ESTIMATION OF MOISTURE IN PRESSBOARD OF POWER TRANSFORMER USING MOISTURE DYNAMIC MEASUREMENT IN TRANSFORMER OIL

V. Sarfi[1] , A.A. Shayegani[2] , H. Mohseni

[1,2,3] High Voltage Laboratory, School of ECE, College of Engineering,
University of Tehran, Iran
Email: vahidsarfi@yahoo.com

Abstract: Proper maintenance of high voltage equipments is one of the most important issues of the power systems. Nowadays high maintenance expenses make electrical companies prefer to operate based on conditions of equipments rather than time schedule. Suitable monitoring of high voltage equipments and diagnosing their faults before lead to a disaster, provides maintenance based on conditions. Water content in a power transformer is considered one of the main parameters of diagnosing its conditions. This parameter causes many problems including electrical breakdown between high and low voltage windings, decrease of partial discharge starting voltage and e. 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. It is worth to mention that determining moisture in pressboard is impossible directly. Therefore, various methods have been proposed to determine the exact moisture content in a transformer that each one has its limitations. In this paper moisture content in a transformer is estimated by analyzing the moisture dynamic in oil, tracking its variations and analysis of parameters such as temperature, without necessity of interrupting the transformer.

1 INTRODUCTION

Moisture as a deteriorating factor plays an important role in decreasing the life span of the high power transformers. The life span of the paper is reversely proportional to its amount of moisture. On the other hand the increase of the moisture in area of high electric field results in reducing the inception voltage of partial discharges and increases its intensity. Consequently leads to serious damages in a transformer.

Today, there are many transformers that are older than 30 years, and it is not possible to determine how many years further they can operate. On the other hand, due to the financial consideration, it is not possible to replace them. In addition, Elec. Co. hopes that they can use their facilities as long as possible. Therefore, if a solution can be obtained to estimate the exact amount of its moisture and its life expectancy, the Elec. Co. can find a reasonable financial motivation to replace their transformers, specifically in countries that have to pay their customers in a case of a power blackout. With this kind of information Elec. Co. can utilize their transformers as long as possible, and when transformer is needed to be replaced, by previous notification, it can be substituted.

Different methods for estimating the moisture in a transformer have been suggested, which be mentioned. In this paper, for this purpose a new on-line method is presented, which is cost efficient and by dynamic analysis of variation of the moisture in a paper of a transformer in a specific period of time and some other parameters, estimates the moisture in the paper and further, estimates moisture in the transformer.

2 DESTRUCTIVE IMPACT OF MOISTURE AND ITS CALCULATION METHODS

The distribution of the moisture in the insulation system is not constant, and depending on its operating conditions varies. The movement of the moisture from paper to the oil is considerably dependent on the temperature. One of the most important solid materials which is extensively used in power transformers, meters, cables and high voltage capacitors, is paper. Its main component is Cellulose. Its cost is low and possesses good mechanical characteristics. But it tends to absorb the moisture which can be improved by saturating it with oil. In figure 1, the aging of the paper versus moisture and temperature is shown.

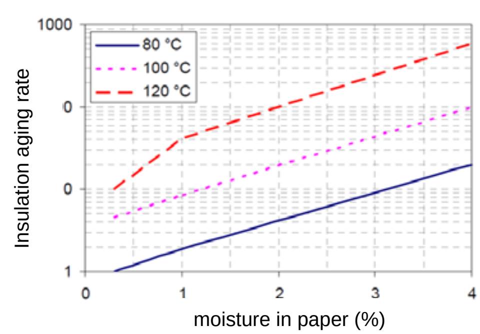

Figure 1: the aging of the paper versus moisture and temperature [1]

As it is mentioned before, moisture in the oil and paper causes the decrease of breakdown voltage and inception voltage of partial discharge and increase of process of aging of the paper. The moisture less than 1% is not dangerous for the transformer. Thus, when the instruments of high voltage are manufactured, they are completely dried and during the operation the amount of moisture must be maintained less than 1%.

The oils used as insulator in the high power transformers, usually tend not to synthesize with moisture. Although this trend is increased when the temperature rises, the total amount of moisture in the oil contributes very little in total amount of moisture. Actually, the amount of the moisture in the oil is less than 1% of the total moisture in the transformer [2].

