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MONITORING OF OIL DISTRIBUTION TRANSFORMER IN LABORATORY CONDITIONS

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Abstract – The paper discusses the issue of analyzing the amount of gas and water contained in transformer oil. Such diagnostics include tests and measurements to verify the insulating and cooling properties of the oil, from which it is possible to determine the degree of transformer degradation. The experimental measurement is mainly focused on the state of the quantity of gases and water on the oil distribution transformer and their mutual ratios using monitoring and off-line measurements. In conclusion, an example of the analysis of the mechanical strength of the winding in the oil container of the aforementioned distribution transformer is the monitoring method of tracking the cooling curves through optical sensors.

Key words – transformer, monitoring, gas analyser, optical sensors

INTRODUCTION

Influence of operating conditions leads to aging of individual parts of transformer, and also to changes of the major electrical and mechanical properties. To the check of the condition greatly contributes electro-technical diagnosis, whose main task is to find a clear relation between the change in functional characteristics of the machine and some measurable values. The assessment of these measured values must be visible not only the rate of change, but also whether it is a permanent or reversible state. The aim of diagnostics of transformers is to verify that the machine complies with the determined conditions in accordance with standards [1].

Insulation diagnostics is one of the requirements for safe operation of transformers. Conventional methods to assessment of insulation condition are its loss factor, insulation resistance and partial discharge measurement, etc. These methods, however, provide only partial picture about the polarization processes in insulating material.

Deregulation of power market has increased the competition and also emphasized on the search for the new, efficient and effective methods for diagnosing the insulating system. The use of the return voltage method is significant way to detect ageing of the insulation of operating power transformer in a non-destructive manner [2].

To prevent a damage state of transformers, we perform different types of the measurements that should illustrate an actual condition of the measured equipment. It is therefore important to choose a suitable diagnostics for the right prediction of such conditions [3], [4].

Currently, it is necessary that the diagnostics of power transformers be correctly set, because there are frequent failures in their construction and insulation system. Thanks to the condition of the transformers, a correct analysis of their lifetime is possible.

Among the most common faults in the structural system are winding deformations, inter-turn short-circuits and faults in the tap system of the transformer. Common degradations in the transformer insulation system include excessive partial discharge activity, aging of the solid paper system, and high conductivity in the transformer oil.

Analysis of transformer oil is part of the overall diagnostics of the dielectric subsystem of every oil-filled electrical device. This diagnostics includes tests and measurements to verify the insulation and cooling properties of the oil. The oil serves as an intermediary for the transfer of components such as moisture, operational aging products, mechanical impurities, and so on [5].

Fig. 1 shows diagnostic options for non-contact and contact measuring methods with analysis of power transformers insulation and structural (mechanical) parts.

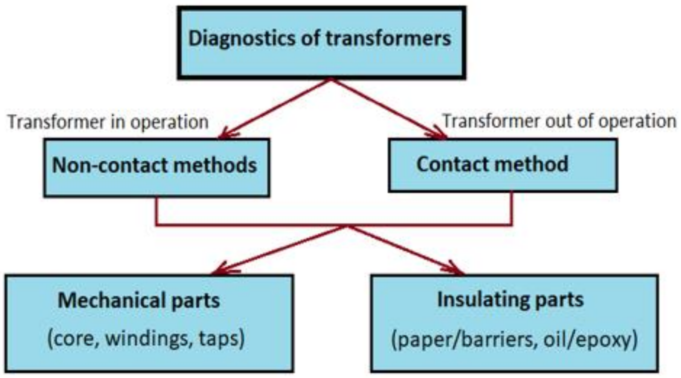

Fig. 1. Scheme of activities for online and off-line measuring methods of power transformers

1 TRANSFORMER DIAGNOSTICS BY USING GAS AND MOISTURE ANALYSIS OF TRANSFORMER OIL

Electrical and thermal stresses transform dielectric oil into various gases. These gases indicate developing damage in electrical machinery or equipment. Their early detection facilitates timely intervention and the financially costly removal of extensive damage. The generated gas dissolves in insulating oil in an amount dependent on the type of gas, the quality of the insulating oil, viscosity, temperature, and pressure.

