Monitoring, diagnostics and drying of transformer oil online

ABSTRACT

The article discusses the approaches to monitoring and diagnostics of the oil-filled transformers insulation system. The positive aspects of using online monitoring and diagnostics systems are shown. The operating principle of the online diagnostics, monitoring, and insulation oil drying system developed by GlobeCore is described. A comparison is provided between the assessment of the insulation oil condition using laboratory analysis and the GlobeCore system.

KEYWORDS:

power transformer, transformer oil, transformer oil drying, online monitoring, online diagnostic

S. MYKYTENKO, O. KRYVOKHYZHA, O. PIEVNIEV, M. GANZHA

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1. Introduction

Power transformers remain an important link in power transmission lines. Failure of even one transformer causes an inconvenience to consumers and financial losses both due to equipment damage and power supply interruptions.

In 2003, at an international conference in Stockholm, William Bartley presented an analysis of damage to oil-filled transformers in terms of power, cause, age, location, and economic damage [1]. The average total financial loss was $3 million per damaged transformer. As for the causes of damage, about 40 % involved the insulation system (oil and paper). Thus, the reliability of the insulation system largely determines the reliability of the transformer.

In order to maintain the high reliability of the insulation system, timely and reliable information about its current condition is required. The availability of such information allows one to detect problems at an early stage of their development and respond appropriately: dry the transformer windings, replace, purify or regenerate oil, etc.

The state of the oil is evaluated by measuring the breakdown voltage, the tangent of the dielectric loss angle, acidity, moisture content, surface tension, the content of solid impurities, and other parameters

2. Approaches to monitoring and diagnosing the condition of the power transformer insulation system

We distinguish two approaches to assessing the state of the insulation system of power transformers. The first approach involves periodic sampling of oil and paper and subsequent analysis of the samples in a laboratory.

It is necessary to drain all insulation oil from the transformer before paper sample collection. Solid insulation ages irregularly, so to recognize its condition adequately, paper samples must be taken from various places. Choosing these specific places represents a separate task. Then, those sections from which samples were retrieved must be repaired before oil filling; otherwise, this poses a risk to the transformer operation. Generally, the entire process is quite expensive and requires a lot of time and effort, so it is rarely used for transformers under exploitation in practice [2].

The state of the oil is evaluated by measuring the breakdown voltage, the tangent of the dielectric loss angle, acidity, moisture content, surface tension, the content of solid impurities, and other parameters. Moisture content and degree of polymerization (DP) are important parameters for paper insulation. The DP test measures the average length of the cellulose molecule in the paper. DP values of 1,000 to 1,300 are considered consistent with new paper, as values of 200 are considered end-of-life, and values of 400 are considered midlife.

The values of oil and paper quality indicators, as well as the scope and frequency of the tests, are provided by applicable standards, test regulations, and electrical equipment manufacturers' manuals.

Until the early 2000s, there has been no alternative to periodic sampling and analysis, although the process can be time-consuming and expensive. However, with the development of measuring equipment and digital technologies, it became possible to implement new continuous transformer online monitoring and diagnostic systems. Such systems, on the one hand, allow the detection of potential problems at an early stage and, on the other hand, allow a gradual transition to servicing transformers based on their actual condition. A logical consequence of the development of continuous online monitoring and diagnostic tools was the systematization of the results gained from the experience of using these tools in the recommendations by the Institute of Electrical and Electronics Engineers (IEEE) [3]. Among other things, these recommendations include the following in particular:

- Parameters that can be used for the online monitoring of transformers (dissolved gas-in-oil analysis, moisture in oil, partial discharge, transformer temperatures, winding temperatures, etc.);
- Standard online monitoring systems elements and their selection features (sensors, indication, electronic hardware, hardware interconnection, communication interface, and data processing);
- Requirements regarding communications protocols (data integrity, efficient data transfer, flexible data transmission, criticality and priority, flexible polling schemes, media-independent, addressable, OSI model-compliant, standards).

