Anna GOS, Mirosław GOS, Paweł MROCZKOWSKI
anna.gos@itee.radom.pl, m.gos@zutenergoaudyt.com.pl,
pawel.mroczkowski@itee.radom.pl

DIAGNOSTICS OF THE STATE OF OIL-PAPER INSULATION IN GROUP 2 TRANSFORMERS

Key words

Transformer oil, oil-paper insulation, transformers diagnosis.

Abstract

The article describes causes of the need to monitor the technical condition of transformers by analysing the physicochemical properties of the oil-paper insulation. The article also describes the importance of individual indicators determining the quality of transformer oil and discusses the results of the operating oil in a 49-year-old transformer before and after exchange.

Introduction

Central generation of electricity in large power sources and its distribution is preferred for economic and technical reasons. For these reasons, in the electric power system, there is a necessary to use transformers. The Group 2 Transformers have turn-to-turn paper insulation, which is flooded with the oil that has electrical insulating properties. Under the influence of the load and the time, the transformer age and wear out. The transformers working time depends mainly on the stability of the insulation, which in turn depends on many factors, such as temperature, humidity, pollution, displacement of windings at extensions and contractions, and vibration. The nominal lifetime of the transformer is estimated at 25 to 30 years. Economic considerations have shaped the trend of the maximum extension of transformers working time, which entails the need for repairs and modernization, in order to ensure their reliability [1, 2]. The reasonable time to prolong the life of a transformer is up to about 40 to 50 years [3, 4]. The type of operation and service care strongly influence the life of the transformer. Paper-oil insulation is one of the key elements of the transformer, determining its proper functioning. The paper is a cable insulation while transformer oil restricts the access of air and functions as coolant and protect against corrosion [1].

Conducting a proper diagnosis on transformers is appropriate from an economic and technical aspect. A relatively small investment in diagnostics can prevent huge losses resulting from the failure of the transformer. Diagnostic tests are intended to determine the current technical condition and usability for further exploitation of the transformer. In the transformer there are systems, within which inferences are made about the current operating state of the unit based on the characteristic size and correlations (e.g. load, temperature, water content and dissolved gases in oil) [1]. Applicable methods are mainly research methods that do not require a disabling the power system and consisting mainly in collecting and examining electrically insulating oil. Ageing of the solid insulation is always in combination with the ageing of the transformer oil. The presence of specific chemical compounds in oil indicates the ageing of paper insulation [5–7]. Examination of the oil in order to determine the degradation of cellulose insulation is a method considerably less time consuming and less expensive than the inspection of the transformer. The oil-paper insulation diagnostic methods allow for the detection of internal damage in the transformer at an early stage of their formation.

In the domestic power industry, there is a large population of transformers with more than 30 years of exploitation, which are characterized by a relatively high risk of failure. Transformers require constant supervision and control of the existing operating condition. In these units, manufactured in accordance with the contemporary technology, operational problems associated with moisture and the insulation oil and paper ageing mainly occur [8–10].

1. Oil-paper insulation

Transformer oil is an integral part of the transformer and, combined with the elements made of cellulose creates a paper-oil insulation.

The main task of transformer oil is to remove heat from the transformer and to provide good electrical insulation. In addition, the transformer oil protects the paper insulation against moisture and air, corrosion, facilitates arc quenching, and improves the strength of the cellulose insulation through their saturation.

Due to the function of the transformer oil, it should be characterized as follows, among others [1]:

- High resistivity;
- Resistance to electrical break-down;
- Low flow point;
- High resistance to oxidation;
- The absence of impurities; and,
- High flash point, guaranteeing safety.

Requirements for transformer oils during use depend on the type of transformers in which they are used and, in particular, on their power. Oils most frequently used in the transformers are mineral oils. These are characterized by high dielectric strength and thermal conductivity. Mineral oils are prepared from highly refined, light fractions of petroleum distillates [11]. The advantage of mineral oil is the compatibility with the materials of construction of the transformer, which include good operating characteristics and a relatively low cost of production. A disadvantage of the mineral oils is the risk associated with the fire safety, resulting from the low flash and fire point, a limited resistance to oxidation, and the tendency to chemical degradation and gas evolution [1, 11].