The type of fault occurring in a transformer can develop slowly or rapidly. Therefore, it is advisable to monitor the transformer's operation in real-time to continuously understand what is happening inside. By observing the breakdown of transformer oil into several gases, it is easiest to monitor this medium [5].

For this purpose, various instruments and systems have been constructed based on years of experience.

According to [6], the influence of temperature, atmospheric oxygen, humidity, and the electric field within the transformer leads, over time, to the generation of aging gas products within the insulation system. Simultaneously, this results in a decrease in the quality of the insulating fluid and paper within the transformer. The quantitative assessment of gases in the oil thus provides an integrated image of the insulation condition of the entire transformer. Gas analysis in transformer oils leads to a clear assignment of gas components to the cause that triggers the fault, allowing the origin of the fault to be determined.

Gas chromatography allows for the analytical tracking of decomposition products by separating individual gas components formed in the oil. These decomposition products differ from each other due to varying energy influences from the faults existing in the transformer, as they involve distinct chemical bonds (i.e., bond energies).

Monitoring the concentration of H_2 and CO is of great importance - hydrogen is the first gas to be released during excessive stress on transformer oil, while carbon monoxide is formed during the degradation of paper insulation. Another important factor affecting the functionality of the transformer is the water content in the system [7].

Moisture can enter the interior of the transformer from the environment or as a product of thermal stress, which causes aging of the paper part of the insulation system. During the operation of the transformer, or in the case of excessive heating, water passes from solid insulation into the oil, which impairs the dielectric properties of the oil, particularly its electrical strength. It can also, due to high temperatures, cause a sudden increase in pressure inside the transformer tank.

Water in transformer oil is relatively easy to measure but complex to interpret. The reason for this complexity lies in the relatively long-time constants for moisture migration between paper and oil. In fact, 96% to 99% of the water is located in the paper insulation rather than in the oil. The relationship between the water content in solid insulation, water content in oil, and temperature is illustrated in the Nielsen diagram (Fig. 2). Moisture analyzers in oil work on the principle of a thin-film and capacitive sensor [5].

Based on quantitative and qualitative analysis of decomposition gases, it is possible to assess not only the degree of thermal aging but also the type of fault (the relative proportions of these gases) that accelerated the aging (partial discharges, electrical arcs, local overheating). Gas analysis in transformer oils leads to a clear assignment of gas components to the cause that triggered the fault, allowing the origin of the fault to be determined [8].

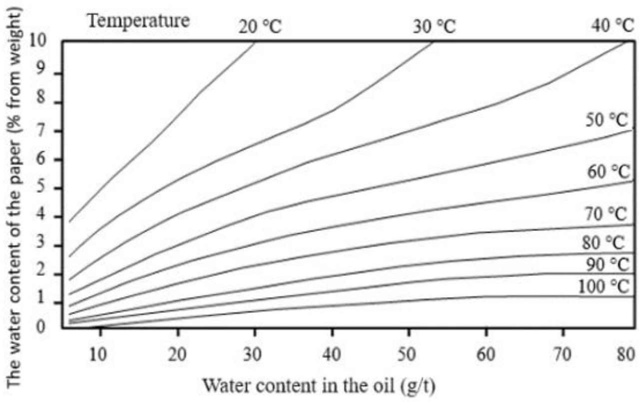

Fig. 2. Nielsen diagram [5]

2 ON-LINE MONITORING COMPOSITE SYSTEMS

Online monitoring is an ideal way to detect developing faults and quantify them, allowing for a reduction in repair costs and significant time savings. Another crucial benefit is the measurement of the machine's lifespan along with the evaluation of key machine parameters.

One of the most widely used and economically accessible systems for simple online compositional monitoring of transformer oil is the Hydran series 201 or M2 system from the Canadian company GE Energy Services - Syprotec (Fig. 3).

This system is precisely utilized in the laboratory on the tested distribution transformer at the Department of Mechatronics and Electronics at the University of Žilina.

The Hydran system detects gases and water content in the oil (only in the M2 model), which are evaluated as absolute and relative values. The device is sensitive to the presence of individual gases, such as hydrogen (H2 - 100%), carbon monoxide (CO - 18%), acetylene (C2H2 - 8%), and ethylene (C2H4 - 1%). The system does not measure the values of specific gases but rather their compositional value, meaning the total amount of combustible gases. This quantity is displayed in the range of 0 – 2000 ppm. The presence of these gases in the oil is a result of the thermal and electrical stress on the transformer and provides information about the condition of the transformer. The time-based monitoring of the concentration of these gases also gives us insights into the development of specific faults in the system.