3. Continuous transformer oil monitoring, diagnostics and drying system

Most of the online monitoring and diagnostic systems available on the market are aimed at identifying transformer problems and defects but do not offer a complete picture of the insulating oil condition, which is more often used as a diagnostic medium in the chromatographic analysis of dissolved gases. In particular, the assessment of the oil aging degree by acid number still requires periodic sampling and laboratory analysis. Sampling, analysis, and insulation treatment (if necessary) take a long time.

Given that some transformer damage can develop in a matter of days or even hours, a new approach is of practical interest: combining an online monitoring and diagnostic system with a transformer oil treatment system. This saves time and extends the service life of transformers due to the availability of more complete information about the state of the insulation system and timely oil treatment.

Let us discuss a combined method for online monitoring, diagnostics and processing of transformer oil. An example of the equipment that implements this method is shown in Fig. 1.

The system is connected to the transformer on a permanent basis. The system includes:

- Transformer insulation system monitoring unit (sensors, controller, high-speed router);
- Transformer oil drying and filtration unit (three adsorbers, filter);
- Software.

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The system algorithm functions in the following manner:

1. Oil constantly arrives from the transformer and is pumped through the sensors and back to the transformer. The sensors measure the oil and environmental parameters once every minute. These parameters are then transmitted to a cloud server via the internet.

All monitored parameters are processed, stored, visualized, and, if necessary, displayed in a special web application with password-restricted access

The following parameters are measured:

- Oil temperature at the top and bottom of the transformer;
- Water activity at the top and bottom of the transformer. Water activity is a measure of water available for exchange between paper and oil. For more information on this parameter, see [4];
- Relative humidity of the oil in the top and bottom part of the transformer;
- Hydrogen content in the oil;
- Ambient air temperature;
- Ambient air relative humidity. It is measured in order to take it into account when predicting future calculation parameters.

2. Other parameters, which provide a more complete picture of the transformer insulation system, are calculated on the cloud server.

The following parameters are calculated:

- Water content in the oil at the top and bottom of the transformer;
- Water content in solid insulation at the top and bottom of the transformer;
- Dielectric breakdown voltage (DBV). DBV is a relative value (in relation to dehydrated transformer oil) in our case. DBV is measured as a percentage and is calculated by the algorithm described in [4];
- Oil quality index (OQI). This parameter is proposed in [5], and we will discuss it in more detail below.

3. All parameters are processed, stored, visualized, and, if necessary, displayed in a special web application with password-restricted access.

The web application offers the following capabilities:

- Indicators that display the status of primary measured and calculated parameters (see Fig. 2). Indicators readings are updated once every minute;