The main factors that affect the intensity of transformer oil ageing during operation are high temperature, the impact of oxygen, the presence of water, the catalytic effect of copper, and the depolymerisation of cellulose in paper insulation. Temperature and the presence of moisture have a determined influence on the aging process of insulation. The more moisture in the cellulose, the faster is the process of depolymerisation. So far, in order to evaluate the condition of paper insulation and its suitability for further service, the degree of polymerization was determined. However, sampling is possible only during an internal review of the transformer or repair. Currently, the degree of cellulose insulation ageing is tested by measuring the concentration and the increase in the content of furan compounds in the oil. The cellulose insulation, as a result of the ageing process, loses its flexibility and becomes more brittle. The consequence of this is a detachment of cellulose microfibrils and then the depolymerisation and release of furan compounds, such as 2-furfural (2-FAL), 2-furfurylalcohol (2-FOL), 2-acetylfuran (2-ACF), 5-methyl-2-furfural (5-MEF), and 5-hydroxymethyl-2-furfural (5-HMF).

2. Research methodology and test results

In order to evaluate the condition of oil-paper insulation dielectric, physical and chemical indicators were examined.

The physicochemical properties of transformer oil that have particular operational importance are classified as appearance, density, kinematic viscosity, flow point, the content of suspended solids, colour, acid value, the flash point, water content, and content of furan derivatives.

The most important parameters determining the dielectric properties are resistivity, dielectric permittivity and dielectric loss factor, breakdown voltage, and surface tension.

To evaluate the operational status of the oil-cellulose insulation basic examinations were selected. These are described below.

2.1. Appearance

Assessment of the appearance of transformer oil was made in accordance with the guidelines of the standard PN-EN 60296:2012: Fluids for Electrotechnical Applications - Unused Mineral Insulating Oils for Transformers and Switchgear. The rating is based on visual observation of a sample having a thickness of about 10 cm in transmitted light at ambient temperature. This method allows one to determine the clarity of the oil, the presence of visible contamination, and the presence of the separated water.

2.2. Determination of water content

The evaluation of water content in the transformer oil is performed by the Karl Fischer method recommended by the standard PN-EN 60814:2002: Insulating Liquids - Oil-impregnated Paper and Pressboard - Determination of Water by Automatic Coulometric Karl Fischer Titration. The analysis was made using an 831 Metrohm KF Coulometer.

2.3. Determination of acid value

An indicator of the intensity of the oil ageing and its suitability for further use is the growth rate of the acid value of transformer oil. Acid products arising as a result of the ageing of transformer oil have a disruptive effect on the mechanical strength of cellulose insulation and are responsible for the corrosion of the metal parts of the transformer. Their content is determined by the acid value according to the standard PN-ISO 6618:2011: Petroleum Products and Lubricants - Determination of Acid or Base Number - Colour-Indicator Titration Method. Determination is performed with a glass burette and titered chemicals.

2.4. Flashpoint

The safe operation of transformers requires that the oil be characterized by a sufficiently high flash point ($\geq 130^{\circ}C$). The test is performed using Pensky Martens Closed Cup method according to PN-EN-ISO 2719:2007. Flash point is the lowest temperature, at a given pressure, in which the vapour of the test sample form a mixture with air and ignite after being exposed to a flame. The determination was performed on a semi-automated Herzog apparatus.

2.5. The content of furan compounds

To test the degree of cellulose insulation ageing there is a need to measure the concentration and the increase in the content of furan compounds in the oil according to the standard PN-EN 61198:2002: Mineral insulating oils – Methods for the determination of 2-furfural and related compounds. The content of furan derivatives in the oil was determined on a Perkin Elmer high performance liquid chromatograph. This method has a high level of detection (0.01 ppm) and a high accuracy of measurement. In order to correctly identify the furan compounds, it is necessary to use chromatographic standards, because chromatograms usually contain additional signals derived from the products of ageing oil. Chromatographic separation was performed on a C18 – reverse phase column, a mixture of water and acetonitrile was used as a carrier phase, and the analysis was performed using an UV-VIS detector at two wavelengths: 220 and 276 nm.

2.6. Breakdown voltage

Breakdown voltage is the parameter used to evaluate the dielectric strength of transformer oil. It is the lowest voltage required to cause an electrical spark to jump between two electrodes immersed in the oil in standard conditions. The value of the breakdown voltage, to a very large extent, depends on the moisture of the sample and the presence of other impurities. Measurements were carried out according to PN-EN 60156:2008: Insulating Liquids –- Determination of the Breakdown Voltage at Power Frequency – Test Method. For this purpose, an automatic device from the MEGGER Company was used. For each sample, 6 determinations must be made. On this basis, the relative standard deviation is calculated.