In contrast to the 201 model, the Hydran M2 has up to 4 analog current inputs, which are used to measure parameters such as load, temperatures from various parts of the machine, or ambient temperature. This allows real-time application of computational models directly within the system, such as the hottest spot in the winding, moisture at this location, bubble formation temperature, cumulative aging of the transformer, cooling efficiency, and more. The data is automatically processed and archived. In case user-defined values are reached or exceeded, binary outputs are activated, as well as digital communication [9].

Fig. 3. Transformer Oil Monitoring Sensor - Hydran M2 [8]

The device uses a polymer membrane where a catalytic oxidation reaction occurs, producing an electrical signal proportional to the amount of dissolved gas (Fig.3). While this sensor is primarily specified for measuring the quantity of acetylene, it is also sensitive to other gases such as hydrogen, carbon monoxide, and ethylene. The resulting accuracy for acetylene measurement is ± 10% of the value ± 2 ppm in the range of 3-500 ppm. The acetylene sensor is mounted on a shared sampling head with the main Hydran sensor, and these are installed on a single valve [10], [11].

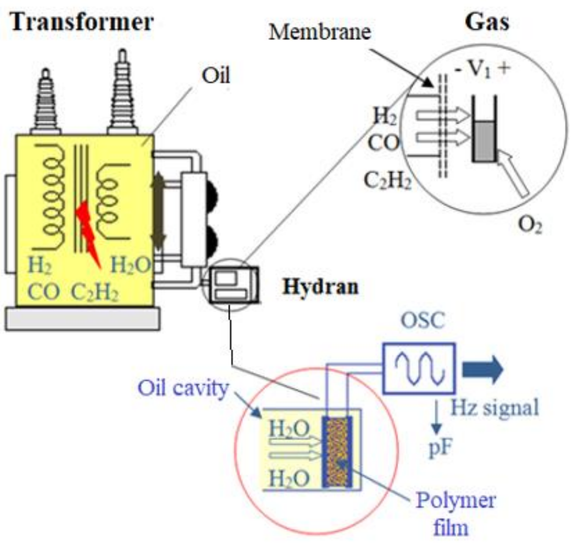

Fig. 4. Principle diagram of Hydran M2 function – gas, humidity and H2O sensor – modification [10], [11].

Key advantages of the Hydran system:

- Provides early warning of the onset and development of faults that could lead to transformer damage.
- Offers hourly and daily trend analysis (ppm changes over a period) with alarm capabilities.
- Stores records for up to a year and logs 500 events with timestamp and data.
- Adjustable alarms based on gas levels and their trends.
- Network connectivity options.
- Both the sensor and the system have auto-test and diagnostic capabilities.
- Calibration is performed using software.
- Remote or local configuration, sensor calibration, and software upgrades.
- Can operate without external software connection [8].

Due to its robustness, resilience, response speed, and multifunctionality, it is an ideal monitoring system for all types of transformers (distribution 22/0.4 kV, 110/22 kV, transmission 400/110 kV, and regulatory). Its straightforward installation also allows for easy relocation if necessary. The system is advantageous in terms of future development, where its functions can be expanded or integrated into extensive monitoring systems. Since the device's sensor cannot percentage-wise distinguish the proportion of individual gases, it is not a gas chromatograph.

3 Off-line Transformer Oil Gas and Moisture Analyzer

The device uses a polymer membrane where a catalytic oxidation reaction occurs, producing an electrical signal proportional to the amount of dissolved gas (Fig.3). While this sensor is primarily specified for measuring the quantity of acetylene, it is also sensitive to other gases such as hydrogen, carbon monoxide, and ethylene. The resulting accuracy for acetylene measurement is ± 10% of the value ± 2 ppm in the range of 3-500 ppm. The acetylene sensor is mounted on a shared sampling head with the main Hydran sensor, and these are installed on a single valve [10], [12].

As our department at Žilina University uses the Transport X device from Kelman for offline oil analysis, this article will focus solely on this measurement system.

