Estimation of water content in oil-impregnated cellulose materials in transformers

ABSTRACT

Oil-impregnated cellulose materials are used in oil-filled transformers. Water in insulation has a negative effect on electrical, mechanical and chemical properties of insulating materials. Since taking insulation samples from the transformer is no easy task, laboratory testing to estimate water content in insulation is conducted with a measurement instrument that is based on a known indirect method. This paper describes the possibility to estimate water content in oil-impregnated cellulose insulation on the basis of results of the measured relative humidity of the oil in the transformer.

KEYWORDS

oil-filled transformer, oil-impregnated cellulose insulation, water content in oil and cellulose insulation

1. Introduction

Oil-impregnated cellulose insulation (CI) is widely used in oil-filled transformers. However, the water content in this insulation can have a negative impact on electrical, mechanical and chemical properties of the insulating materials. While direct methods can be used to estimate the water content in the oil (W_o), the estimation of the water content in the oil-impregnated cellulose insulation (W_p) is typically carried out by indirect methods. The relationship between the water in the oil and the water in the cellulose materials makes it possible to estimate the water content in the insulation by measuring the relative humidity (RH) of the oil at fixed temperatures.

2. The relationship between the water in the air and the water in the cellulose insulation

The wood consists of cellular tissue which is up to 85 % alpha cellulose $(C_6H_{10}O_5)_n$, and it is the raw material generally used for the fabrication of insulation materials such as paper and pressboard.

The elementary chains in the cellulose polymer consist of glucose rings. The degree of polymerization (DP) is a parameter describing the average number of glucose rings in the cellulose macromolecules that form the fibre. For a new CI, the DP is 1100-1350 [1].

Water in insulation has a negative effect on electrical, mechanical and chemical properties of insulating materials

The hydroxyl groups in the glucose rings have an influence on the increase in the sorption ability (hygroscopic properties) of cellulose materials.

The structure of the CI is determined by the structure of the cellulose fibres as well as the manufacturing technique used to fabricate the cellulose materials. The porosity of paper insulation is determined by the packing of individual fibres as well as the porosity of individual fibres, and can be characterized in terms of the relative pore volume and the effective capillary radius. A microscopic picture of pressboard is presented in Figure 1. The characteristic isotherms for sorption of water by cellulose materials in contact with air (relative humidity of air ϕ) are shown as S-shaped (Figure 2) [2].

The sorption curves for CI can be interpreted as follows:

- Monomolecular absorption (for relative humidity of air $\phi < 0.2–0.3$)
- Poly-molecular absorption (for $\phi = 0.2–0.7$)
- Filling of micro-pores and macro-capillaries with water (for $\phi > 0.7$)

One special case of a general equation for the absorption isotherm is the Freundlich formula:

$$W_p = cP^n, \quad (1)$$

where c and n are coefficients which depend on the structural, mechanical, physical, and chemical properties of the material and the sorption temperature, and P in torr is water vapour pressure. For example, pressboard at the air conditions where $T = 20$ °C and $\phi = 0.6$, has $c = 1.97$ and $n = 0.6$.

The advantages of the equation (1) lie in its simplicity and good agreement with experimental sorption curves. This is in fact the region which corresponds to W_p = 5-6 % of CI, which is of greatest interest when describing the effects of moisture content on the electrical properties of CI in transformers. During the assembly of transformer's active part at the air conditions of $T = 20$ °C, $\phi = 0.6$, CI has $W_p \approx 8$ %. After the drying process, the dew point of gas (air or nitrogen) can be measured at a given temperature, while pressure in the oven and the tank can be measure before the oil is filled The estimation of W_p can be obtained from the moisture equilibrium charts [3] and, as a rule, equals $W_p < 0.5$ %.