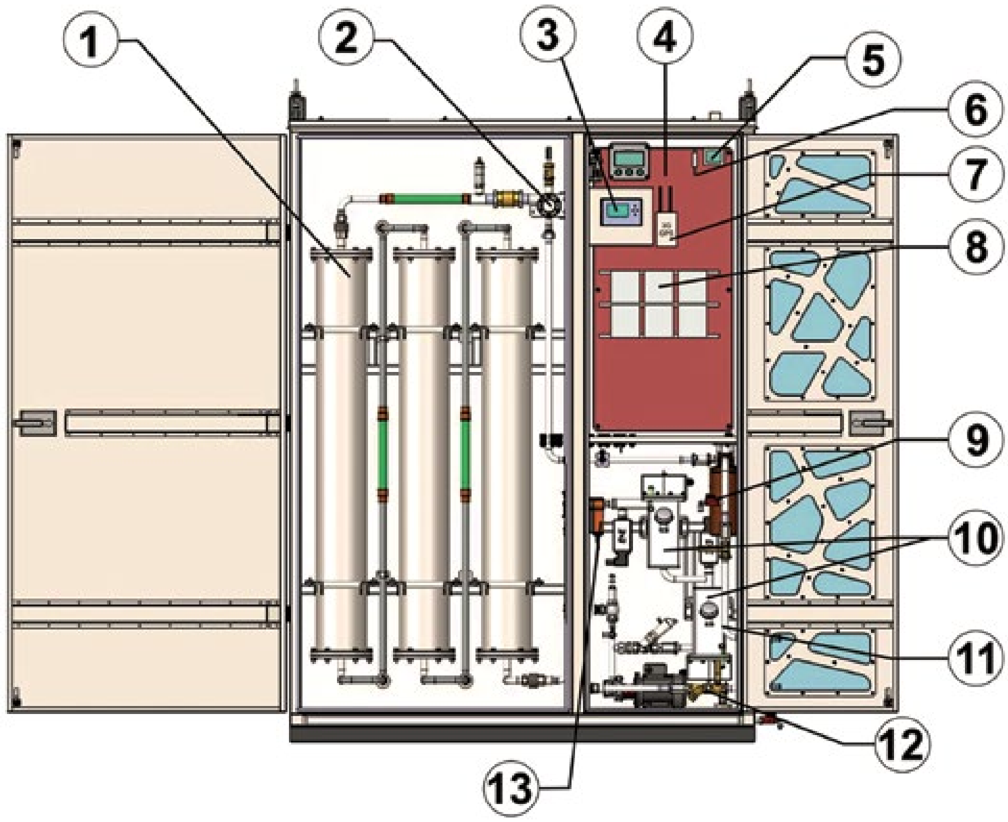

Figure 1. Online transformer oil monitoring, diagnostics and drying system: 1 – adsorber, 2 – air trap, 3 – controller, 4 – control cabinet with pump, 5, 6 – sensors, 7 – high-speed router, 8 – brackets for additional equipment installation, 9 – filter, 10 – heater, 11 – oil outlet, 12 – oil inlet, 13 – electrically driven three-way valve

Figure 2. Visualization of the transformer insulation system parameters. Indicators.

