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Estimation of water content in a power transformer using moisture dynamic measurement of its oil

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Abstract: Careful monitoring of high voltage equipments and diagnosing the critical conditions before they lead to a disaster are prerequisites of condition-based maintenance. Moisture content in a transformer is regarded as one of the major factors in diagnosing its conditions. It causes many problems for a power transformer including electrical breakdown between either its windings or one winding with neutral, increase in the amount of partial discharge and sundry minor problems. Since paper insulation of a power transformer carries large portion of water content, determining moisture content in this part of the transformer is essential. However, the problem is that the direct measurement of moisture in paper is impossible. Therefore, various methods have been proposed to measure the moisture content in a transformer but each one has its limitations. In this study, an approach is introduced to measure water content in a transformer by analysing the moisture dynamics in oil, tracking its variations and analysis of parameters such as temperature, without necessity of disconnecting the transformer from the power grid.

1 Introduction

Moisture plays an important role as a deteriorating factor in the aging process of the high power transformers. It could significantly decrease their life span [1, 2]. To be more specific, the life span of the paper insulator in high power transformers is inversely proportional to the amount of moisture. As a matter of fact, as moisture in the high electric field within a transformer increases, it causes the inception voltage of partial discharges (PDs) to reduce, and consequently, it increases its intensity and it leads to serious damages in the transformer [3, 4].

Nowadays, there are many working transformers in the power system older than 30 years, and it is quite difficult to determine how many more years they could operate reliably due to the fact the internal insulation system of them are basically inaccessible [5]. In addition, power transformers are capital intensive, and it is terribly expensive to replace them. Therefore, the replacement timing of power transformer is a major issue in power system. Moreover, power utilities and electric companies typically try their best to use their facilities to the fullest. On the other hand, if they miscalculate the replacement time of the power transformer, the delay in replacement may lead to equipment failure and consequent power outage, which could be extremely costly for power utilities. Therefore, if a non-invasive method be found to estimate the exact amount of the moisture in a transformer and its life expectancy, the power utilities are very motivated to utilise the method and replace their transformers in a right time, especially in countries that the utilities are required to compensate their customers' financial loss in case of a power outage. Moreover, the accurate estimation of transformer life can help utilities to use their power transformers to the fullest extent, and replace them when it is necessary.

In the literature, a variety of indirect and non-destructive testing techniques [6] are proposed to estimate the condition of a power component. Traditionally, the moisture content has been estimated by using the chemical analysis of oil. If oil in transformer remained stable (no change in temperature) for a long time, the moisture content of paper or pressboard could be estimated from equilibrium curves [7]. However, in recent years, dielectric response is utilised for the purpose of estimating the moisture content. The researchers in CIGRE Task force [8–10] have tried to correlate the measurement of dielectric responses with moisture content evaluation according to Karl Fischer titration analyses. Also, the authors in [11] have collected the measurement from 161 power transformers from Poland, Germany and Sweden by dielectric response spectroscopy in the frequency domain. They have used these measurements to estimate the insulation's moisture content.

Moreover, frequency domain spectroscopy (FDS) measurement is one of the recently utilised techniques to measure the transformer insulation. For example, the authors in [12] have explored the impact of moisture and aging on FDS measurements. Moreover, the authors in [5] have utilised FDS to provide a wide range of observation spectra of oil impregnated paper and pressboard samples, which could help to estimate the moisture content in power transformers.

Also, acoustic techniques are utilised in recent years to detect the PDs in electrical insulation in power transformers. Since moisture content and PD have correlation with together, the PD can be a reliable way to evaluate the status of the insulation [13]. The authors in [2] have used acoustic technique to locate the PD sources. Moreover, the authors in [14] attempted to estimate the moisture content of power transformer's oil by using acoustic signals and spectral kurtosis. In this approach, the spectral kurtosis of the discharge acoustic signals is calculated and then the correlation between the magnitude of these signals (maximum value) and the moisture content of oil is assessed. This correlation could serve as a function to evaluate the moisture contamination of oil.