The presented methods of estimating the level of moisture in a transformer are as follows:

1) Karl fisher method

2) Measuring the polarization and depolarization current

3) Recovery Voltage Measurement

4) Frequency Domain Spectroscopy

5) Method of using the moisture sensitivity

6) Method of using the moisture equilibrium curves

In the 6th method, the curves illustrate the relation between the absorbed moisture and the moisture in the oil, obtained by different people. They can be used only when the system of oil and paper is in equilibrium state. Figure 2 shows the last developed curve.

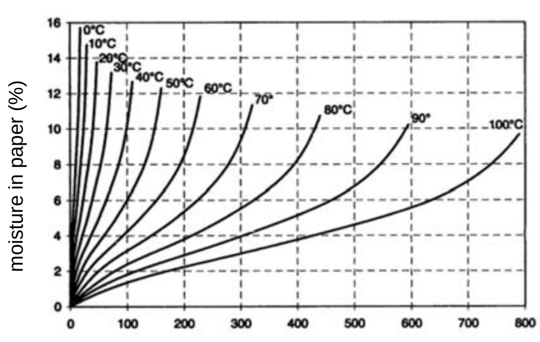

Figure 2: MIT developed curves for water equilibrium in paper/oil system [3]

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 figure 3, a Couette facility is shown.

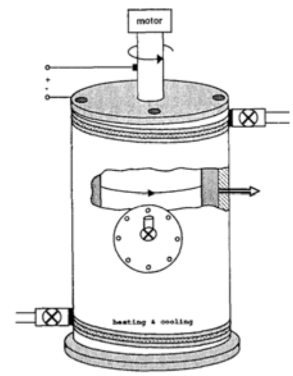

Figure 3: Couette Facility [4]

To calculate the moisture concentration in a paper/oil system, molecular time constants of paper and oil are defined as [5]

$$\tau_o = d\delta_d / 2D_o \tag{1}$$

$$\tau_p = \Delta^2 / D_p \tag{2}$$

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.

It should be mentioned that δ_d, D_o and D_p are extremely depend on temperature and they define as

$$\delta_d = \frac{(11.7\,\mathrm{v_o})}{\mathrm{S}^{1/3}\ \nu_o} \tag{3}$$

$$D_O = b\frac{kT}{q} \tag{4}$$

$$D_p = D_{P0} exp\left[W_p\left(\frac{1}{T_{P0}} - \frac{1}{T}\right)\right] \tag{5}$$

where $\mathrm{v_o}$ is kinematic viscosity of the oil, S is the Schmidt number, ν_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.

In order to, the values of parameters for a concentration of water in the paper are

$$D_{P0} = 1.71 \times 10^{-13} \frac{m^2}{s}, W_P = 8047K \text{ and } T_{P0} = 288K$$

The thickness of the diffusion sublayer at 15 °C and 70 °C is given in table (1) along with the dimensions of the Couette Facility.

Table 1: Dimensions of the Couette Facility and The thickness of the diffusion sublayer at 15 °C and 70 °C

Height of Couette Facility	L	40.6 cm
Radius of outer cylinder	R2	10.2 cm
Radius of inner cylinder	R1	6.7 cm
Thickness of pressboard	Δ	1 mm
Thickness of sublayer at 15oC	δ_d	15.7 µm
Thickness of sublayer at 70oC	δ_d	14.4 µm