2.7. The resistivity and dielectric loss factor

The measurement of resistivity and dielectric loss factor allows the assessment of the quality and degree of the contamination of transformer oil. The method of measuring the resistivity and dielectric loss factor is based on the standard PN-EN 60247:2008: Insulating Liquids – Measurement of Relative Permittivity, Dielectric Dissipation Factor (tan δ) and D.C. Resistivity. Both measurements were made using an automatic oil tester BAUR DTL C.

The resistivity is the ratio of the intensity of the constant electric field and the determined value of current density. The value of this parameter depends on the temperature, electric field strength, and time of voltage application. Oil resistivity measurements were performed at a constant voltage of 0.25 kV/mm field strength after 60 seconds from the time of the application of voltage.

The dielectric loss factor is the tangent of the phase displacement angle between the applied voltage and current, which differs by $\pi/2$ radians, when the dielectric in a capacitor is composed exclusively of electro-insulating liquid. The dielectric loss factor depends on the viscosity of the liquid and, to a lesser extent, on the voltage. Oil tan δ measurement was performed with alternating voltage with a frequency of 50 Hz and an intensity of the electric field of 1 kV/mm.

The object of the research was an insulating oil obtained from the 49-year-old transformer with power 4 MVA (Group 2). To detect the furan compounds, chromatographic analysis of the oil was performed. Figure 1 shows the chromatogram of this transformer oil.

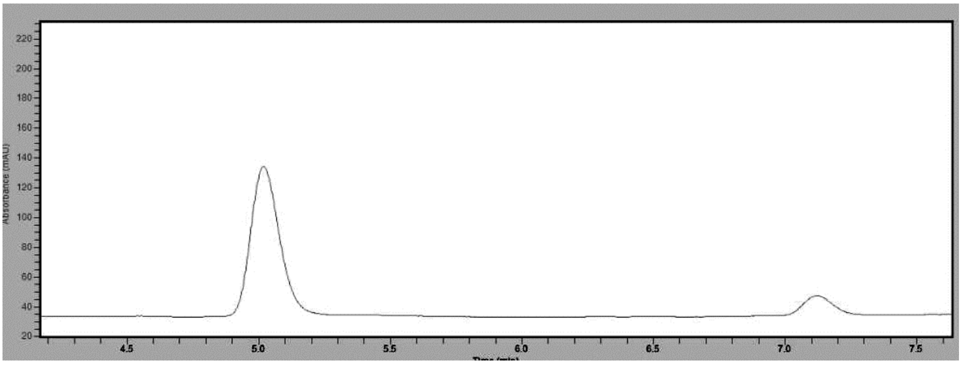

Fig. 1. The chromatogram of transformer oil obtained from the 49-year-old transformer

Based on chromatographic separation, a significant amount of 2 furfural - 6.02 mg/kg was determined. This amount of furan derivative indicates a rarely found degree of cellulose insulation ageing.

Table 1 shows the obtained results of the oil analysis and acceptable values for Group 2 Transformers.

Table 1. Results of the insulating oil determination

Type of the test	**Unit**	**The measured value**	**The required value**
The clarity	-	turbid	limpid
The separated water content	-	does not contain	does not contain
The suspended solids content	-	contains	does not contain
The breakdown voltage	kV	37.9*)	≥ 45
The relative standard deviation	%	36	≤ 20
The resistivity at 50°C	Ωm	1×10^{10}	$\geq 5 \times 10^{9}$
The dielectric loss factor Tan δ (50ºC)	-	0.022638	≤ 0.07
The water content by Karl Fischer method	ppm	24.3	≤ 25
The acid value [mg KOH/g]		0.19	≤ 0.25
The flash-point	ºC	158	≥ 130

*) The arithmetic mean of 6 the relative standard deviation measurements (20,3; 37,8; 31,2; 34,1; 60,6; 43,5).

Based on the test results listed in the Table 1, it can be concluded that the test transformer oil does not meet the requirements for insulating oils in transformers (Group 2) in operation. The oil is turbid and contains solid foreign objects. It is characterized by very a low breakdown voltage and high standard deviation.