The Transport X device (Fig. 5) represents a progressive generation of testing equipment for dissolved gas analysis, which, when used correctly, can provide relatively fast, accurate, and reliable results.

Fig. 5. Transport X device

The Transport X utilizes photoacoustic spectroscopy (PAS) for the analysis of transformer oil. This enables the measurement of seven significant fault gases, including moisture. These gases are hydrogen (H2), carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), ethane (C2H6), ethylene (C2H4), acetylene (C2H2), and water vapor (H2O) [13].

This method operates based on the photoacoustic effect principle (see Fig. 6). The analyzed sample absorbs radiation at a specific wavelength (such as infrared radiation), leading to an increase in the temperature of the gases present in the sample.

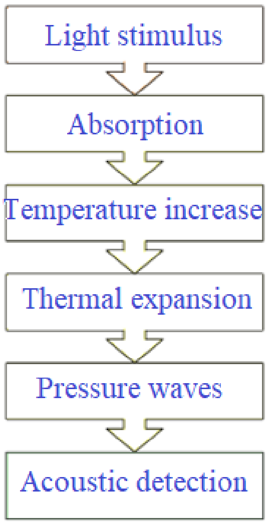

Fig. 6. Principle of photoacoustic spectroscopy

If the sample (and therefore the gases contained within it) is sealed in a hermetically sealed container, the temperature increase will result in a proportional increase in pressure. This change in pressure propagates in the form of acoustic waves, which can be detected using highly sensitive microphones. The final level of each gas is determined based on the evaluation of pressure changes [13].

4 ANALYSIS OF THERMAL PROCESSES IN THE DISTRIBUTION OIL TRANSFORMERS

By changing the voltage level in the transformer and thus by flowing current, the windings, magnetic circuit and other parts of the transformer are heated. At the same time, the temperature of individual parts in the transformer can significantly exceed the temperature of the surrounding environment. The heating of the transformer increases with the increasing load and with the losses arising in it, and also depends on the intensity of cooling of the windings, magnetic circuit and other heated parts.

Different insulating materials used in transformers react differently to temperature rise. Insulating paper plays a fundamental role in the current construction of transformers and is one of the least heat-resistant insulators. With long-term exposure to oil temperature (95-105 °C), the insulating properties of the paper are still without critical negative changes.

From the thermal point of view, the transformer is an inhomogeneous body. Sheets of the magnetic circuit are characterized by high thermal conductivity and a relatively small thermal capacity. They alternate with layers of insulation (varnish, etc.) whose thermal conductivity is not great. Similarly, the winding of the transformer is a complex configuration of copper or aluminum, which has a high thermal conductivity together with an insulating material that forms not only electrical but also thermal insulation [14], [15].

During the operation of the transformer, the metal parts of the magnetic circuit and the copper windings also act as a heat source. Through thermal conductivity, the heat in the magnetic circuit and windings is removed to the outer surface.

In oil transformers, the magnetic circuit and the winding are surrounded by transformer oil, the level of which is considerably higher than the highest part of the magnetic circuit. Oil molecules, touching the warm surface of the winding and the magnetic circuit, heat up, rise up and transfer their heat through the walls and lid of the container to the surroundings. Cooled oil molecules sink down and make way for other warmer ones. In this case, heat sharing happens by convention. A certain temperature difference is established between the winding and the magnetic circuit on one side and the oil on the other side. At the same time, the temperatures of the oil and other parts of the transformer at different heights of the container are different [14], [15].

Fig. 7 shows the typical course of temperature change depending on the height of the 22/0.4 kV transformer.