Another group of estimation methods are the ones that use monitoring sensors. The recent development of these sensors opened new doors for research on moisture content [15]. These sensors can measure the moisture dissolved in transformer oil and it can be used to estimate moisture content in oil impregnated paper or pressboard [16, 17].

In this paper, moisture content in a transformer is estimated by analysing the moisture dynamics in oil, tracking its variations, and analysis of parameters such as temperature. Then, based on the

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results of the analysis, the moisture in insulation pressboard is estimated.

The remaining of this paper is organised as follows. An overview of the impact of moisture on power transformers and the methods to calculate such impacts are presented in Section 2. Afterwards, in Section 3, moisture dynamics in paper/oil systems are discussed, and the necessary mathematical equations are introduced and explained. In Section 4, the simulation results are provided and discussed. Then, based on the moisture dynamics in paper/oil system, the moisture in pressboard is estimated by using measurement of moisture dynamics in oil in Section 5. The paper then concludes in Section 6.

2 Destructive impact of moisture and its calculation methods

The distribution of the moisture in the insulation system is not uniform. The movement of the moisture from the paper to the oil is considerably dependent on the temperature. One of the most important solid materials which is extensively used in power transformers, cables and so on is paper. It possesses good mechanical characteristics but it tends to absorb the moisture.

Moisture in the oil and paper causes the decrease of breakdown voltage and inception voltage of PD and accelerate the aging process of the paper. The moisture content of less than 1% is not harmful to the transformer. As a matter of fact, during the manufacturing of the high voltage instruments, all moisture content of transformers will get completely dried up. Moreover, during the operation of power transformer, the amount of moisture must be maintained less than 1%. The oil used as an insulator in power transformers usually tend not to synthesise with moisture. Although the synthesise increases when the temperature rises, the total amount of moisture in the oil contributes very little in the total amount of moisture. Actually, the amount of the moisture in the oil is less than 1% of the total moisture in the transformer [18].

The dynamics of oil and paper is the subject of many studies. In the literature, there many papers conducting different experiments to find the moisture equilibrium curves. These curves illustrate the relation between the absorbed moisture and the moisture in the oil. The curves could be utilised when the system of oil and paper is in equilibrium state. Fig. 1 illustrates one the latest developed curves [19].

3 Moisture dynamics in paper/oil systems

In this paper, a Couette facility is used to study charge transfer processes at paper/oil interfaces. This facility consists of coaxial metal cylinders covered with pressboard. The annulus formed by the concentric cylinders is filled with oil. The outer cylinder controls the temperature in the system and the inner cylinder is able to rotate. In Fig. 2, a Couette facility is shown [20].

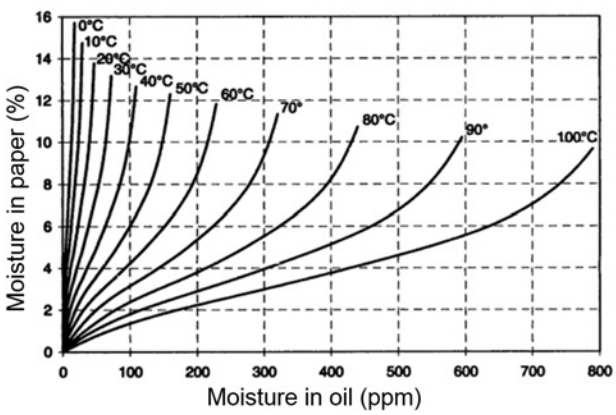

Fig. 1 *MIT developed curves for water equilibrium in paper/oil system [19]*

To calculate the moisture concentration in a paper/oil system, molecular time constants of paper and oil are defined as