Using parameters in table 1, equations (1&2) are plotted in figure 4

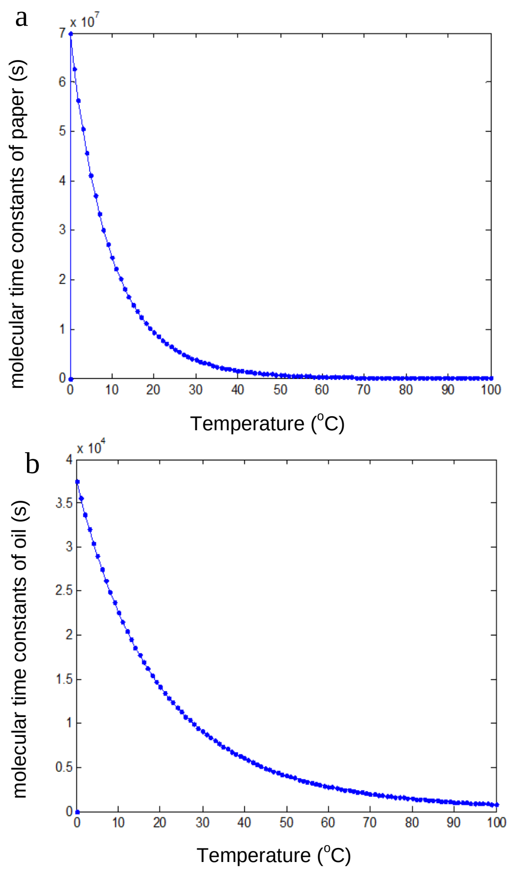

Figure 4: molecular time constants of paper (a) and oil (b) as a function of temperature

Assuming that moisture does not appreciably contribute to the weight of oil-impregnated paper, the mass transport equation for moisture in oil-impregnated paper can be described as

$$\frac{\partial c_p}{\partial t} = D_p \frac{\partial^2 c_p}{\partial x^2} \qquad (6)$$

where c_p is the mass fraction of moisture in oil-impregnated paper. The initial and final conditions are defined as

$$c_p = c_{pi} \rightarrow t = 0 \qquad (7)$$

$$c_p = c_{pf} \rightarrow t = \infty >> \tau_p \qquad (8)$$

The boundary conditions can be expressed as

$$\left.\frac{\partial c_p}{\partial x}\right|_{x=\Delta} = 0 \qquad (9)$$

$$\rho_p D_p \left.\frac{\partial c_p}{\partial x}\right|_{x=0} = \rho_o D_o \frac{c_w - c_o}{\delta_d} \qquad (10)$$

where c_w and c_o are the concentration of water in the sublayer and oil which are defined as

$$c_o = c_w = K_i c_{pi} \rightarrow t < 0 \qquad (11)$$

$$c_w(t) = K(t) c_p(x = 0, t) \qquad (12)$$

$$c_o(t) = K_i c_{pi} - \frac{r_m}{\Delta} \int_0^{\Delta} \left(c_p(t) - c_{pi}\right) dx \qquad (13)$$

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.

$$r_m = \left(\frac{\rho_p}{\rho_o}\right)\left[\frac{2\pi(R_1 + R_2)\Delta l}{\pi(R_2^2 - R_1^2)l}\right] = \left(\frac{\rho_p}{\rho_o}\right)\left[\frac{2\Delta}{d}\right] \qquad (14)$$

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 that in the paper.

In this paper, in order to calculate K(t), figure 2 will be used if the mass fraction is more than 1% and figure 5 will be used if the mass fraction is less than 1%.

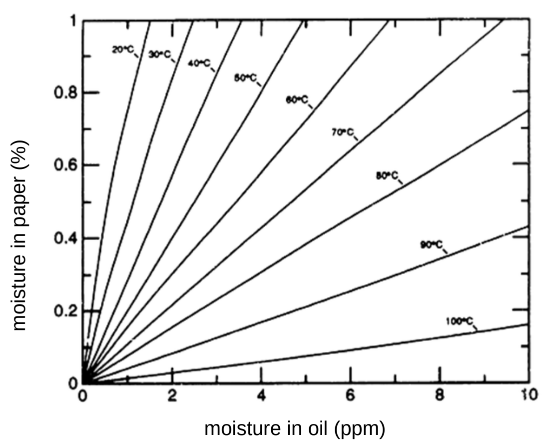

Figure 5: Guggenberg curve [5]

4 SIMULATION RESULTS

In this section, a few curves are plotted using equations and curves above and dimensions of the Couette Facility. In all these curves, the initial moisture content of the paper (c_{pi}) is assumed 1%.

Spatial distribution of the concentration of water in the paper as a function of time is shown in figure 6. The conditions are such that the system is heated from 15°C to 70°C.

