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Current Issues Regarding the Analysis of the Physico-Chemical and Electrical Properties of Transformer Oil

Mircea Emilian Ardeleanu*, Aurelia Scornea†, Dan Gabriel Stănescu*, Ionuţ Marius Burciu* and Ioana Gabriela Sîrbu*

* University of Craiova/Department of Electrical, Power and Aerospace Engineering, Craiova, Romania, mardeleanu@elth.ucv.ro, dstanescu@elth.ucv.ro, burciuionut95@yahoo.com, osirbu@elth.ucv.ro

† National Institute for Research, Development and Testing in Electrical Engineering/ High Voltage Division, Craiova, Romania, scornea@icmet.ro

Abstract **– Researchers and practitioners interested in the operation, monitoring and diagnosis of electrical equipment (such as: transformers, motors and generators, circuit breakers, etc.) know that in order to ensure a safe operation of such equipment it is necessary to know, among other things, the condition of the insulation system. This is one of the essential information to know because about 40% of failures which occur in the operation of the electrical equipment are due to insulation breakdown; in some cases they can reach even close to 100%. In this context this paper proposes the presentation of several modern methods and equipment for the study and analysis of physical and chemical properties (namely: analysis of water content, density and interfacial tension, dissolved gas analysis and furan components determination) and electrical parameters (namely: determination of loss factor and relative permittivity) of transformer oil. Samples of transformer oil type MOL TO 30.01 (uninhibited electrical insulator, non-additive), new StaSo Transformer Oil I (high quality inhibited insulating oil) and TR 30 oil were studied. Two samples were collected directly from the original barrel, two samples were collected from the transformer tank after dielectric tests at the transformer's manufacturer and also two samples of used TR 30 oil were collected from two transformers. The tests were carried out in an accredited laboratory with calibrated equipment. The results highlighted the properties of each analyzed sampled. The interpretation of the results emphasized the qualities and defects of each analyzed oil sample and whether or not they fit the standards in the field.**

Cuvinte cheie: *ulei de transformator, factor de pierdere, permitivitate relativă, tensiune interfacială, analiza gazelor dizolvate.*

Keywords: *transformer oil, loss factor, relative permittivity, interfacial tension, dissolved gas analysis.*

I. INTRODUCTION

From the practice of operation and maintenance of electrical equipment (transformers, motors and generators, etc.) it is known that, in order to ensure a safe operation and functionality, it is necessary to know, among other things, the condition of the insulation system, because about 40% of malfunctions which occur in operation are due to damaged insulation. In some cases, this percentage can even reach close to 100% [1-3].

Therefore, ensuring a safe and long-lasting operation of electric power transformers, an important and essential element in the electricity transmission and distribution system, is a permanent concern and a main objective for both manufacturing companies and users [3].

The insulation system of electrical equipment, in general, is subjected, during the entire operation, to a complex of stresses: electrical, mechanical, thermal etc. Thus, in the case of an electrical transformer, its insulation system must withstand and transmit at the same time to the coolant (transformer oil) the heat developed in the various construction elements (windings, magnetic circuit) [1, 4, 5]. Electrical insulation systems do not withstand the suddenly degradation process, but under the action of various stresses the insulation gradually undergoes irreversible structural transformations, which causes their electrical characteristics to worsen.

The ageing degree is determined by the variation of the values of the dielectric material parameters at a given time, compared to the initial values of these parameters. The ageing rate is different if all the electrical, thermal, and mechanical stressors act simultaneously, separately or in a certain sequence [4, 6].

Transformer faults generally result from the long term degradation of oil and paper due to the combination of heat (pyrolysis), moisture (hydrolysis) and air (oxidation). Due to electrical and thermal stresses that in-service power transformer experiences, oil and paper decomposition occurs, resulting in a number of gases related to the cause and effect of various faults. Gases produced due to oil decompositions are hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4) and ethane (C_2H_6), while carbon monoxide (CO) and carbon dioxide (CO_2) are mainly produced by paper decompositions and can be used as a trigger source for paper monitoring [7].