The relationship between the water in the oil and the water in the cellulose materials makes it possible to estimate the water content in the insulation by measuring the relative humidity of the oil at fixed temperatures

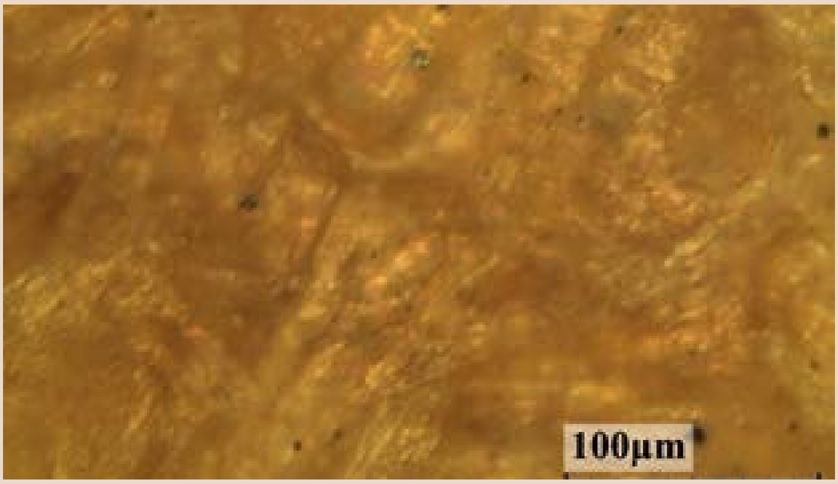

Figure 1. A microscopic picture of pressboard

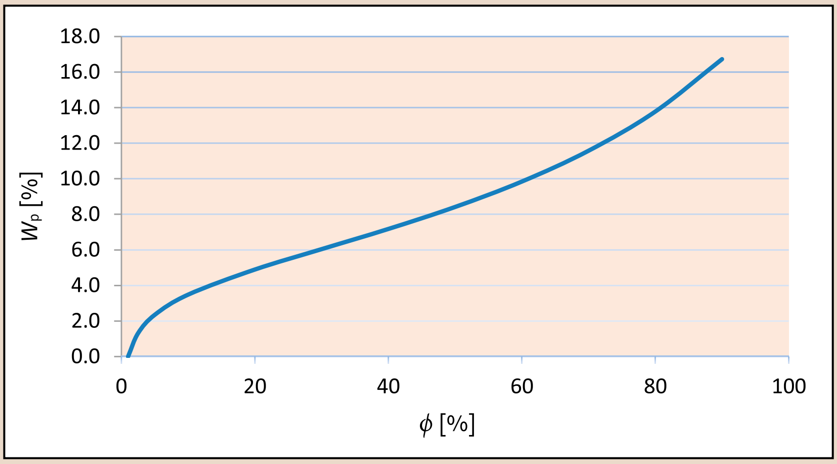

Figure 2. The relationship between W_p and ϕ

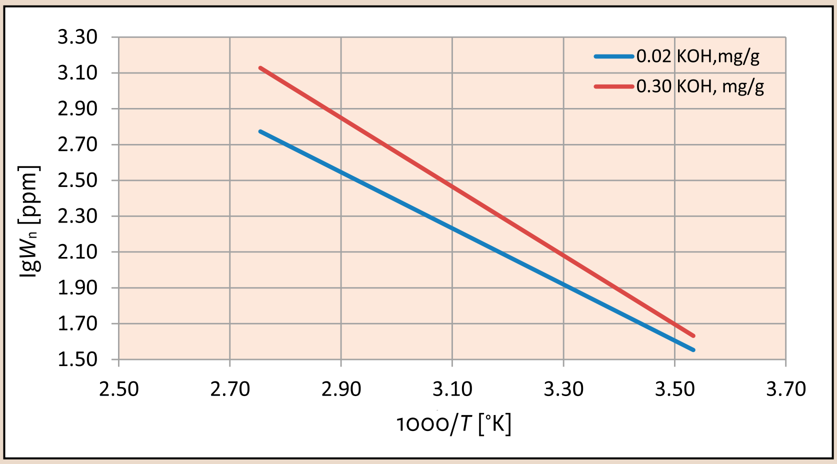

Figure 3. The relationship between W_n and oil temperature T for different oil acidity

