethane and methane are produced at around the temperature 500 °C. Carbon particles are generated already at 500 – 800 °C. Acetylene production is correlative of temperatures 800 – 1200 °C. [6]

According to IEC 60599 [6] standard, causes of gas generation can be classified into three main categories. Corona and low energy partial discharges are mainly accompanied by formatting of hydrogen H_2 and methane CH_4. These faults are characterized by releasing of low energy. Second category is represented by thermal degradation or overheating of the oil. Gases ethylene C_2H_4, methane CH_4 and ethane C_2H_6 are mainly generated during these faults. Arcing, sparking and flashover are typical of high energy releasing. High amount of hydrogen H_2 and acetylene C_2H_2 is produced because of these harmful faults. In Fig. 1, there is shown gas production for particular faults.

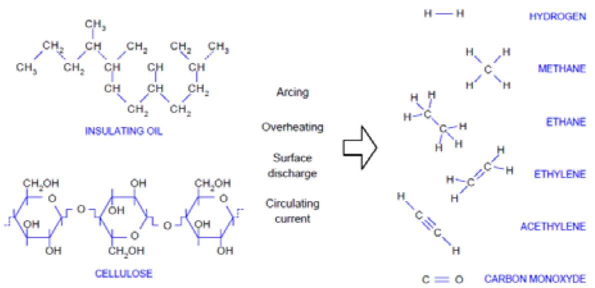

Fig.1. Gas production during particular faults [7]

There are several diagnostic methods that are used for evaluation and investigation of each particular fault. According to IEC 60599 [6] standard and several publications [8, 9, 10, and 11], the most used methods are following: Doernenberg's ratio method, Duval's triangle and Roger's ratio method. All these methods are based on the information obtained by gas chromatography method DGA (dissolved gas-in-oil analysis).

Methods of gas detection

There are several tools and sensors used for dissolved gas in oil detection. In case of offline laboratory tools, above mentioned dissolved gas-in-oil analysis, based on the principle of gas chromatography, is one of the most used. Furthermore, on-line gas monitoring sensors have been widely applied for the last decade. There are two optional types of sensors – simple or complex. Simple sensors detect just particular gases; on the other hand complex on-line sensors can monitor wide range of gases dissolved in oil. Simple gas sensor is installed at the free transformer flange. The most well-known sensors are Calisto, Hydrocal 1003 and Hydran. They usually monitor hydrogen H_2 as main indicator of thermal fault within the transformer and carbon monoxide CO, main product of thermal degradation of the insulating paper. Gas detection principles are different from their producers. In case of installation of multi-gas sensors, there are necessary two flanges and pipeline for oil feeding to the detector equipment located out of the transformer tank. The most known multi-gas sensors are Serveron TM8, Hydrocal 1008 or Transfix. Some of these on-line DGA sensors are based on the principle of gas chromatography, where the carrier gas as well as calibration gas is consuming part. Other complex sensors are based on the principle of photo-acoustic spectroscopy. All these multi-gas sensors are capable to detect e.g. hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide, carbon dioxide, oxygen, nitrogen etc. In the case of oil immersed electrical devices with conservators, the Buchholz relay is used as a protective and safety device. It is obvious that incipient gases come up into the Buchholz relay installed in the pipe between the top of the transformer and the conservator. Sensor installed at the degassing valve of the Buchholz relay has been recently developed for monitoring of integral value of gases [12, 13 and 14]

A. Dissolved gas-in-oil analysis - DGA

The most powerful and widely used diagnostic tool for investigation of faults and root causes of failures is dissolved gas-in-oil analysis DGA. It is based on gas chromatography a laboratory method which can identify the content and type of dissolved gas in oil. This analysis includes four processes that significantly influence accuracy and plausibility of the final results. There are oil samplings and their transportation to the laboratory, where the oil sample has to be protected against sunlight activity and must not to content the air bubbles. Following process of DGA is dissolved gas out of oil extraction. The most used methods are multiply extraction using Toepler's exhauster, one-time vacuum extraction, stripping method or head space. Then gases are identified and quantitatively determined by adsorption gas chromatography, where the gas sample is injected to flow of carrier inert gas (helium or argon). There is interaction between gas and solid phase in chromatograph, where particular gas components are held in colony in dependence of their surface adsorption. There is detector at the colony output that recognises type and content of particular gases from the peak location in time dependence. Final process of DGA is expert evaluation of causes of gas inception according to above mentioned methods. [2, 4 and 10]

B. HYDRAN sensor

Nowadays, Hydran is one of the most popular and the most frequently used sensor for gas online monitoring. Hydran sensor detects a composite value of particular gases in ppm (H_2, CO, C_2H_4 and C_2H_2) with different sensitivity (see in table 1) [15].