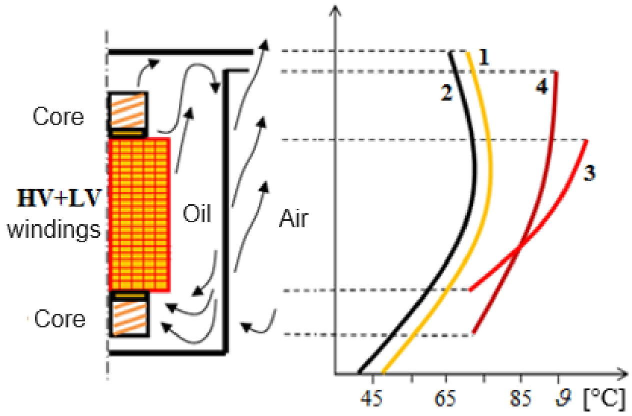

Fig. 7 Typical temperature curves in relation to the height of the transformer (1 – oil temperature, 2 – tank (conservator) temperature, 3 – winding temperature, 4 – core temperature)

The heat passes through the wall of the transformer vessel by conduction. Heat transfer from the surface of the container is caused by convention, i.e. by the movement of heated moving air particles as well as by the radiation of heat. The temperature difference between the container and the surrounding air can reach several tens of degrees.

5 Experimental Analysis of the Gas Amount and Water in Transformer Oil

An example from practice can be the use of the Hydran M2 system and the Transport X gas chromatograph on a distribution transformer rated at 22/0.4 kV, 30 kVA in the Laboratory of Electrical Machine Diagnostics at the University in Žilina.

For measuring gas concentrations and humidity in the oil, only one valve was used, the drain valve, located at the bottom of the transformer tank cover (Fig. 8). The instrument was installed without the need for additional oil hoses, and no additional pump or moving part was required. In this case, oil circulation is ensured by passive circulation due to temperature changes.

Before putting the "cold" transformer into operation, chromatographic analysis of the transformer oil was performed, which was refined using the Transport X instrument during the transformer long-term shutdown (Table 1).

Table 1. Analyzed elements of the tested transformer

Diagnostic gas/water	Amount ppm
H2	2
CO2	3062
CO	80
C2H4	35
C2H6	51
CH4	7
C2H2	0.05
H2O	13

The values obtained from the analysis using the Transport X instrument were processed according to equations (1) to (3), and these results were then plotted on the Duval triangle (Fig. 8):

$$P_1 = \%C_2H_2 = \frac{100C_2H_2}{C_2H_2 + C_2H_4 + CH_4} \tag{1}$$

$$P_1 = 0.12\%$$

$$P_2 = \%C_2H_4 = \frac{100C_2H_4}{C_2H_2 + C_2H_4 + CH_4} \tag{2}$$

$$P_2 = 83.3\%$$

$$P_3 = \%CH_4 = \frac{100CH_4}{C_2H_2 + C_2H_4 + CH_4} \tag{3}$$

P_3=16.7%

Fig. 8. A view of the measured transformer in the Laboratory of Electrical Machine Diagnostics at the University of Žilina

According to Fig. 9, this result is defined as a possible thermal fault with a temperature exceeding 700°C. In our case, this is a consequence of the transformer long-term shutdown and, as a result, the carbonization of the insulation paper in the oil or its discoloration.

Furthermore, according to another chemical analysis method, such as Rogers method, an increase in temperature in solid insulation can manifest itself during operation.

A high amount of carbon dioxide was measured before operation, which proves the high degradation of the insulating paper due to the long-term shutdown of the transformer (Table 1). When measuring insulation resistances, the polarization index of the machine was 1.3. Also from these parameters it is possible to conclude that the problem of the transformer is on the side of the solid paper insulation due to long-term shutdown.

After starting the transformer and with its 10% load (Fig. 10), we observed a gradual increase in the amount of gas (a slight increase in hydrogen). It was a consequence of the heating of the transformer by passing currents and possible weak thermally insignificant partial discharges, where, according to [6], hydrogen is produced as a product of the splitting of aromatic hydrocarbons. The influence of acetylene and ethylene at such a small load could be neglected. Both gases are created on the basis of high temperatures as a result of high activity of partial discharges (faulty contacts, arcs, partial breakdowns).