In the ageing process transformer oil undergoes structural changes due to the decomposition of constituent aliphatic, naphthenic and aromatic hydrocarbons [5].

Therefore, in the maintenance activity of the electrical transformers it is necessary to carry out a permanent monitoring of the electrical, physical and chemical parameters of the transformer oil.

Insulation degradation is a major concern for these aged transformers. Insulation materials in transformers degrade at higher operating temperatures in the presence of oxygen and moisture. Practicing engineers currently use a number of modern diagnostic techniques to assess the insulation condition of aged transformers [8].

Thus, in this paper we propose to present offline methods and modern equipment used for the study and analysis of physical and chemical properties (analysis of water content, density and interfacial tension, dissolved gas analysis, and determination of furan components) and electrical properties (determination of loss factor tanδ and relative permittivity ε_r) of the transformer oil.

Samples of transformer oil type MOL TO 30.01 (uninhibited electrical insulator, non-additive) and new StaSo Transformer Oil I (high quality inhibited insulating oil) were studied: two samples collected directly from the original barrel, two samples collected from the transformer tank, after dielectric tests at the transformer's manufacturer; there were also studied two samples of used TR 30 oil, collected from two transformers.

The experimental determinations were carried out in the specialized laboratory, within The National Research, Development and Testing Institute for Electrical Engineering - ICMET Craiova .

II. Some Aspects Regarding the Liquid Electrical Insulating Materials

The liquid electrical insulating materials are those that are in a liquid state during the entire period of use and operation [1]. This category of electrical materials includes both natural and synthetic electrical insulating oils.

The chemical structure of oil is very complex, oil being made up of a large number of hydrocarbon and non-hydrocarbon molecules. The hydrocarbons consist of paraffins, naphthenes and aromatics. The non-hydrocarbons consist of acids, esters, alcohols, ketones, iron and copper. The chemical composition of the oil can have significant effects on the properties it exhibits such as oxidation behavior and dielectric strength [9].

Most liquid electrical insulating materials are flammable, which requires a lot of attention and caution in operation. Likewise, these materials are oxidizable, from this chemical process resulting gases, water, acids etc. which are factors that lead to changes in their dielectric properties [10].

Mineral oils are achieved by the frequent distillation of crude oil. Therefore, from a chemical point of view, mineral oils constitute a mixture of naphthenic, aromatic and paraffinic hydrocarbons [10, 11].

For the cleaning of unstable chemical impurities, the oils are subjected to the refining process. The refining process consists, in essence, in the treatment with sulphuric acid, neutralization with alkaline solution, washing with water, drying and settling. Another efficient method of refining is that of the Romanian engineer Lazăr Edeleanu, known in the literature as the "Edeleanu process", which is based on the specific solubility of some classes of hydrocarbons in liquid sulphur dioxide [1,10].

Transformer oil, being a non-polar material, has a low value of relative permittivity (ε_r = 2.2 .... 2.4) and the loss factor tanδ is dependent on the temperature, increasing with temperature due to the increase of electrical conductivity. The increase in temperature also influences the value of the dielectric strength due to the increase in the oxidation rate, the solubility rate and the water emulsification.

Ageing, wear and therefore degradation of the dielectric properties of transformer oils are favored by factors such as the presence of oxygen, high temperature, electric field, electric arc, light and some metals [11].

III. Experimental Results and Analysis of Some Transformer Oils

A. Test Samples

For the study of some physical, chemical and electrical properties of the transformer oil, samples of transformer oil type MOL TO 30.01 (uninhibited electrical insulator, non additive) and new StaSo Transformer Oil I (high quality inhibited insulating oil) were used in this paper: two samples collected directly from the original barrel, two samples collected from the transformer tank after dielectric tests at the transformer's manufacturer; there were also studied two samples of used TR 30 oil, collected from two transformers.

The experimental determinations were carried out in the specialized laboratory, within The National Research, Development and Testing Institute for Electrical Engineering - ICMET Craiova.