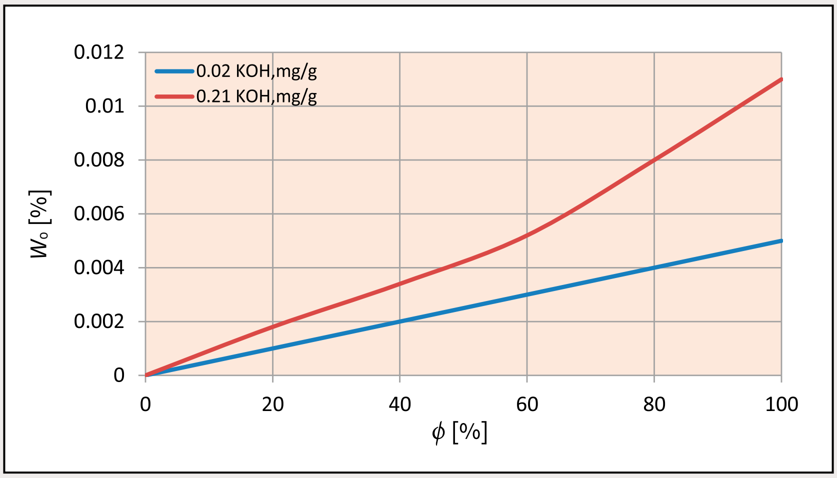

Figure 4. The relationship between water content in oil (%) and air humidity (%)

The solubility of the water in the oil is highly dependent on the hydrocarbons present in the oil and increases with an increasing concentration of aromatic hydrocarbon in the oil

3. The relationship between water in air and water in mineral oil

The substantial size difference existing between the hydrocarbon molecules in transformer oils and water molecules means that the solubility of water in these oils is low. By increasing the oil temperature, the water solubility in the oils will increase as well.

The limiting water solubility in oil (W_n) as a function of temperature is described by the following equation:

$$\log W_n = A - B/T, \quad (2)$$

where A and B are coefficients and T is the temperature in K [4].

Graphs of the function $W_n = f(T)$ [5] become linear curves when log W_n is plotted as a function of $1/T$ (Figure 3, and may be described using the following equations:

$$\log W_n = 7.09 - 1567/T; \quad (3)$$

$$\log W_n = 8.42 - 1921/T. \quad (4)$$

In this case, the equation (3) corresponds to the oil with an acid content of 0.02 mg/g, and equation (4) corresponds to the oil with an acid content of 0.30 mg/g. The correlation coefficients determined for these equations are 0.99.

The solubility of water in the oil is highly dependent on the hydrocarbons present in the oil. The solubility of water increases with increasing concentration of aromatic hydrocarbon. As transformer oil ages, organic acids are formed, and higher concentrations of such acids lead to increased solubility of water in the oil [4]. The solubility of water in oil is a nearly linear function of relative humidity for temperatures between 0 °C and 100 °C, and is described by the Henry equation:

$$\phi = P/P_n = W_o/W_n \quad (5)$$

where P is the water vapour pressure in air, P_n is the maximum possible vapour pressure in air, W_o is the moisture content in the oil, and W_n is the maximum possible moisture content in the oil. This relationship may become non-linear at a relative humidity greater than 70 % for oils with an elevated acid content (Figure 4) [6].

Oil containing dissolved water has slightly impaired dielectric properties. However, the fact that the solubility of water in oil is strongly dependent on temperature means that the water readily makes the transition from the dissolved state to the emulsified state as the temperature decreases below the critical value, which leads to an increase in conductivity, a decrease in the electrical breakdown strength of the oil, and an increased likelihood of water condensation on the surface of the solid insulation in the transformer. The sorption of water by solid insulation may lead to surface partial discharge and potential breakdown.

4. Water content in transformer oil

Karl Fisher method is a well-known technique for the measurement of water content in oil [7].