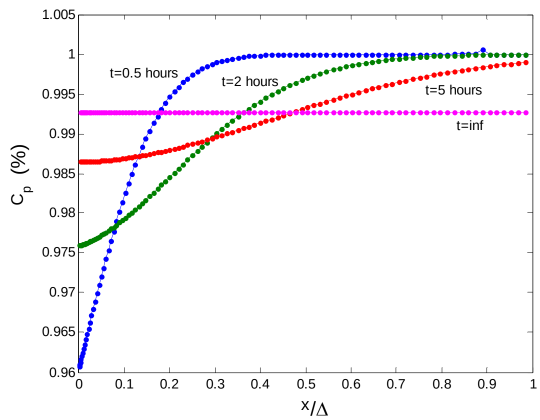

Figure 6: Spatial distribution of the concentration of water in the paper as a function of time when heating happens

The concentration of water in the sublayer and oil as a function of time is shown in figure 7. The conditions are such that the system is heated from 15°C to 70°C.

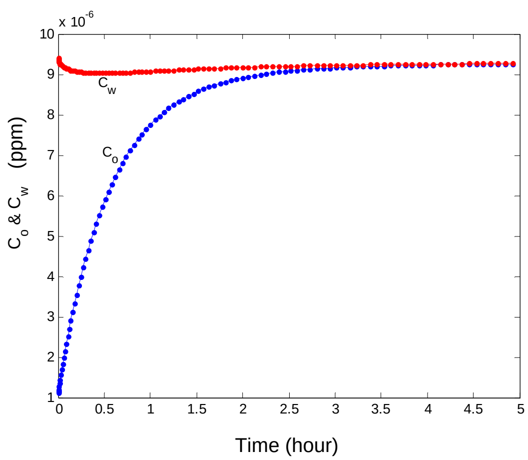

Figure 7: c_w and c_o as a function of time when a heating happens

Spatial distribution of the concentration of water in the paper as a function of time is shown in figure 8 when the system is returned to its original conditions at 15°C.

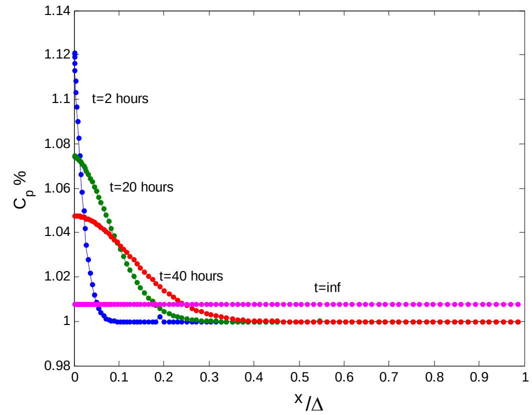

Figure 8: Spatial distribution of the concentration of water in the paper as a function of time when a cooling happens

The concentration of water in the sublayer and oil as a function of time when a cooling happens from 70°C to 15°C is shown in figure 9.

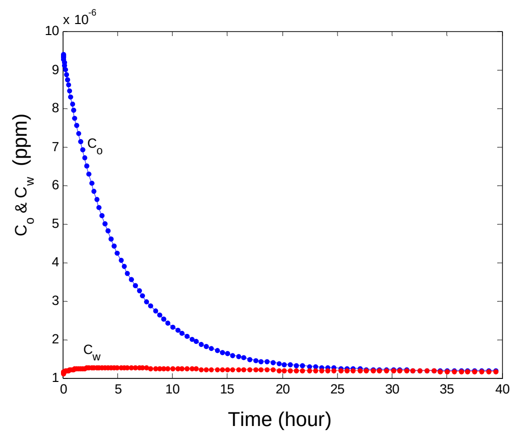

Figure 9: c_w and c_o as a function of time when a cooling happens

All figures above are about conditions that the paper/oil system is the process of applying a temperature decrease or increase of an initial equilibrium moisture content and temperature to secondary equilibrium. But it is clear that in the actual conditions, the paper/oil system is constantly changing.

Spatial distribution of the concentration of water in the paper as a function of time is shown in figure 10. 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.