Before starting the test, in order to facilitate the recognition of each type of analyzed oil during the tests, a coding of them was carried out to ensure their identification [1]. In table I this coding is presented.

B. The Experimental Determinations

1) Visual Analysis

The visual examination is applicable to electrical insulating liquids that have been used in transformers, oil circuit breakers or other electrical apparatus as insulating or cooling media, or both. Poor transparency, cloudiness or the observation of particles indicates contamination such as moisture, sludge or other foreign matter [1,12].

A first analysis of the oils is the visual analysis which aims to establish the degree of clarity, transparency, appearance of the oil. Colour is often used as a qualitative method.

The colour of the oils, depending on the condition of the insulation system, is in the range from yellow-colourless to brown and intensifies by use when the oils become opaque by wear during the operation of power transformers [5]. In Fig. 1[1] the studied samples are depicted.

TABLE I.

Identification Codes of Tested Oils

No.	Identification codes of tested oils	
	Oil type	***Code assigned for experiment***
1	StaSo Oil, new, inhibited insulating oil	S100
2	StaSo Oil collected from the transformer tank after stand tests	S102
3	MOL TO 30.01RO oil, new, uninhibited	M200
4	MOL TO 30.01RO oil collected from the transformer tank after stand tests	M202
5	TR 30 oil, used, reddish color	300
6	TR 30 oil,used, brown	400

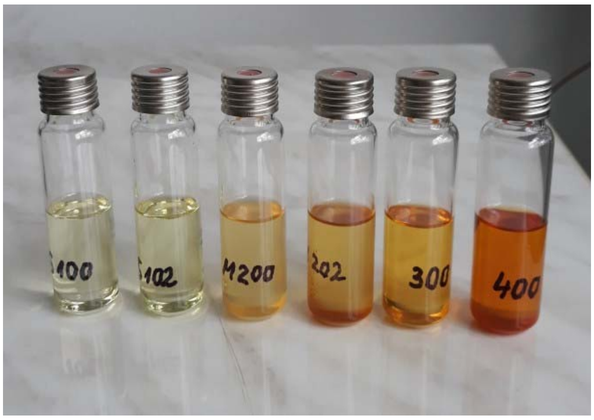

Fig. 1. The studied oil samples.

It is observed that S100 oil sample is clear, while a slight coloration appears at the S102 sample (oil after tests in the stand) and it is no longer so clear. The same observation is made for M200 and M202 oil. In the case of used oils codes 300 and 400, their reddish-brown colour is observed, which attests the state of advanced wear.

2) The Analysis of Water Content From The Oil

Water content in insulation materials increases its electric conductivity and dissipation factor and reduces dielectric strength [14].

The moisture in transformer is generated from several sources: remaining moisture in insulation during manufacturing, humid air from outside during transportation and/or assembling in substation, humid air from outside through the breather (non-sealed), moisture ingress through gaskets, chemical decomposition of cellulose, moisture absorption from outside during some maintenance operations such as on site control of active part or bushing replacement, topping-up of oil level made with humid oil (non-dried) [12].

Water is, therefore, one of the most important factors, which affects the life of the electrical insulation system of the power transformer. Water can exist in the transformer in several forms [1,5]:

- ✓ free water at the bottom of the tank;
- ✓ ice at the bottom of the transformer tank;
- ✓ water in the form of emulsion, highlighted by determining tan δ;
- ✓ dissolved water, which is determined by the Karl Fischer method;
- ✓ free water, in the situation when the oil saturation is exceeded and the formation of small drops of water begins.

The water solubility in transformer oil increases with temperature and oil neutralization index. The water absorption capacity of the electrical insulating mineral oil increases rapidly with increasing temperature (about 4-5 times higher at a temperature of 80°C than at a temperature of 20°C) [5]. This analysis, on the water content, is carried out in the laboratory using a device called coulometric titrator, which uses the Karl Fisher analysis method, the result being reported as the concentration of water in ppm (parts per million).

Fig. 2. The image of the Karl-Fisher coulometric titrator model CA-21 used in the experimental results.

TABLE II.