$$\tau_o = \frac{d\delta_d}{2D_o} \quad (1)$$

$$\tau_p = \frac{\Delta^2}{D_p} \quad (2)$$

where τ_o and τ_p are molecular time constants of oil and paper, Δ is the thickness of pressboard, d is the gap spacing between inner and outer cylinders, δ_d is the thickness of the diffusion sublayer, and D_o and D_p are molecular diffusion coefficients of water in oil and paper [21]. It must be mentioned that δ_d, D_o and D_p are largely dependent upon temperature, and they are define as

$$\delta_d = \frac{11.7 v_o}{S^{(1/3)} v_o} \quad (3)$$

$$D_o = b\frac{kT}{q} \quad (4)$$

$$D_p = D_{p_0} \cdot e^{W_p((1/T_{P_0})-(1/T))} \quad (5)$$

where v_o is the kinematic viscosity of the oil, S is the Schmidt number, v_o is friction velocity, k is Boltzmann's constant (1.38066×10^{-23} J/K), q is the charge of the assumed monovalent ions (1.6022×10^{-19} C), and b is the mobility of ions in highly insulating liquids.

The other necessary values for calculating the concentration of water in the paper are

$$D_{p_0} = 1.71 \times 10^{-13}\ \mathrm{m^2/s}, \quad W_p = 8047\ \mathrm{K}, \quad T_{p_0} = 288\ \mathrm{K}$$

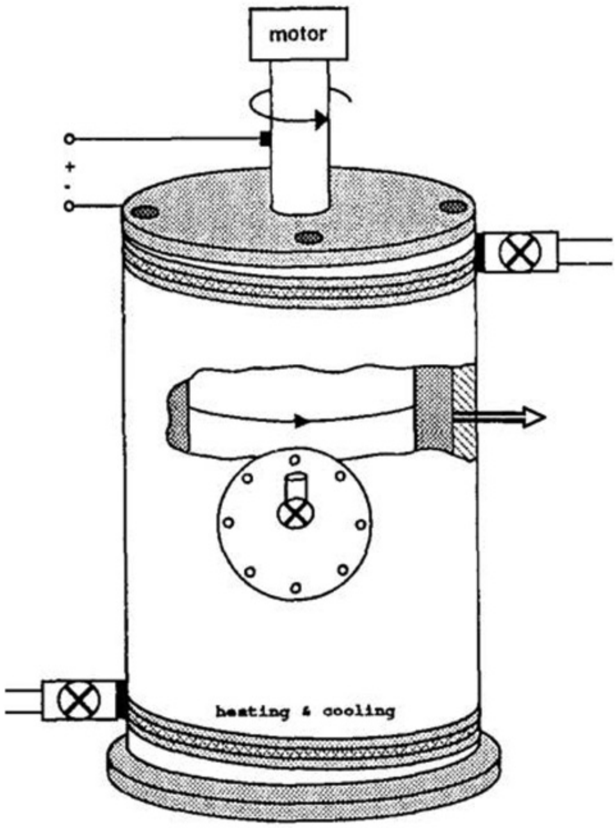

Fig. 2 *Couette facility [20]*

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Table 1 Dimensions of the Couette facility and the thickness of the diffusion sublayer at 15 and 70°C

height of Couette facility	L	40.6 cm
radius of outer cylinder	R_2	10.2 cm
radius of inner cylinder	R_1	6.7 cm
thickness of pressboard	Δ	1 mm
thickness of sublayer at 15°C	δ_d	15.7 µm
thickness of sublayer at 70°C	δ_d	14.4 µm

The thickness of the diffusion sublayer at 15 and 70°C is given in Table 1 along with the dimensions of the Couette facility. Using parameters in Table 1, (1) and (2) are plotted as shown in Fig. 3. Assuming that moisture does not significantly contribute to the weight of oil-impregnated paper, the mass transport equation for moisture in it can be described as

$$\frac{\partial c_{\rm p}}{\partial t} = D_{\rm p} \frac{\partial^2 c_{\rm p}}{\partial x^2} \tag{6}$$

where $c_{\rm p}$ is the mass fraction of moisture in oil-impregnated paper. The initial and final conditions are defined as