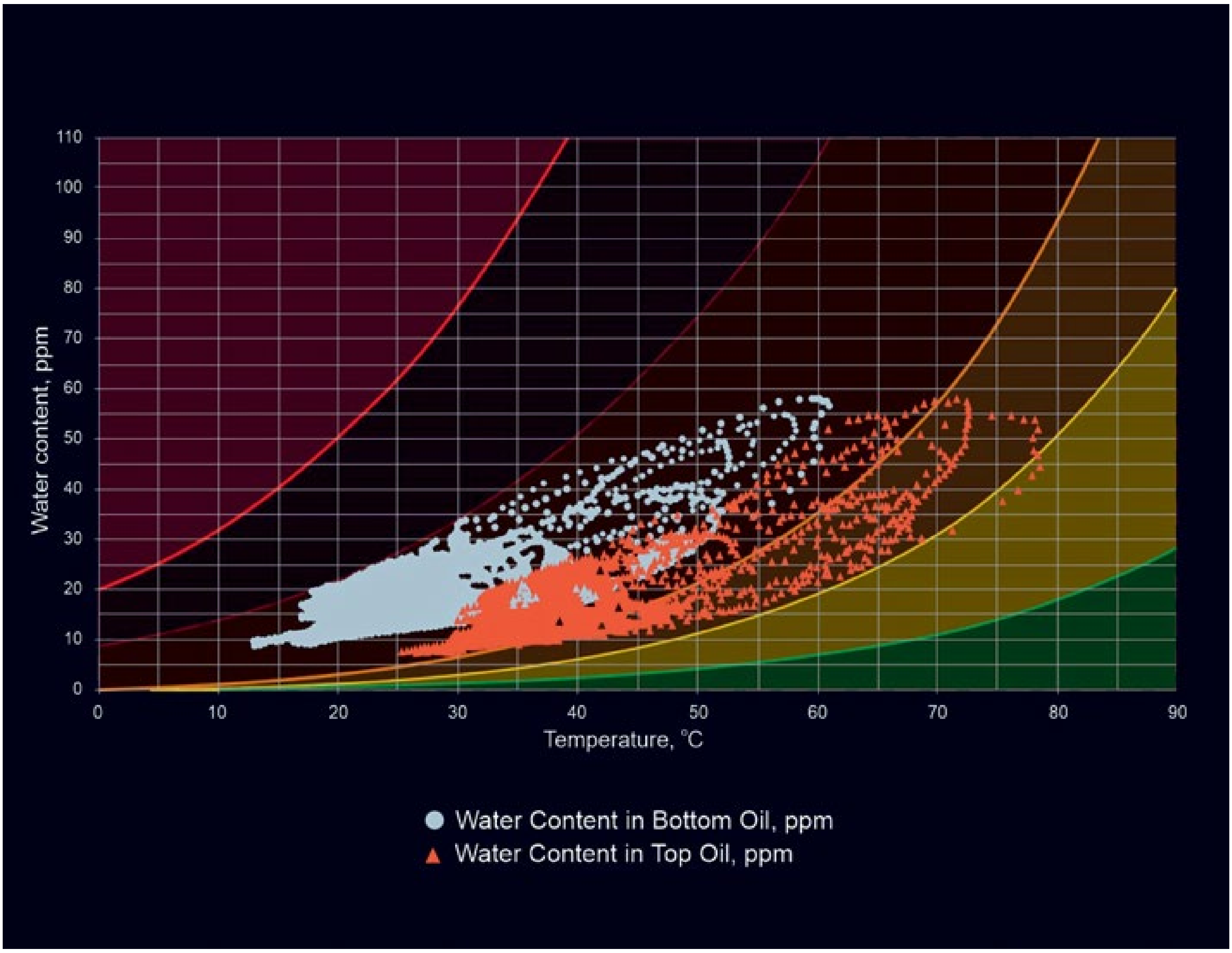

Figure 3. Visualization of the transformer insulation system parameters. Dot cloud chart of water content.

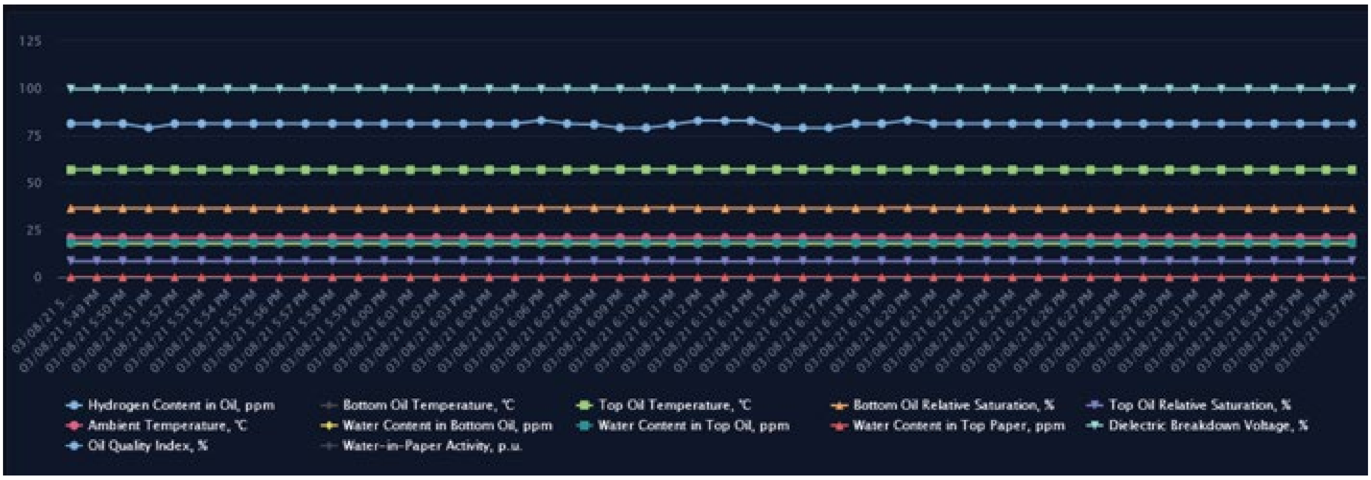

Figure 4. Visualization of the transformer insulation system parameters. Linear parameter graph.