THE EXPERIMENTAL RESULTS

No.	**The experimental results achieved regarding the amount of water contained in the oil**		
	Code assigned for experiment	***Water content in ppm***	**Maximum allowed value according to the regulation** PE 129-99
1	S100	21.16	30 ppm
2	S102	24.72	
3	M200	26.54	
4	M202	11.17	
5	300	29.87	
6	400	38.21	

Fig. 2 shows the coulometric titrator type Karl-Fisher model CA-21, manufactured by Mitsubishi Japan used in the experimental results. In table II [1] the obtained experimental results are presented.

3) Determination of Electrical Insulating Oil Density and Interfacial Tension

Some theoretical aspects regarding the interfacial tension are worth specifying. It is known from chemistry and specialized literature that at the fluid interface, the Van der Waals type forces are no longer compensated but have an inward-oriented resultant. Thus, the potential energy of the molecules inside the fluid is lower than at the surface and consequently additional energy is distributed on the free surface. To create 1 cm^2 of free surface it is necessary to consume energy equal to the interfacial voltage. The interfacial tension at the surface of a fluid is determined by evaluating the force perpendicular to any segment placed on the surface of the fluid and relative to its length. The interfacial tension is quantified as a force per unit length, equivalent to the energy per unit area of the fluid. It is expressed in [N/m] in the international system or [dyne/cm] [1,6, 13]. The analysis for determining the density and the interfacial force is carried out according to the STAS 9654-74 standard.

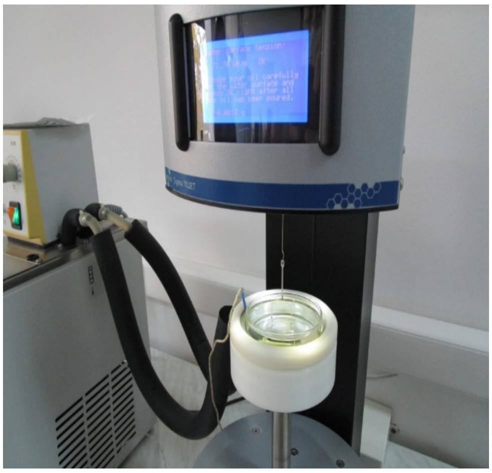

Fig. 3. The image of the tensiometer type KSV Sigma 702ET used in experiments.

TABLE III.

THE EXPERIMENTAL RESULTS

NR.	The experimental results on the determination of density and interfacial force		
	Code assigned for experiment	*Density (g/cm^3)*	*Interfacial tension (dyne/cm)*
1	S100	0.867	40.27
2	S102	0.870	39.99
3	M200	0.849	37.01
4	M202	0.854	29.27
5	300	0.871	24.86
6	400	0.873	16.57

The equipment used for the practical determination of oil density and interfacial tension is the tensiometer type Sigma 702ET, produced by KSV Instruments Finland and equipped with thermostatic bath LAUDA RA 104, shown in Fig. 3. The tensiometer is provided with an arm in which it is hanged either a glass ball (to determine the oil density) or a Du Noüy ring (to determine the interfacial tension). The Du Noüy ring is a thin platinum wire ring with a circumference of 9.545 mm, from which a hook is welded, also made of platinum wire.The experimental results are depicted in table III [1].

4) Dissolved Gas Analysis (*DGA*)

Dissolved gas analysis (DGA) is one of the most widely used diagnostic tools for detecting and evaluating faults in electrical equipment filled with insulating liquid. However, interpretation of DGA results is often complex and should always be done with care, involving experienced insulation maintenance personnel [14].

The equipment with which this analysis is performed is the gas chromatograph type CLARUS 600, model 4087, produced by PerkinElmer USA. Chromatographic separation is based on the differentiated interaction of the components of a test against two phases, called: stationary phase and mobile phase (moving in relation to stationary phase).

The process takes place in a chromatographic column, or on the surface plan of a plate on which the stationary phase is deposited.

Fig. 4. The image of the chromatograph type CLARUS 600 that was used in tests

Chromatographic analysis is a coupled process between chromatographic separation and determination (detection) of separate compounds (process that is based on measuring a physical property).