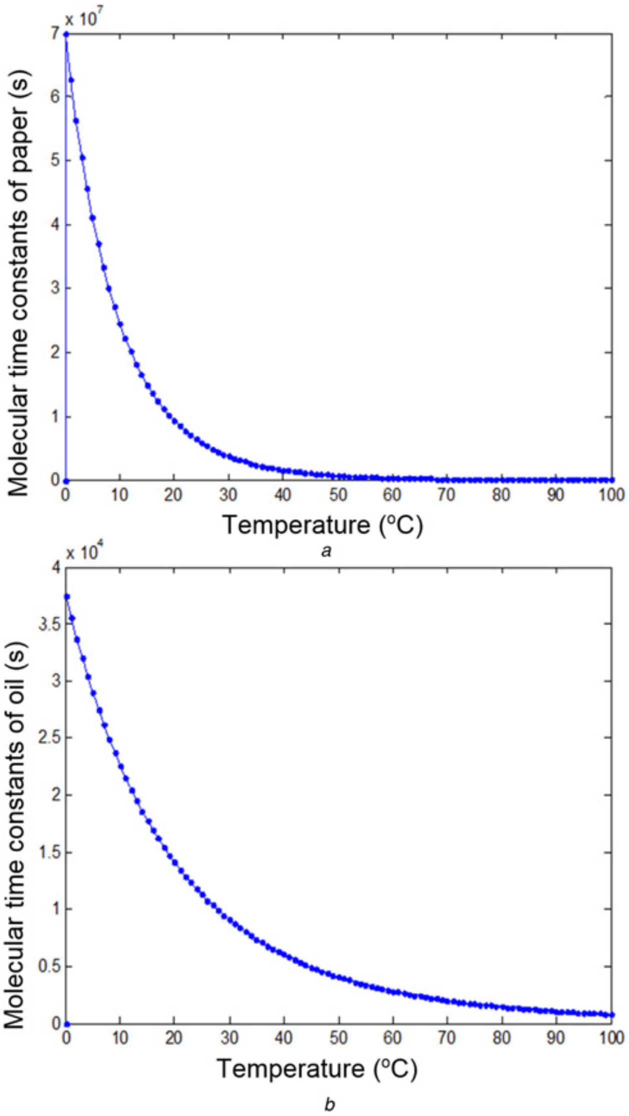

Fig. 3 *Molecular time constants of*

a Paper
b Oil as a function of temperature

$$c_{\rm p} = c_{{\rm p}_i} \to t = 0 \tag{7}$$

$$c_{\rm p} = c_{{\rm p}_f} \to t = \infty \gg \tau_{\rm p} \tag{8}$$

The boundary conditions can be expressed as

$$\frac{\partial c_{\rm p}}{\partial x}|_{(x=\Delta)} = 0 \tag{9}$$

$$\rho_{\rm p} D_{\rm p} \frac{\partial c_{\rm p}}{\partial x}|_{(x=0)} = \rho_0 D_0 \frac{c_{\rm w} - c_{\rm o}}{\delta_{\rm d}} \tag{10}$$

where $c_{\rm w}$ and $c_{\rm o}$ are the concentrations of water in the sublayer and oil, which are defined as

$$c_{\rm o} = c_{\rm w} = K_i c_{{\rm p}i} \to t < 0 \tag{11}$$

$$c_{\rm w}(t) = K(t) c_{\rm p}(x = 0, t) \tag{12}$$

$$c_{\rm o}(t) = K_i c_{{\rm p}i} - \frac{r_m}{\Delta} \int_0^{\Delta} (c_{\rm p}(t) - c_{{\rm p}i}) {\rm d}x \tag{13}$$

where r_m is the ratio of the weight of the oil-impregnated paper on the two cylinders to the weight of the oil in the annulus

$$r_m = \left(\frac{\rho_{\rm p}}{\rho_{\rm o}}\right) \left[\frac{2\pi(R_1 + R_2)\Delta l}{\pi(R_2^2 - R_1^2) l}\right] = \left(\frac{\rho_{\rm p}}{\rho_{\rm o}}\right) \left[\frac{2\Delta}{d}\right] \tag{14}$$

In addition, $K(t)$ is a temperature-dependent distribution coefficient, which is equal to the ratio of the concentration of water in the oil to the same in the paper.