- Dot chart of water content in the oil, which shows the water content in the upper and lower part of the transformer in the form of a point cloud (see Fig. 3). The chart is updated when the page reloads;
- Linear parameter graph. The graph shows all the parameters, both obtained from the sensors and calculated. The time interval for displaying the data is one minute. Numeric values, dates, and time are displayed as a tooltip when hovering over a graph line point (see Fig. 4).

The system uses three colours to display the status of the parameters:

- Green means the parameter is within normal limits;
- Yellow means the parameter is out of limits, but not critical. Operator attention is required;
- Red means the parameter is critical. Urgent intervention in the operation of the transformer is required.

The following ranges are standard for moisture content in solid insulation: 0–1 % — green colour, 1–2 % — yellow colour, and more than 3 % — red colour.

Fig. 2 and 3 show the examples of parameter display in the web application.

4. If the oil moisture content exceeds the safe threshold, the system automatically switches from the monitoring mode to the oil treatment mode by pumping the oil through the filter and sorbent cartridges. In this way, water is removed not only from oil but also from paper insulation, which is possible due to the constant migration of water from the oil to the paper and vice versa, taking place in a transformer under load.

In addition to the known parameters (moisture content in oil and solid insulation, dielectric strength), the system also determines the transformer oil quality index

The threshold value of the transformer oil moisture content is set by the operator and is less than the critical value of moisture content accepted as per the industry standards (30–35 ppm). For example, the threshold value may be set at 20 ppm.

After completing the oil treatment, the system reverts to the parameter monitoring mode.

The positive effect of transformer oil dehydration on reducing solid cellulose insulation moisture content is confirmed from the experience of using the system with one of the transformers of a GlobeCore's client in Latin America. In particular, in the continuous dehydration mode of a 4 MVA transformer, using the adsorbers for eight months, it was possible to reduce [6] the following:

- Absolute water content in oil from 25 to 14 ppm;
- Relative water content in oil from 16.9 to 9.3 % at a temperature of 20 °C;
- Water content in solid insulation from 1.3 to 0.7 %.

4. Oil quality index (OQI)

In addition to the known parameters (moisture content in oil and solid insulation, dielectric strength), the system also determines the transformer oil quality index. This parameter indicates the degree of aging of the oil and its suitability for further use in general. The index varies from zero to one or from 0 to 100 %. Very poor quality oil corresponds to zero, and very good quality oil corresponds to one.

The method of calculating the quality index of transformer oil is described in [4]. It is based on the fact that water dissolves better in aged oil than in new oil because the molecules of carboxylic acids formed during oil aging, as well as water molecules, are polar. Therefore, the change in solubility compared to the solubility in the new oil is also a good indicator of aging.

5. The results of experimental studies

To test the hypothesis that the change in water solubility in oil correlates well with the acid number, five samples of oil of varying quality were taken:

- Sample 1 – the darkest and oldest oil;
- Sample 2 – dark, non-degassed oil;
- Sample 3 – clear, new oil;
- Sample 4 – dark oil after filtration;
- Sample 5 – clear oil after regeneration.

A photo of the samples is given in Fig. 5.

The samples were examined in a laboratory to determine the following parameters:

- Color;
- Acid number;
- Interfacial tension;
- Refractive index;
- Content of aromatic hydrocarbons;
- Breakdown voltage;
- Tangent of the dielectric loss angle.

In parallel, each type of oil was pumped through system sensors to determine the quality index. The results obtained are shown in Table 1.