The chromatogram represents the time dependence of the property measured by the chromatographic system detector. In a chromatogram we find chromatographic peaks and a baseline (constant or variable). Chromatographic separation of a mixture of *n* components should result in a chromatogram with *n* chromatographic peaks.

The chromatographic signal is called the chromatographic peak, the shape of which actually represents an image of the distribution equilibrium of the analyzed molecules between the mobile phase and the stationary phase, which occur in the chromatographic column [7].

Dissolved gas analysis was made for all the oil samples presented above. Below, the chromatogram for one of the cases is presented (oil-code 202). From the analysis of the chromatogram in Fig. 5, it is observed that the analyzed oil shows small peaks for the following gases: O_2, N_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO, CO_2, aspect that denotes their presence in the composition of the analyzed oil.

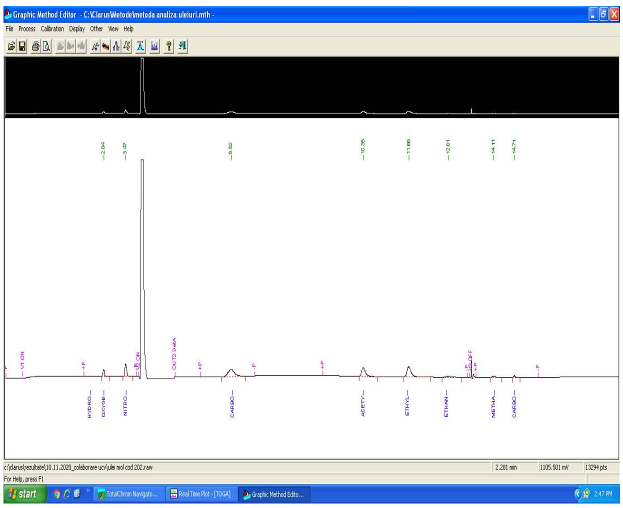

Fig. 5. The chromatogram obtained for the analysis of oil code 202.

From the analysis of the other studied oils, their chromatograms did not detect the presence of dissolved gases.

5) The Furans Determination

The furanic compounds that are mainly produced due to paper oxidation and hydrolysis processes could be directly extracted from the oil to characterize the thermal decomposition of insulation paper. The furan concentration in transformer oil depends on the mass ratio between oil and cellulose [15].

Furans are major degradation products of cellulose insulation paper and are found in the insulation oils of operational transformers [8].

The analysis was performed according to the standard SR EN 61198: 2004 [16].

This analysis was performed using HPLC 1100 High Performance Liquid Chromatograph, manufactured by SHIMADZU CORPORATION KYOTO Japan (Fig. 6).

Fig. 6. The image of the High Performance Liquid Chromatograph (HPLC 1100).

In principle, this analysis consists in determining the 2-furfural and its derivative compounds from the electrical insulating oil by the method of separating the elements into columns, characterized by different specific wavelengths and transferring them to a detector with a different degree of light absorption. It determines a distinct chromaticity for each detected furan component; it is called high performance liquid chromatography (HPLC).

Five furan derivatives are related with cellulosic insulation degradation in transformer oil; 2-Fulfural (2FAL), 2-Fulfurol (2FOL), 5- Hydroxy methyl-2-furfural (5HMF), 5-Methyl-2-furfural (5MEF) and 2-Acetyl furan (2ACF) [15].

Quantitative Results

PDA

ID#	Ret. Time	Area	Area %	Conc. ppm (mg/kg)	Name
1	2.244	1194	0.046	0.006	5-hidroximetil 2-furfural (5-HMF)
2	0.000	0	0.000	0.000	alcool 2-furfurilic (2-FOL)
3	3.560	1880	0.066	0.008	2-furfural (2-FAL)
4	0.000	0	0.000	0.000	2-acetil furan (2-ACF)
5	0.000	0	0.000	0.000	5-metil 2-furfural (5-MEF)

Grouping Results

PDA

Group#	Group Name	Conc. ppm (mg/kg)	Area
1	FURANI	0.014	3074
	Total	0.014	3074

Fig.7. The content of furanic components in used oil code 400.