In this paper, to calculate $K(t)$, the curve of Fig. 1 will be used if the mass fraction is more than 1% and the curve of Fig. 4 will be used if the mass fraction is less than 1%.

4 Simulation results

In this section, the results of the theoretical analysis of the previous section will be presented by plotting the distribution curves of moisture using previously mentioned equations, curves, and dimensions of the Couette facility. In all these curves, the initial moisture content of the paper ($c_{\rm pi}$) is assumed 1%.

Spatial distribution of the concentration of water in the paper as a function of time is shown in Fig. 5. The conditions are such that the system is heated from 15 to 70°C. This figure shows that by increasing temperature, the concentration of water in the paper decreases from 1 to around 0.993% eventually. Moreover, this

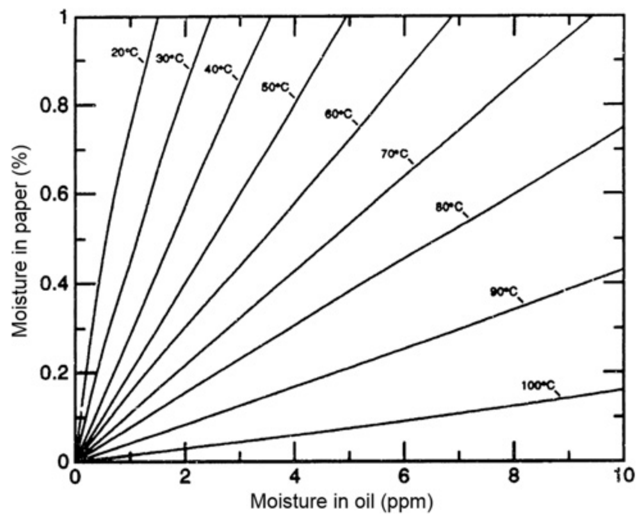

Fig. 4 *Guggenberg curve [21]*

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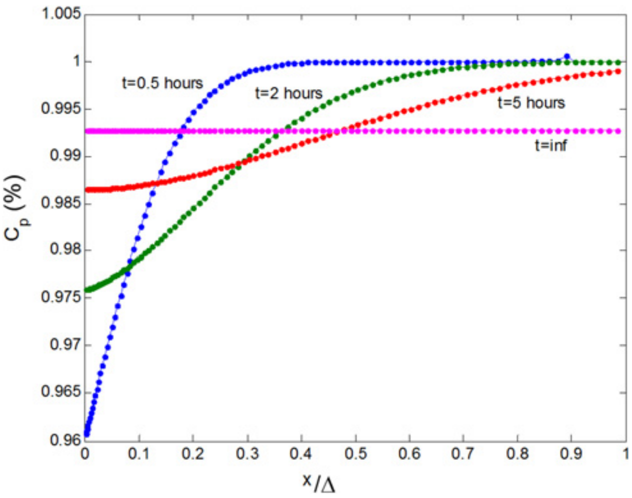

Fig. 5 *Spatial distribution of the concentration of water in the paper as a function of time when heating happens*

figure indicates that after passing 0.5 h, the part of the paper which is in touch with the oil loses its water first and after passing a few more hours the moisture content of the paper goes to its second equivalent value.

The concentration of water in the sublayer and oil as a function of time is shown in Fig. 6. The conditions are such that the system is heated from 15 to 70°C. As it mentioned before, the concentration of water in the oil will increase when the temperature increases. Fig. 6 shows when a heating happens, the concentration of water in the oil goes up from 1 to almost 9 ppm although this procedure needs about 3 h.