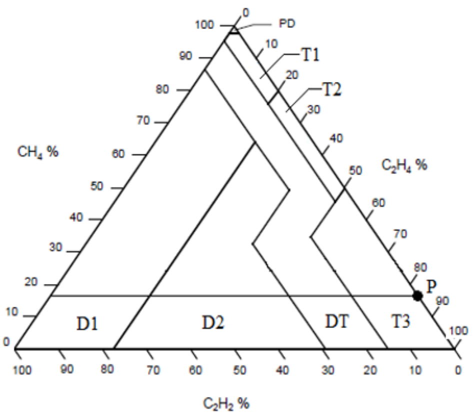

Fig. 9. Evaluation of the insulation condition of the transformer according to Duval's triangle

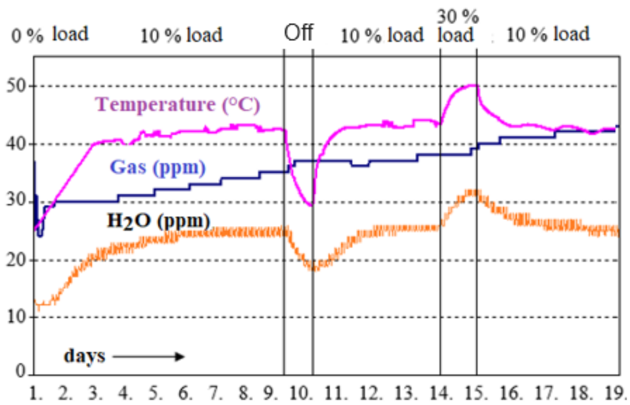

Fig. 10. Monitoring of temperature, gas and water content during the test

After starting the transformer and its subsequent loading, the temperature increased from the original ambient temperature of 25 °C to 42 °C within 2 days. When turning off the transformer, we observe a rapid exponential temperature drop of up to 75%. After turning it on again, the temperature stabilized at the original 42 °C. When the load changes to 30%, the temperature rises again. The transformer reaches its characteristic working temperature at full load.

One of the additional parameters that we could monitor was the water content in the transformer oil. Here, we can observe the increase in water content after turning on the transformer. The increase in water content is associated with the transfer of water stored in the paper insulation as it heats up. The increased presence of water is one of the main factors affecting the deterioration of the dielectric properties of transformer oil.

The relationship between the amount of water in the oil follows the temperature dependency with very little delay. For example, a rapid drop in temperature when the transformer is turned off or an increase in temperature due to a change in load to 30%, the amount of water decreases or increases almost simultaneously.

During a several-hour temperature drop to 75% of its steady-state value, the gas exhibited a very small decrease in ppm, albeit with a delay of up to 24 hours. The process of changing the ratio of hydrogen to carbon monoxide in the oil, therefore, occurs very slowly. This is due to the fact that the water content in the oil decreased by 25% due to retransfer into the paper insulation (Fig. 10 at the time of shutdown (Off) - Day 10).

The experimental measurements mentioned showed that depending on the load of the transformer used, the steady-state temperature and water content in the transformer oil change, and the gas content increases even after a short-term transformer outage [16].

Measurement during the long-term shutdown of the transformer allowed obtaining dependencies of states that cannot occur during normal operation and at full load.

Hydran M2 was able to determine the water content during the test, but the gas content sensor has a major disadvantage, which is the inability to differentiate the amount of individual gases in the oil. This deficiency can be overcome by chromatographic analysis.

Tests confirmed that the water content in the oil depends on the temperature corresponding to the load of the transformer. One way to reduce this dependence is to regenerate the insulating oil directly on the transformer to reduce the water content from solid insulation, especially from insulating paper.

When evaluating the measurements of online compositional and offline chromatographic analysis, it can be concluded that the transformer should be put into operation gradually - from a de-energized state to a gradual load state. Since the value of the $CO2 / \Sigma CxHy$ ratio is relatively low, it is possible that in the case of long-term operation of the transformer, damage to it may occur due to reduced insulation quality.

The insights gained in this measurement provide a good basis for further investigation under various operating conditions of the transformer.

6 Experimental Analysis of the Temperature in Transformer by Optical Sensors

The experimental measurements were carried out again on the same distribution oil transformer with natural cooling 22/0.4 kV, 30 kVA, which is located in the Laboratory of Diagnostics of Electric Machines (Fig. 8). To measure the winding temperature, two optical sensors with a NEOPTIX T measuring unit were used, which were mounted on the upper and middle parts of the primary phase B before the actual operation (Fig. 11 - white tapes).

The optical sensors were brought out using special bushings to the upper part of the transformer container and from there further brought out by two optical fibers to the NEOPTIX T measuring system (Fig. 11), which subsequently evaluated the measured values of the winding temperature.