The analysis of the obtained results showed only in the case of the test of the oil code 400 (TR 30 oil, used, brown) the presence of the components 5-HMF (5-Hydroxy methyl-2-furfural) and 2-FAL (2-Fulfural).

6) Determination of the Dielectric Loss tanδ and The Relative Dielectric Permittivity ε_r at 90°C

These determinations are carried out simultaneously using a tester manufactured by BAUR Austria, shown in Fig. 8. The tests were carried out according to IEC 60247: 2004 [17]. The experimental results are presented in Table IV [1].

Fig.8. The image of the BAUR DTLC tester.

TABLE IV.

THE EXPERIMENTAL RESULTS

No.	The experimental results for tanδ and ε_r		
	Code assigned for experiment	*tan δ*	ε_r
1	S100	0.0030	2.12
2	S102	0.0117	2.13
3	M200	0.0041	2.09
4	M202	0.0244	2.10
5	300	0.0103	2.14
6	400	0.0888	2.17

C. Analysis of Experimental Data

From the analysis of the results presented in Table II, it is observed that the oil code 400 (used oil) exceeds the value of 30 ppm and the oil code 300 (also a used oil) has the amount of water very close to the limit value (29.87 ppm compared to 30 ppm). The other oil samples comply with the regulations.

In terms of density, according to [18], all analysed samples correspond to a density of less than 0.895 g/cm^3.

The interfacial tension is considered appropriate according to PE 129-99, if it has a value higher than 20 dyne/cm. From the data presented in Table III, it can be seen that only oil code 400 (used TR-30 oil) does not correspond.

According to [17], the dielectric loss factor tanδ must be a maximum of 0.004. It can be seen from the data recorded in Table IV that only the oil sample code 400 (used TR 30 oil) exceeds this value.

The value of the relative permittivity ε_r determined experimentally and recorded in Table IV falls within the known limits of the literature [10, 11].

IV. CONCLUSIONS

As it is known, both from practice and from the specialized literature, the deterioration of the insulation system is the major cause of transformer problems and failure. Thus, a first stage in establishing a proper electrical insulation is carried out in the design and testing phase of the equipment for choosing the best electrical insulation materials, with high performance.

In the operation phase of electrical equipment (electric motors and generators, electrical transformers, circuit breakers etc.), the maintenance activity aims to monitor the proper functioning of the electrical equipment.

In the case of electrical transformers, indispensable elements in electricity transmission and distribution networks, online and offline monitoring of the state of electrical insulation (solid and liquid) ensures their proper functioning by preventing the occurrence of fails that could occur and can disturb various economic processes.

It is known from the literature and practice that transformer oil plays a key role in the proper operation of transformers. The analysis of transformer oil can reveal several types of anomalies (electrical, thermal defects, premature ageing, loss of insulation capacity etc.).

This paper proposed and presented some of the modern methods of offline analysis of physical, chemical and electrical properties of transformer oil (determination of water content, density, interfacial tension, dissolved gas analysis, determination of furan components, relative permittivity and loss factor). Samples of transformer oil type MOL TO 30.01 (uninhibited electrical insulator, non-additive) and new StaSo Transformer Oil I (high quality inhibited insulating oil) were studied: two samples collected directly from the original barrel, two samples collected from the transformer tank, after dielectric tests at the transformer's manufacturer; there were also studied two samples of used TR 30 oil, collected from two transformers.

The achieved results showed that the oil samples type MOL TO 30.01 and StaSo Transformer Oil I, taken from the original barrel and from the transformer tank after specific stand tests of the electrical transformer correspond to the norms in force, while the oil samples type TR 30 taken from transformers with many hours of operation show signs of ageing [1].

Future studies will focus on the comparative analysis of other physical, chemical and electrical properties that feature the state of wear of transformer oil as well as the analysis of the solid-liquid insulation system (cellulose type insulation impregnated with transformer oil).

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