Figs. 5 and 6 show the conditions that paper/oil system is in the process of temperature increase when they move from an initial equilibrium moisture content and temperature to secondary equilibrium. The same procedure happens if the temperature decreases but at this time, the water goes from the oil to the paper. However, in reality, the temperature of a paper/oil system is constantly changing.

Spatial distribution of the concentration of water in the paper as a function of time is shown in Fig. 7. In this case, three hours after heating at 70°C, a cooling happens and the system tries to return to its original conditions at 15°C. In addition, the concentration of water in the sublayer and oil as a function of time in this case is shown in Fig. 8. These two figures show that when a heating happens, the water tries to go from the paper to the oil but before

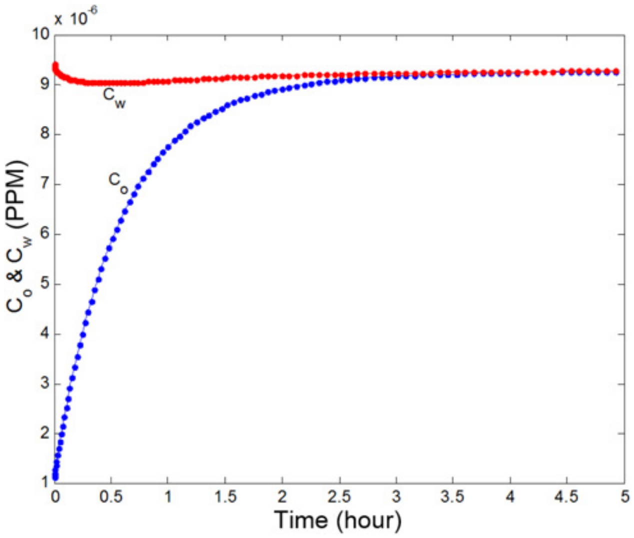

Fig. 6 c_w *and* c_o *as a function of time when a heating happens*

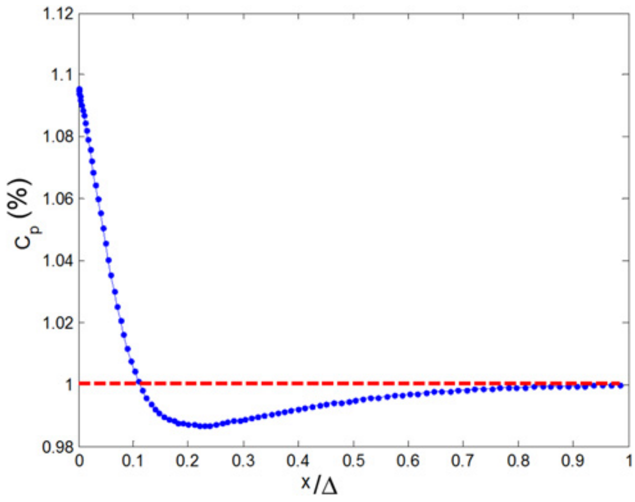

Fig. 7 *Spatial distribution of the concentration of water in the paper as a function of time when a cooling happens at 3 h after a heating*

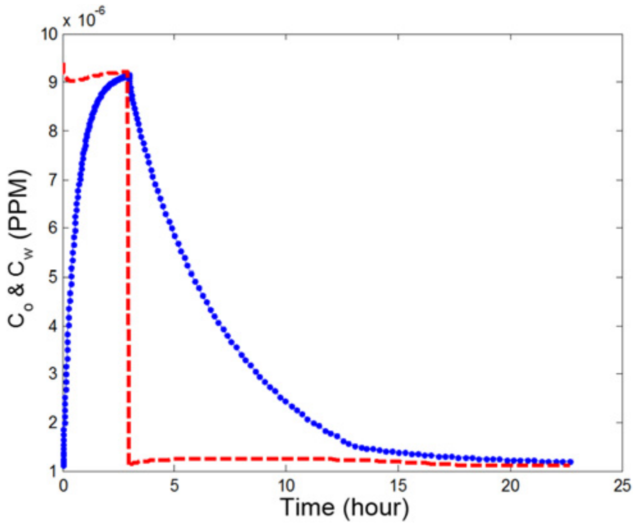

Fig. 8 c_w *and* c_o *as a function of time when a cooling happens at 3 h after a heating*

the whole paper/oil system gets to its new equilibrium condition, the temperature drops again and the water goes back from the oil to the paper and the system tries to get its first equilibrium condition again. It takes time for both oil and paper to achieve their first equilibrium conditions.