Due to no satisfactory results, an improvement of the properties of the oil was needed. For this purpose, the oil was subjected to vacuum treatment. This was followed by a series of analyses designed to test the effectiveness of the process of exchange.

Figure 2 shows the chromatogram of the transformer oil after the process of exchange.

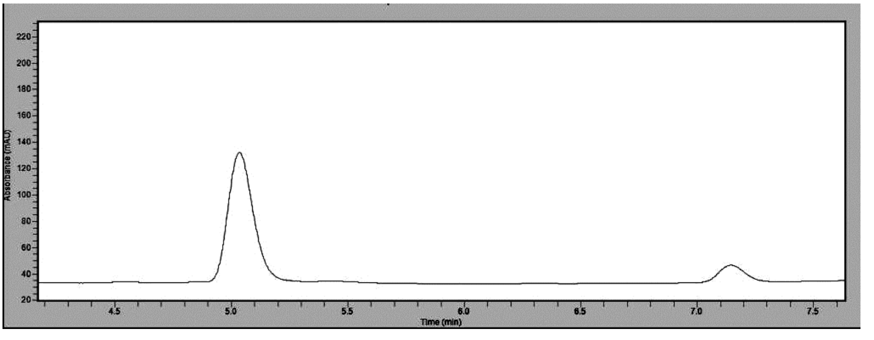

Fig. 2. The chromatogram of transformer oil obtained from the 49-year-old transformer after exchange

Based on chromatographic analysis, it was found that the exchange process does not affect the presence of the furan derivative. The content of 2-furfural is still at a high level. This parameter is for information only, because the limit on the 2-furfural and other furan derivatives is not specified in the standards concerned. Table 2 shows the obtained results of the oil after exchange analysis and acceptable values for Group 2 Transformers.

Table 2. Results of the insulating oil after exchange

Type of the test	**Unit**	**The measured value**	**The required value**
The clarity	-	limpid	limpid
The separated water content	-	does not contain	does not contain
The suspended solids content	-	does not contain	does not contain
The breakdown voltage	kV	70.3*)	≥ 45
The relative standard deviation	%	19	≤ 20
The resistivity at 50°C	Ωm	1.1×10^{10}	$\geq 5 \times 10^9$
The dielectric loss factor Tan δ (50ºC)	-	0.020230	≤ 0.07
The water content by Karl Fischer method	ppm	14.4	≤ 25
The acid value [mg KOH/g]		0.19	≤ 0.25
The flash-point	ºC	155	≥ 130

*) The arithmetic mean of 6 the relative standard deviation measurements (62.8, 49.8, 83.0, 85.1, 65.4, and 76.1).

In terms of these parameters, the oil meets the requirements of insulating oils in transformers (Group 2) in operation. Many parameters have been improved significantly, including the clarity and solid impurities content. The value of breakdown voltage increased and the relative standard deviation is at the right level. The water content in the oil significantly decreased and ignition temperature does not exceed a required safe value 130°C.

Summary

In order to determine the current technical condition and suitability of a transformer for further exploitation, a series of diagnostic tests is needed. Conducting proper control of oil and insulation in transformers is appropriate from an economic and technical point of view. Relatively small investments in diagnostics can prevent huge losses arising from the failure of the transformer, because diagnostics allows the detection of internal damage in the transformer at an early stage of its formation.

In order to assess the condition of oil-paper insulation, the dielectric and physicochemical indicators were checked, including visual evaluation of the sample, water content, acid value, breakdown voltage, and dielectric loss factor. Based on the analytical results, it was found that the tested transformer oil does not meet the requirements for insulating oils in transformers (Group 2) in operation. The oil contained suspended solids and was turbid. The oil was characterized by a very low voltage breakdown and high relative standard deviation and a high content of furan derivatives. Based on the results of the analysis, the oil was exchanged, which caused the improvement of physicochemical properties.

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Diagnostyka stanu izolacji papierowo-olejowej transformatorów drugiej grupy

Słowa kluczowe

Olej elektroizolacyjny, izolacja papierowo-olejowa, diagnostyka transformatorów.

Streszczenie

W artykule opisano przyczyny konieczności monitorowania stanu technicznego transformatorów poprzez analizę właściwości fizykochemicznych izolacji papierowo-olejowej. Opisano znaczenie poszczególnych wskaźników decydujących o jakości oleju transformatorowego oraz omówiono wyniki oleju pracującego w 49-letnim transformatorze przed i po jego wirowaniu.