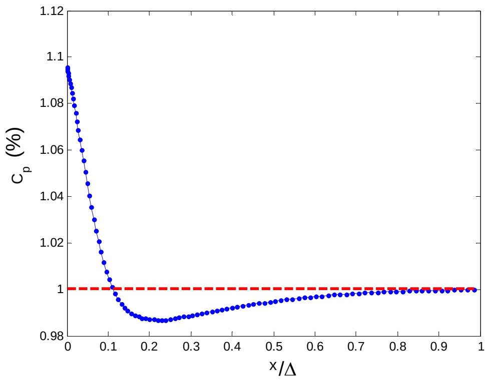

Figure 10: Spatial distribution of the concentration of water in the paper as a function of time when a cooling happens at 3 hours after a heating

The concentration of water in the sublayer and oil as a function of time in this case is shown in figure 11.

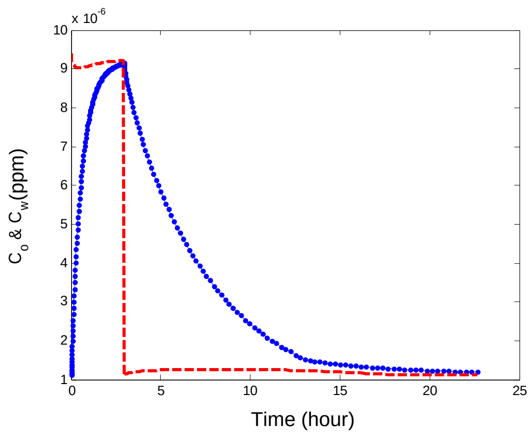

Figure 11: c_w and c_o as a function of time when a cooling happens at 3 hours after a heating

Spatial distribution of the concentration of water in the paper as a function of time is shown in Figure 12. In this case, three hours after cooling at 15^{o}C, a heating happens and the system tries to return to its original conditions at 70^{o}C.

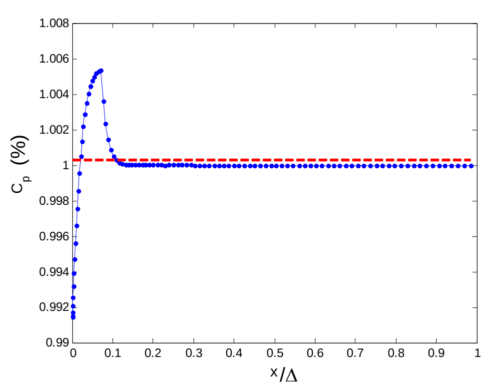

Figure 12: Spatial distribution of the concentration of water in the paper as a function of time when a heating happens at 3 hours after a cooling

In this case, the concentration of water in the oil as a function of time is shown in Figure 13.

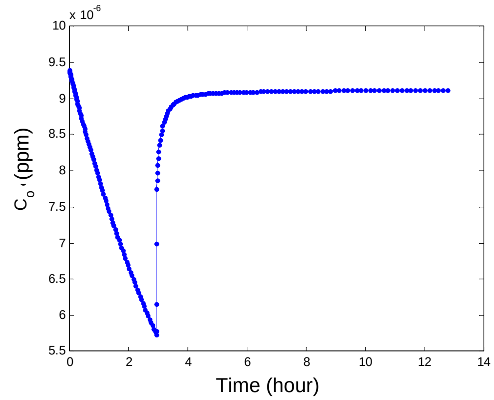

Figure 13: co as a function of time when a heating happens at 3 hours after a cooling

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 assumes 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^{o}C to 70^{o}C during four hours, is shown in Figure 14.

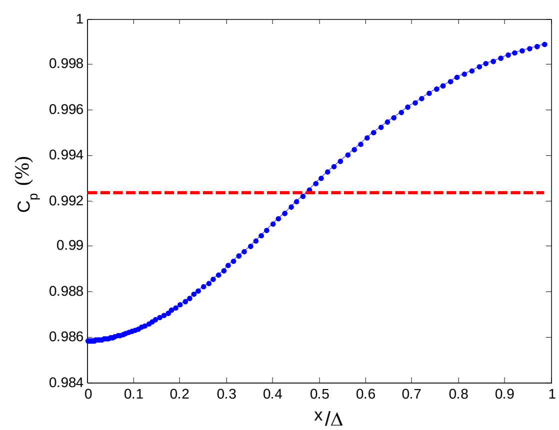

Figure 14: Spatial distribution of the concentration of water in the paper as a function of time when a heating happens from 10^{o}C to 70^{o}C during 4 hours

The concentration of water in the sublayer and oil as a function of time is shown in figure 15.