Table 1. Gas detection sensitivity of Hydran sensor

Gas	Concentration
Hydrogen H_2	100 %
Carbon monoxide CO	15 % ± 3 %
Acetylene C_2H_2	8 % ± 2 %
Ethylene C_2H_4	1,5 % ± 0,5 %

The principle of operation is based on the gas detection by fuel cell. Gases dissolved in oil diffuse through the membrane of the sensor and only these gases are allowed to pass. These gases are subsequently detected by fuel cell that generates the signal directly proportional to the content of gases in oil. Hydran sensor is usually installed at the free flange of the transformer as it is shown in fig. 2. Recommended placement of the Hydran sensor installation is at the bottom of the transformer. [12, 15]

Fig.2. Hydran sensor

Assumptions of gas detection methods analysis

Above mentioned challenge of experts working in power transformer diagnostics is research of correlations between conventional off-line diagnostic methods and on-line parameters. These correlations can help to establish condition based maintenance thus, results in reducing the off-line diagnostics and maintenance costs.

For these reasons, analysis whose objective is plausibility comparison of two gas detection methods in medium-term period has been carried out. These gas detection methods are above mentioned off-line diagnostic laboratory method DGA and on-line Hydran sensor. This analysis is follow-up to an earlier one [16], where the verification of the response capability of particular detection tools had been presented. On-line sensor Hydran, different multi-gas sensors as well as off-line DGA method had been already tested during this analysis. Measurement was carried out at the power transformer model. There were injected pre-known amount of gases into the oil. Gas concentration was monitored by mentioned tools. From the following results, it is obvious that all tested tools show correct functionality in lab. All these tools sufficiently quickly respond to injection of particular gases. In fig. 3., there are presented particular results of this analysis [16].

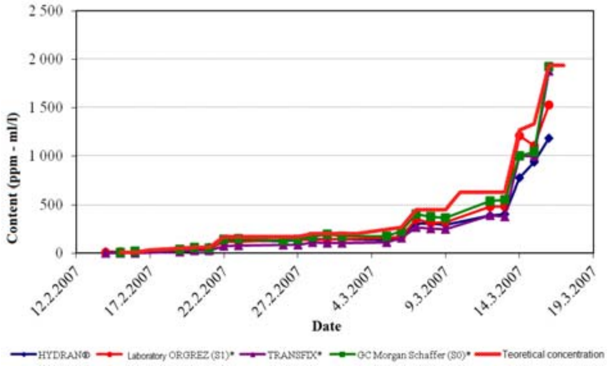

Fig.3. Comparison of response capability of particular detection tools [16]

Six power transformers of CEPS (Czech TSO) have been chosen for this medium-term comparison analysis of two different gas detection methods. These transformers have been made by one producer, thus production know-how and technical specifications (voltage, power, cooling system) are identical as well as monitoring systems used for condition monitoring. All these transformers were put into the operation in 2007 – 2008, thus they are in the beginning of their technical lifetime. Furthermore, these reasons of selection leads to unification of analyzed data and hereby elimination of result misinterpretation.

There is another assumption for this elimination that comes out of the transmission system power transformer operation method. Continuity ensurance of electrical power supply results in characteristically lower loading of transformers (necessary fulfil the basic security criterion of power system reliability N-1). Lower loading leads in lower temperature within the transformer that has minor impact on the aging of the electro insulation system. Lower production of gases within the transformer can be also assumed from the aforementioned reasons.