After several weeks of operation of the transformer at approximately 10-30% load, an analysis of the measured temperature values was performed on the measured phase of the winding as a function of time during its sudden shutdown.

It should be noted that in a container with oil, the upper part of the winding reacts differently to sudden work changes than the middle part. In this way, possible differences in the behavior of the two parts of the winding during cooling after turning off the machine were monitored. The levels of cooling down may include the degree of mechanical strength of the winding, its insulation quality, as well as the viscosity of the oil in the transformer tank.

Fig. 11. Location of optical sensors (covered by white tapes)

Fig. 12 shows a comparison of the measured values of the winding temperature as a function of the time "after shutdown" of the machine. The temperature drop to 48 °C in the upper part of the winding (W1) took 75 seconds and in the middle part (W2) only 50 seconds, which also corresponds to the expected temperature distribution of the oil after switching off the transformer.

The temperature of the oil in the transformer tank rises from a certain minimum at the bottom of the tank to a maximum value - approximately to the height of the upper edge of the winding. This maximum temperature is mostly maintained in the entire mass of oil under the upper lid of the transformer [16].

At the chosen falling temperature ϑ = 48 °C (which is approximately 60% of the height of the exponential curve), it is possible to determine the cooling time for W1 t_1 = 75 seconds and for W2 t_2 = 50 seconds from the graph.

By comparing these two times using the relation (1), a 1.5 times greater stress on the mechanical strength due to thermal shocks (short-circuit currents) was found on the upper part of the winding (W1) than in the middle part (W2), which is also proven by the subsequent calculation

$$n = a = \frac{A_1}{A_2} = \frac{t_2}{t_1} = \frac{75}{50} = 1.5 \quad (4)$$

where the coefficients A_1, A_2 are damping coefficients during the cooling process and t_1, t_2 are the cooling times of both measured points after turning off the transformer [17].

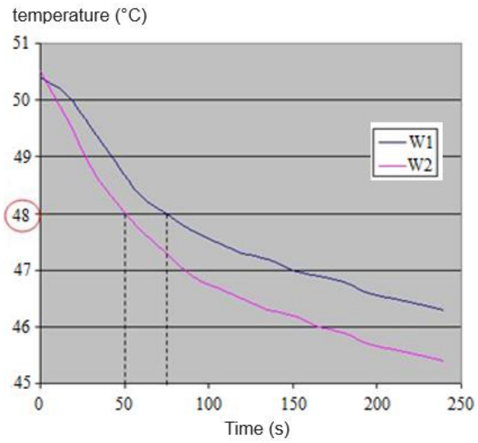

Fig. 12. Winding temperatures measured at two locations in a time interval

It is obvious that the upper part of the winding will be most heavily burdened by the degrading thermal effects of short-circuit currents.

In practical calculations of heating and cooling of the transformer, it is necessary to use experimentally obtained data characterizing the sharing of heat from the warm surface of the winding, the magnetic circuit and the vessel.

If the load on the transformer changes during short intervals, then when calculating the warming, characterizing the transient thermal process in the winding, in the magnetic circuit and in the oil of the transformer.

Experimental measurements and subsequent analysis have proven the practical applicability of the theory of the decrease in the mechanical strength of conductors also for the windings of oil power transformers. It is obvious that the degree of mechanical strength of the winding, its insulation quality, as well as the viscosity of the oil in the transformer tank affect the overall degradation by thermal shock (a sharp rise in temperature during the duration of the short circuit and its decrease after the interruption of the current).

7 CONCLUSIONS

In this paper was presented the combination experiment for diagnostics and measurement of insulating and mechanical properties of high-voltage oil distribution transformer 22/0.4 kV by using monitoring gas and optical systems in the laboratory conditions.

Both monitoring systems are unique in terms of analysis of insulating and mechanical condition of oil power transformers in their normal operation. In comparison with other off-line methods, it is possible to evaluate the moisture condition of the insulation paper and conductivity in oil of the power transformer with high accurate.

Information and outcomes mentioned in the paper are the basis for future investigation, which will focus on enlarging the knowledge of and determining clear relation in gas, moisture and temperature domain and condition of the insulating (paper, oil) or mechanical (core, windings, types) system of distribution transformers.

ACKNOWLEDGMENTS

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