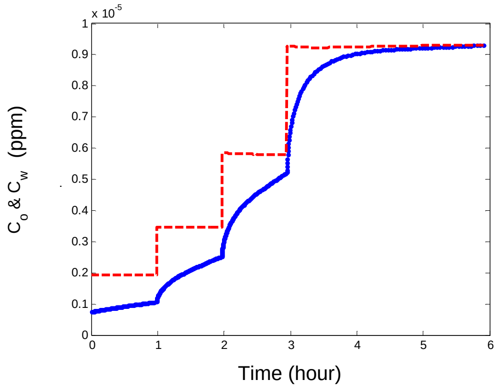

Figure 15: c_w and c_o as a function of time when a heating happens from 10°C to 70°C during 4 hours

5 ESTIMATION OF MOISTURE IN PRESSBOARD WITH MEASUREMENT OF MOISTURE DYNAMICS IN OIL

As formulated, the model assumes that the initial in the pressboard are described by a uniform distribution. This assumption is valid only when the system is in equilibrium. This is not the case for power transformers where the period associated with variations in the load is typically smaller than the time constant associated with the diffusion of water in the pressboard.

So far, all simulations and figures were derived from c_{pi} , but it must be mentioned that in a real system, c_{pi} is the most important unknown parameter that must be calculated. In general, the target of this article is obtaining moisture content of the paper. Therefore, to measurement the water content in pressboard that is represent of moisture in transformer, at first we draw c_o curve through a sampling period such 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, after that we obtain c_o by using equations above and the initial guess of c_{pi} and then we compare these c_o to $c_{o\_exprimental}$ with help of The method of least squares. Finally, if they were close enough, we had the right answer otherwise we should optimize the initial guess and do all of these again.

For example, if we assume that we have obtained parameters in table (2) and curves in figure 16 by using temperature and moisture sensors in a sample transformer during a day and put them into the program based on previous paragraph, we would reach c_{pi}= 3% after some stages.

Table 2: Temperatures of a day divided into 4 parts

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

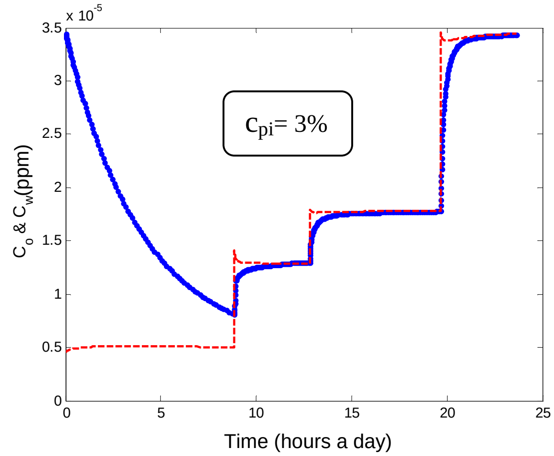

Figure 16: The concentration of water in the sublayer and oil as a function of time by using table (2)

6 CONCLUSION

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 can be estimated. In addition, in this method there is no need to interrupt the transformer from the power system.

Simulations show that this new method is more accurate and cheaper than old methods.

7 REFERENCES

[1] A. N. Jahromi, R. Piercy, S. Cress, Jim R. R. Service, and W. Fan “An approach to power transformer asset management using health index”, IEEE Electrical Insulation Magazine, Vol. 25, No. 2 , March/April 2009

[2] Y. Sheiretov, M. Zahn "Dielectrometry Measurements of Moisture Dynamics in Oil-impregnated Pressboard" IEEE TDEI, Vol. 2, No. 3; June 1995

[3] Y. Du, “Measurements and modeling of moisture diffusion processes in transformer insulation using interdigital dielectrometry sensors”, Ph.D. thesis, Massachusetts Institute of Technology, May 1999

[4] A.J. Morin, M. Zahn, J.R. Melcher, “Fluid electrification measurements of transformer pressboard oil insulation in a Couette charger”, IEEE Transactions on Electrical Insulation Vol. 26, No. 5; October 1991

[5] P.A. von Guggenberg, “Applications of interdigital dielectrometry to moisture and double layer measurements in transformer insulation”, Ph.D. thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, June 1993