In a paper-oil system, water is distributed between the paper and oil based on the temperature and stabilization time of diffusion. Therefore, the assessment of water content in oil must be done in consideration of the oil temperature at the time of sampling from the transformer tank. Obviously, when the transformer temperature is higher, the quantity of water in oil increases as well. In the oil sample taken from the warm transformer, the water concentration in the oil may be high at a room temperature, and this quantity may be above the limit, exceeding the values recommended by a standard [5]. This may lead to a wrong conclusion about the oil condition.

Another method for the measurement of RH of the oil is that using the capacitive sensor [8]. Some instruments used for RH measurement give recalculated values of RH in relation to water content in ppm. For this recalculation, the coefficients A and B in the equation (2) need

In a paper-oil system, water is distributed between the paper and oil based on the temperature and stabilization time of diffusion

to be known to enable the calculation of limiting solubility of water in oil at a given temperature. The water content in ppm may be calculated using the following equation (6):

$$W_o = PH \cdot W_n. \quad (6)$$

Using the coefficients (A and B) as constant values will lead to an error when determining the water content in the oil. Obviously, constant coefficient values are defined by two extreme lines of limiting solubility, between which a set of lines with different coefficients values may occur [5]. Therefore, it is important to know these coefficients for each oil sample.

5. Moisture content in the oil-impregnated cellulose materials

The moisture content in the oil impregnated cellulose insulation may be estimated using the classical Fabre–Pichon curves (Figure 5) in order to obtain the relationship between the moisture content in new transformer paper (W_p) and moisture content in oil (W_o) at different temperatures [9].

The Freundlich formula (2) and the Henry formula (5) can be combined to calculate the moisture content in cellulose material (W_p) between 0 % and 6 % through the following equation:

$$W_p = c(P_n(W_o/W_n))^n, \quad (7)$$

The maximum vapour pressure of water in air (P_n) in torr is an exponential function of air temperature, as follows:

$$\log P_n = 8.94 - 2254/T. \quad (8)$$

A substitution of the maximum solubility of water in the oil (from equations (3) or (4) obtained experimentally for each oil type) and the maximum vapour pressure of water in air from equation (8) into equation (7) was carried out. After some algebra, the following equation for the moisture content of the CI was obtained as a function of the RH of the oil:

$$W_p = m(W_o/W_n)^n = m\,(RH)^n, \quad (9)$$

where m and n are coefficients that depend on both the temperature and the properties of the cellulose insulation.

The assessment of the water content in the oil must be done in consideration of the oil temperature at the time of sampling from the transformer tank