Technique for comparison of gas detection methods

For the correct interpretation, it is necessary to compare results of particular gas detection methods. In case of transmission system power transformer, oil sampling for DGA is taken up of the valve at the bottom of the tank once a year. Hydran sensor is usually installed on the flange as well at bottom of the tank. It is assumable, that gases dissolved in oil are detected by these detection tools in identical concentration. In case of Hydran sensor, there is problem with the different detection sensitivity of particular gases as shown in table 1. For this purpose, Hydran expected composite value of gases was established. This value is calculated from results of off-line DGA based on gas chromatography according to equation (1) [15]:

$$Hydran = 100\%H_2 + 15\%CO + 8\%C_2H_2 + 1\%C_2H_4 \quad (1)$$

where: H_2 – hydrogen, CO – carbon monoxide, C_2H_2 – acetylene, C_2H_4 – ethylene

This equation is consequently used for comparison of results obtained by DGA and Hydran sensor [14, 15, 16 and 17].

In practice, oil sampling for DGA is performed in different temperatures. Temperature significantly influences content of gases detected in oil, because particular gases are dissolved in oil in temperature dependence, as shown in [11]. Better comparison of results and plausibility between Hydran and off-line DGA would require setting up dissolved gas in oil temperature dependence coefficients.

Statistical technique correlation is used for linearity and dependence testing of the particular gas detection results. Statistical correlation represents interrelationship of two random variables. In case of correlation of two variables, it is probable that they depend on each other, but it is not known their causal relationship. Pearson's correlation coefficient r indicates the strength of a linear relationship between two random variables and is defined as (2):

$$r = \rho_{X,Y} = \frac{E[(X-\mu_x)(Y-\mu_y)]}{\sigma_X \sigma_Y} = \frac{E(XY) - E(X)E(Y)}{\sqrt{E(X^2) - E^2(X)} \cdot \sqrt{E(Y^2) - E^2(Y)}} \quad (2)$$

where:
X, Y – random variables
μ_X = E (X) - expected value X
μ_Y = E (Y) - expected value Y
σ_X – standard deviation of variable X
σ_Y – standard deviation of variable Y

Pearson's correlation coefficient is some value in interval <-1; +1>. In perfect positive (increasing) linear relationship r equals +1, in case of perfect decreasing (negative) linear relationship r is -1. Pearson's correlation coefficient is 0, if the variables are independent to each other. Next step for correct data interpretation is necessary to test the statistical confidence of the Pearson's correlation coefficient. This statistical confidence is determined by confidence criterion t and is defined as (3):

$$t = \frac{|r| \cdot \sqrt{n-M}}{\sqrt{1-r^2}} \quad (3)$$

where:
r – Pearson's correlation coefficient
n – number of values
M – number of variables

Pearson's correlation coefficient is statistically confident, if t exceeds the critical value of Student distribution with parameters degree of freedom (n-M) and confidence level α (usually chosen α = 5 %). [18]

Results and discussion

There were performed 20 dissolved gas-in-oil analysis of oil samplings during the technical life of six power transformers of CEPS. Results of all these analyses were consequently compared with gas composite values of Hydran sensor. Development of Hydran composite value of gases within one of the analyzed transformers is shown in fig. 4.

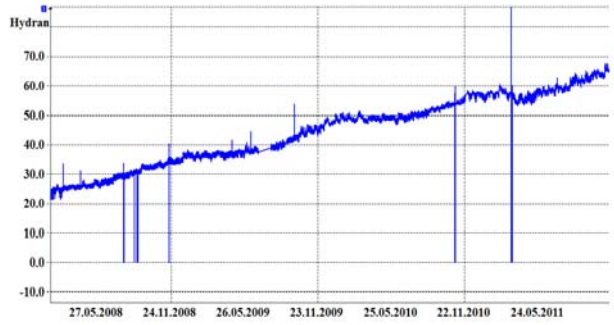

Fig.4. Development of Hydran composite value of gases within one of the analyzed transformers

There are presented monitored and calculated composite gas values and sampling temperature for one of the analyzed transformers in table 2. For better illustration of gas development trend, these values are furthermore shown as bar graph in fig. 5.