Sometimes temperature of a transformer changes too slowly. In this case, temperature changes can no longer operate as a step function. Therefore, the c_o–time curve must be divided into some parts that each of them could be assumed as a step function. Spatial distribution of the concentration of water in the paper as a function of time when a heating happens from 10 to 70°C during four hours is shown in Fig. 9. In addition, the concentration of water in the sublayer and oil as a function of time is shown in Fig. 10.

5 Estimation of moisture in pressboard with measurement of moisture dynamics in oil

As it mentioned in Section 3, the model assumes that initial conditions in the pressboard and oil are described by a uniform distribution. This assumption is valid only when the paper/oil system is in an equilibrium condition for a long time; but this is not the case for power transformers where the period associated with variations in the load is typically smaller than the time

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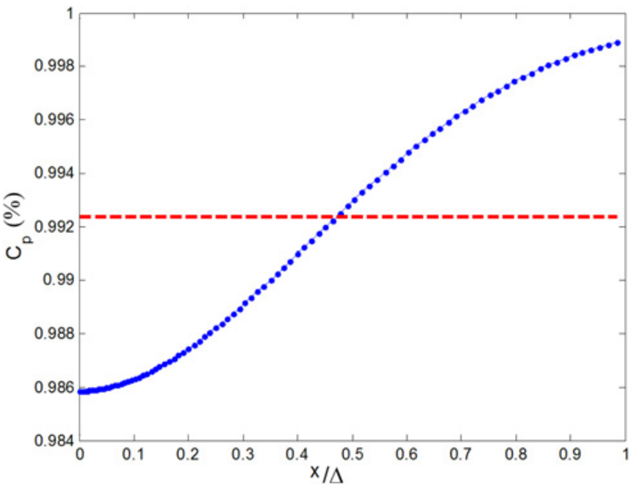

Fig. 9 *Spatial distribution of the concentration of water in the paper as a function of time when a heating happens from* 10 *to* 70°C *during 4 h*

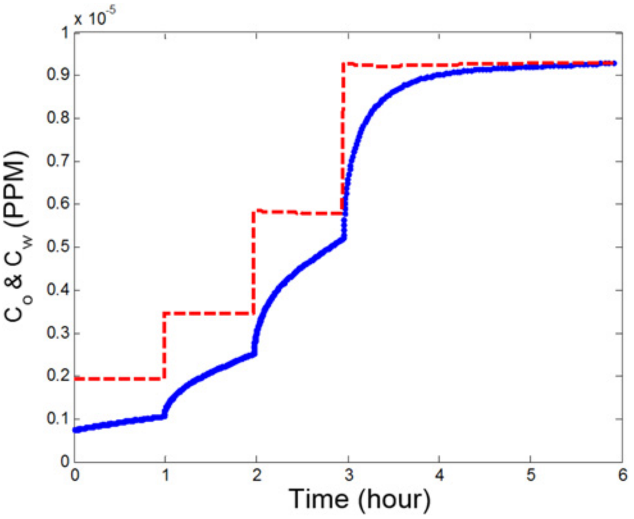

Fig. 10 *c_w and c_o as a function of time when a heating happens from* 10 *to* 70°C *during 4h*

constant associated with the diffusion of water in the pressboard that means in a real situation, there is no equilibrium condition for paper/oil system.