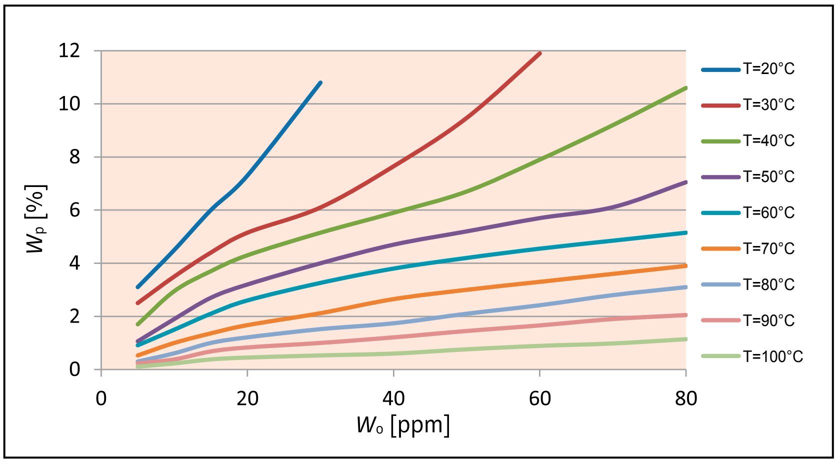

Figure 5. The relationship between W_p and W_o

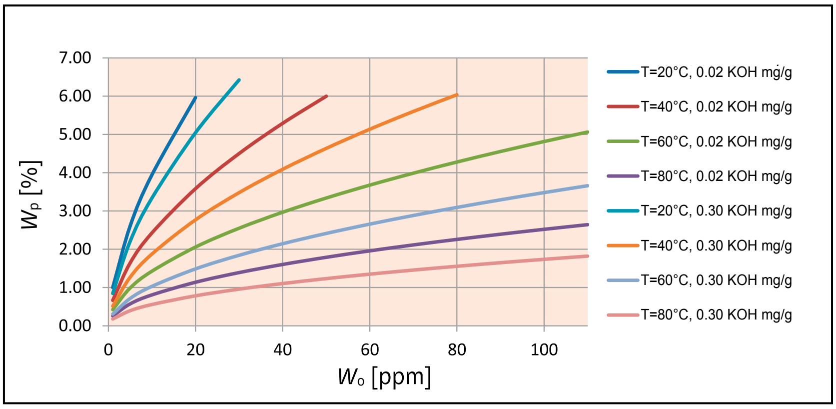

Figure 6. The relationship between W_p and W_o for different oil acidity and oil temperature T

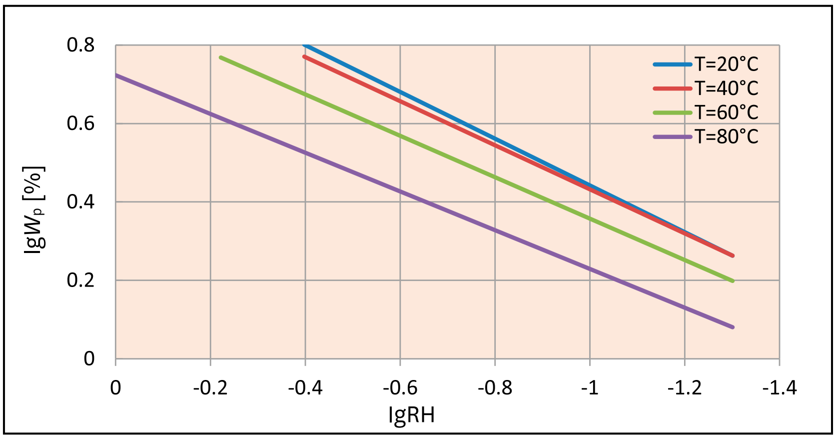

Figure 7. Relationship between W_p and relative humidity at different temperatures

The reliability of the graphical description of W_p may be improved if it is plotted as a function of the relative humidity

Figure 8. Apparatus for the measurement of the relative humidity and temperature

In a power transformer, the absolute moisture content of the oil is virtually uniform

Graphs of the function $W_P = f(W_o)$ were calculated for electrical pressboard–oil system with two levels of oil acidity (Figure 6).

The reliability of the graphical determination of W_P may be improved if it is plotted as a function of the RH (Figure 7); which is not dependent on the oil properties. This conclusion follows from the equation (9) in which the coefficients m and n do not depend on oil parameters and may be used for all insulating liquids (mineral oils, natural and synthetic oils).

In a power transformer, the absolute moisture content of the oil is virtually uniform throughout the transformer. When temperature data is available for various areas in the transformer insulation, then the moisture content of the cellulose insulation in the transformer can be calculated.

The comparative analysis of the assessment methods for the water content in the cellulose insulation (Fabre-Picon, Weidmann, Oommen, Grifin, ABB, Serena, Shkolnik) has previously been presented [10].

For the assessment of water contained in the cellulose insulation, it is necessary to know the RH values of the oil and the temperature near the insulation zone. The temperature can be measured at the points of the winding by the temperature sensors established in the transformer or calculated on the basis of the temperature rise test results.

Taking the RH and temperature at two points (RH_1 and T_1 at the top; and RH_2 and T_2 at the bottom) in a transformer by means of the sensors (measurement instruments) placed on the tank of the transformer, it is possible to determine factor B by the following formula:

$$B = \log\left(\frac{RH_1}{RH_2}\right) / \left(\frac{1}{T_1} - \frac{1}{T_2}\right) \qquad (10)$$

> **The measurement of the relative humidity of the oil at different temperatures makes it possible to estimate the water content in the cellulose insulation regardless of the oil properties**

According to the temperature in the corresponding insulation zone in the transformer, it is possible to calculate relative humidity of oil and moisture content of CI. In the absence of these sensors on the transformer, measurements can be done in the laboratory on the oil samples taken from the transformer. The apparatus (shown in Figure 8) consists of two RH/T measurement probes connected to a measuring unit, and displays the RH and temperature results. The unit can also display a graphic representation of results.