As can be seen from the table, new oil (sample 3) and regenerated oil (sample 5) showed the best results regarding colour, the tangent of dielectric loss angle, and acid number. Also, these oils have the highest quality index of 83 and 80 %, respectively. The worst results in terms of color, the tangent of dielectric loss angle, acid number, and quality index were displayed by the old (sample 1) and the non-degassed (sample 2) oil.

The various oil temperature values, as well as relative oil humidity values at different temperature values (heating and cooling), were used as input data for calculating the oil quality index. The calculation itself was carried out according to the algorithm described in [5].

The correlation coefficient between the quality index and the acid number of the transformer oil was also calculated. This calculation resulted in a value of -0.9852, indicating a very high correlation between these parameters, i.e., the quality index can be used to assess the degree of aging of transformer oil online.

Figure 5. Examined transformer oil samples

Online oil monitoring, diagnostics, and processing systems are relevant not only for new transformers but also for aged transformers, as well as for special-purpose transformers

Table 1. The test results of transformer oil samples

Parameter	Standard	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Oil quality index, %	-	47	38	83	61	80
Color, units	ASTM D1500	3	2.5	1	2.5	2
Acid number, mg KOH/g	IEC 60422	0.03	0.03	0.01	0.02	0.01
Interfacial tension at 25 °C, mN/m	ISO 6295	34.4	29.9	33.2	29.9	34.4
Refractive index at 30 °C	ASTM D1807	1.4882	1.4816	1.4801	1.4856	1.4806
Content of aromatic hydrocarbons, % weight	IEC 60590	18.1	15.6	13.3	16.5	13.7
Breakdown voltage, kV	IEC 60156	38	28	33	32	48
Tangent of the dielectric loss angle at 90 °C	IEC 60247	0.027507	0.026116	0.006214	0.014518	0.006117

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Conclusion

The article discusses the example of a new approach to transformer maintenance that combines online monitoring and insulating oil treatment.

The main distinguishing features of this approach are the following:

- Determination of absolute oil humidity;
- Determination of not just one paper humidity value, as is the case in other known monitoring systems, but of a range of values (humidity at the top and bottom of the transformer);
- Automatic switching between parameter monitoring and oil processing;
- Drying of not only oil, but also paper isolation in online processing mode by pumping oil through adsorbers;
- The use of the oil quality index, which makes it possible to identify the suitability of the oil for further operation "online", without sampling and laboratory tests. The high correlation between the quality index and the acid number of the oil has been confirmed experimentally;
- The quality index can be used to identify the need for oil regeneration if deeper changes in its composition become evident.

Applying such an integrated approach can prevent failures and extend the life of transformers, create the necessary basis for equipment maintenance based on its actual condition, as well as prolong maintenance intervals and save money.

Online oil monitoring, diagnostics, and processing systems are relevant not only for new transformers during their installation phase in order to receive measurement and calculation data throughout the entire transformers service life, but also for aged transformers, as well as for special-purpose transformers that operate under heavy loads (traction, mining, ship, electric furnace, and others).

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PEER REVIEWED

Authors

Stanislav Mykytenko, Founder and Director of GlobeCore. The author of new ideas for the development and improvement of the equipment in the field of transformer maintenance and transformer oil regeneration by the zero-waste method.

Oleg Kryvokhyzha, Founder and Director of GlobeCore. He obtained a professional degree in Engineering Physics (National Technical University "Kharkiv Polytechnic Institute"). He has more than 20 years of process management experience in the field of manufacturing transformer maintenance equipment.

Oleksandr Pievniev is the Head of GlobeCore Industrial Automation Department. Oleksandr holds a degree in automation of industrial plants and technological complexes (National Technical University, Poltava). He specializes in the design and configuration of equipment for the purification and diagnostics of liquid dielectrics and has over 15 years of experience in the field.

Maxim Ganzha is a full-stack web developer with 20 years of experience. He specializes in the development of data processing and analysis systems accessed via the Internet. Maxim graduated from the National Technical University in Poltava with a degree in Industrial Automation.
His hobby is the design and construction of electronic devices for IoT, smart home installations, etc.