In addition, all simulations and figures in the previous section were derived from c_{pi}, but it must be mentioned that in a real situation, c_{pi} is the most important unknown parameter that must be calculated. In general, the whole purpose of this research is obtaining moisture content of the paper when the power transformer is working when actually there is not a direct access to its paper. Therefore, to measure the water content in pressboard, which represents the moisture content in transformer, at first, we draw c_o curve through a sampling period in a day by using one or more sensors and name it $c_{o\_exprimental}$, then we guess an initial value for c_{pi} by using c_o curve. In the subsequent step, we obtain c_o by using previously mentioned equations and the initial guess of c_{pi} and then afterwards we compared these c_o to $c_{o\_exprimental}$ with the help of least squares method. Finally, if they were close enough, we found the correct answer for the water content in pressboard; otherwise, we should modify the initial guess based on that comparison and do all aforementioned steps again.

Table 2 Temperatures of a day divided into four parts

Time period, hours of a day	Temperature, °*C*
22-7	20
7-11	40
11-18	50
18-22	75

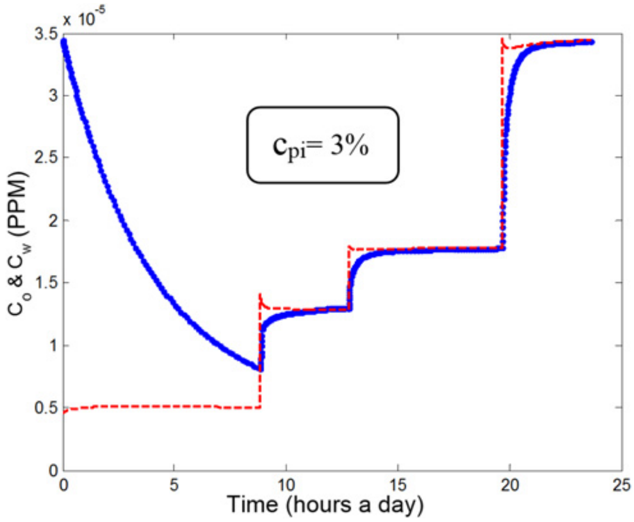

Fig. 11 *Concentration of water in the sublayer and oil as a function of time by using Table 2*

For example, if we assume that we have obtained parameters in Table 2 and curves in Fig. 11 by using temperature and moisture sensors in a sample transformer during a day and put them into the program based on the previous paragraph, we would reach $c_{pi} = 3\%$ after some iterations.

6 Conclusion

Condition-based maintenance and replacement require careful monitoring and precise diagnosis methods. These diagnostic methods require researchers to study the dynamics of oil/paper insulation in power transformer. Water content in a power transformer is regarded as one of the major factors in diagnosing its conditions. It causes many problems for power transformer. Since more than 90% of water content in a power transformer is in its paper insulation, so determining moisture in pressboard as the main part of paper insulation is essential.

In this paper, the moisture content in a transformer is estimated by analysing the moisture dynamics in oil, tracking its variations, and analysis of parameters such as temperature. Then, based on the results of the analysis, the moisture in insulation pressboard is estimated.

The following conclusions are drawn from the results of this study:

(i) With the help of this method and calculating water content in the paper of transformer, the condition of the transformer could be determined, and if it is critical, the problem could be addressed before a fault happens and affect the whole power system.
(ii) The description of spatial and temporal evolution of moisture in the Couette facility shows that by using the moisture dynamic in oil and tracking its variations, moisture content in a transformer paper can be estimated.
(iii) The simulations show that the proposed method is working and it can be tested in a real experiment.

Since temperature is a key factor for moisture migration and temperature distribution is not uniform in a transformer, so moisture distribution in different part of a transformer is not the same. Judging the moisture in paper basing on the moisture concentration in the sublayer oil might be more accurate. As a

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future study, the simulation results of this paper can be investigated by an experimental work and then based on this approach, an online monitoring system can be introduced to monitor the water content of paper/oil system in a transformer continuously.

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