The experiment is performed under controlled conditions. Samples are poured into two flasks (300 mL) and probes are mounted into the two samples. The "cold" sample is allowed to remain at a room temperature, while the "hot" sample is heated up to 60 °C. Once the temperature and humidity readings have become stable, the results are recorded. Thus, four results are obtained – the final temperature and the relative moisture content for the "cold" sample, and the same for the "hot" sample.

For example, if the temperature at the top of the winding is 64 °C, the temperature at the bottom of the winding is 53 °C. The relative humidity of the oil sample at 22 °C is 0.12 and at 57 °C is 0.03. The W_P which is then calculated for the pressboard is 1.03 % and 1.39 %, respectively, for the top and bottom parts of the winding.

To illustrate further, the calculation of the water content in the insulation of the transformer 45 MVA, 161/24 kV by the presented RH measurement method has yielded the following results: 2.4 % for the top insulation zone and 3.2 % for the bottom zone. The Dielectric Dissipation Factor (DDF) was measured at 10 kV and a frequency of 50 Hz over two days after the shutdown of the transformer for different insulation zones at a temperature of 28 °C and the result equalled 1.8-2.5 %. The DDF was measured again after drying of the transformer and the results decreased to 0.4-0.6 %, while the water content calculated by the presented method was estimated to be 0.7 %.

6. Conclusion

1. The method based on the mechanism for sorption of water by the oil impregnated cellulose insulation in contact with air (the Freundlich formula) combined with the mechanism for sorption of water by oil in contact with air (the Henry equation) may be used for the estimation of the water content in the oil impregnated cellulose insulation (W_P) as a function of relative humidity and temperature of oil in different zones of the transformer active part.

2. The measurement of the relative humidity of the oil at different temperatures makes it possible to estimate the water content in the oil impregnated cellulose insulation (W_P) of the transformer regardless of the oil properties, such as oil acidity.

3. The presented method for the estimation of water content in the cellulose insulation in different transformer zones has been used over two years to inform the decision about the need to dry the insulation.

Bibliography

[1] Ch. Krause, L. Dreier, A. Fehlmann, J. Cross, *The Degree of Polymerization of Cellulose Insulation*, 2014 Electrical Insulation Conference, Philadelphia

[2] J.C. Salamone, *Concise Polymeric Materials Encyclopedia, Technology & Engineering*, 1998

[3] T.V. Oommen, *Moisture equilibrium charts for transformer insulation drying practice, IEEE Transaction on Power Apparatus and Systems*, Vol. PAS-103, No. 10, October 1984

[4] Y. Du, A.V. Mamishev, B.C. Lesieutre, M. Zahn, S.H. Kang, *Moisture Solubility for Differently Conditioned Transformer Oils,* IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 8, No. 5, October 2001

[5] *Supervision and maintenance guide for mineral insulating oils in electrical equipment,* IEC Standard 60422

[6] R.A. Lipshtain, M.I. Shahnovich, *Transformer oil,* Energoatomizdat, Moskow, 1983

[7] *Insulating liquids, oil-impregnated paper and pressboard, determination of water by automatic coulometric Karl Fisher titration,* IEC Standard 60814

[8] S. Leivo, J. Lepaaanen, 23rd International Conference on Electricity Distribution Lyon, 15-18 June 2015 Paper 0374

[9] J. Fabre and A. Pichon, *Deteriorating processes and products of paper in oil*, 18th International Conference CIGRE 1960, p. 137

[10] B. Pahlavanpour, M.A. Martins and M. Eklund, *Study of moisture equilibrium in oil-paper system with temperature variation*, 7th International Conference on Properties and Applications of Dielectric 2003, pp. 1124-1129, Vol. 3

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