Table 2. Monitored and calculated composite values of gases in temperature dependence within one of the analyzed transformers

Sampling date	Hydran online [ppm]	Temperature [° C]	DGA Hydran [ppm]	Temperature [° C]
9. 4. 2008	26	39	20	36
6. 5. 2009	37	36	31	32
4. 3. 2010	49	39	45	34
5. 10. 2011	63	40	50	41

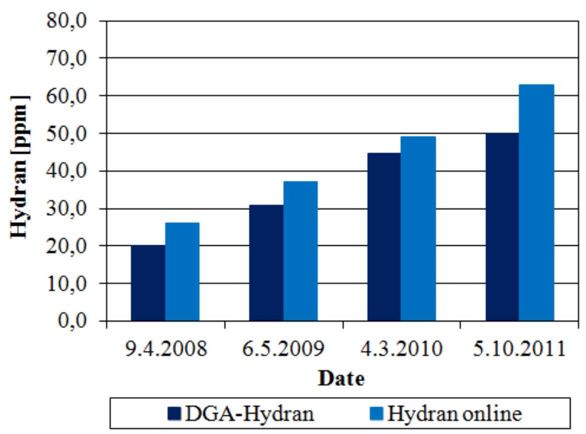

Fig.5. Comparison of monitored and calculated Hydran composite value of gases within one of the analyzed transformers

Comparison of monitored and calculated Hydran composite gas value of 20 oil samplings of the all analyzed transformers is shown in fig. 6. There is obvious positive linearity of calculated composite gas value and on-line composite value of gases monitored by Hydran sensor. Pearson's correlation coefficient of these two variables is $r = 0{,}843$ and it is statistically confident on the confidence level $\alpha = 5\ \%$. As evident, this linearity results in statement that Hydran sensor sufficiently correctly responds to gas in oil development within analyzed transformer in medium-term period. Furthermore, the plausibility of the gas detection using Hydran sensor was proved. Thus, it is just one step to change to condition based diagnostics and maintenance. It would imply in application of DGA just as corrective diagnostic method. DGA would be then used just in case of verification urgency of higher gradient gas in oil development.

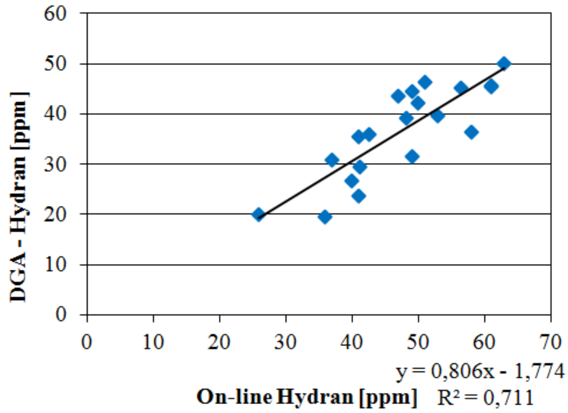

Fig.6. Comparison of monitored and calculated Hydran composite gas value of the all analyzed transformers

Conclusion

This article deals with the study of gas development during the technical life of the power transformer. There is described production of specific gases corresponding with particular types of faults. Furthermore, there are presented gas detection methods focused on off-line laboratory dissolved gas-in-oil analysis DGA and on-line Hydran sensor. Next part of this article is concerned with comparison technique of gas in oil detection methods.

The aforementioned results confirmed that on-line sensor Hydran sufficiently correctly responds to gas in oil development within analyzed transformers in medium-term period. Results monitored by Hydran sensor correspond to results obtained by conventional method DGA. Better results and plausibility comparison would require setting up coefficients of gas dissolved in oil in temperature dependence into the equation of the Hydran expected composite gas value.

Moreover, these results allow one change step from the time based maintenance into condition based diagnostics and maintenance. Thus, DGA would be used just as corrective diagnostics method for confirmation of higher gas in oil gradient. For the full change step to the condition based maintenance, it is necessary to define gas production gradients after their exceeding, corrective DGA would be performed. It requires next investigation within power transformer lifetime.

In security and reliability point of view, monitoring systems failure rate is generally higher than power transformer failure rate. For these reasons, monitoring systems must not be used for control protective devices of power transformer as well as for control of power transformer itself. Harmful fault within the transformer is accomplished by rapid gas production that leads to well-timed Buchholz relay response followed by tripping and dispatch disconnection out of the transmission and distribution network.

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