Advanced Online Moisture Measurements in Power Transformers

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Abstract **– This paper investigates new approaches to determine water in oil-paper-insulated power transformers. Moisture diffusion and equilibrium are described in terms of water potential. Measurement methods for water in oil paper insulations were compared. Since the conventional application of moisture equilibrium diagrams leads to erroneous results, diagrams adapted to the moisture absorption capacity and ageing state of the involved materials were created. An advanced representation of equilibrium diagrams using relative moisture in oil leads to much better results. Beyond this the moisture determination as active water in oil and cellulose provides easy, accurate and continuous measurements and reflects directly the destructive potential of water in oil paper insulations. Its integration in online monitoring systems is shown.**

Index terms - **Aging, Humidity measurement, Monitoring, Moisture, Oil paper insulation, Power transformers**

I. INTRODUCTION

Reliable assessment of the ageing state of high voltage power transformers is a basic condition for a failsafe and cost-saving service. Moisture in cellulose and oil is an ageing accelerator and determines beside others the life cycle of the transformer insulation. Moisture equilibrium diagrams represent moisture in cellulose and in oil under equilibrium conditions at different temperatures. There is only a small number of investigations regarding moisture equilibrium and moreover they imply solely new materials. This investigation improves equilibrium diagrams firstly by the additional use of aged materials, secondly by an advanced representation and thirdly by applying active water content. The results enable for a more precise evaluation of moisture in HV-transformers especially in automated online monitoring systems.

II. WATER IN OIL PAPER INSULATED TRANSFORMERS

A. Moisture Diffusion and Equilibrium

Systems tend to reach equilibrium because in this state the global entropy is the highest. Therefore the value of equilibrium constants depend on thermodynamic and chemical potentials of the system. The exchange of water between cellulose and oil is caused by the dependence of water solubility on temperature. With increasing temperature the chemical potential to absorb water in cellulose

decreases while that of oil *increases*. Thus the tendency to reach the highest possible entropy forces water molecules to diffuse from cellulose to oil. For decreasing temperatures it is obviously the other way round.

Thermodynamic equilibrium is reached, when its macroscopic observables (pressure, temperature etc.) have ceased to change with time. In a power transformer a global thermodynamic equilibrium will hardly ever be achieved. Time constants are very long at low temperatures. A homogenous temperature and pressure distribution is impossible during service. Nevertheless a local thermodynamic equilibrium (LTE) will occur. For LTE the macroscopic observables are varying in space and time, but so slowly, that for any point one can assume thermodynamic equilibrium in some neighborhood about that point. Thus LTE will occur if a transformer is operated at a constant load for a sufficient time. Therefore equilibrium diagrams are applicable but their validity is limited to areas with LTE. At low temperatures even LTE won't exist.

B. Equilibrium and Relative Moisture Content

Moisture diffusion tries to establish equilibrium in the way, that water potential Ψ is the same at every location in the system. Water potential or the partial specific Gibbs free energy describes the thermodynamic state of water in materials and is an equilibrium measure. According to the first equation (1) it depends above all on water activity a_W, further on Kelvin temperature T, gas constant R and molecular weight of water M_W.

$$\Psi = \frac{RT}{M_W}\ln(a_W) \qquad (1)$$

Water activity is a direct measure of the energy state of water in materials. It is numerically related to the relative humidity $C_{W,rel}$ by

$$C_{W,rel} = a_W \cdot 100\,\% . \qquad (2)$$

Thus moisture exchange could be described by a simple proposition: The moisture content *relative to saturation level* $C_{W,rel}$ in adjacent materials becomes equal.

$$C_{W,rel,Cel} = C_{W,rel,Oil} = C_{W,rel,Air} \qquad (3)$$

This way the LTE and the highest entropy in the system is reached.

C. Water Solubility in Oil

Pure mineral transformer oil consists of saturated hydrocarbons such as paraffins and naphthenes. Because of their nonpolar molecule structure pure oil cannot dissolve water. However insulation oil in power transformers is polluted by remains from refinery, ageing byproducts and cellulose particles. Thus water can be dissolved and exists in the following states:

- Bound to ageing byproducts by Van Der Vaals and hydrogen bonds
- Absorbed by impurities e.g. cellulose fibers
- Small drops, when the saturation level is exceeded

The moisture content C_W is usually related to oil weight (ppm as μg water / g oil) or to the saturation value (%).

$$C_{W,rel} = \frac{C_W}{C_{W,S}} \cdot 100\% \qquad (4)$$

Mineral oil detoriates because of oxidation depending among others on oxygen level, temperature and moisture. Ageing products are alcohols, aldehydes, ketones and finally acids. All these oxidation products are polar by nature and able to coalesce Van Der Waals and hydrogen bonds and thus to dissolve water. Van der Waals bonds base on interactions of dipoles (attraction of opponent charges). For a hydrogen bond one hydrogen atom (proton) is bound between two atoms with a high electronegativity. This bond occurs between water and oil ageing products and between free water molecules too so that water forms drops if the saturation level is transgressed. Because ageing products in mineral oil are able to dissolve water, the water solubility and saturation level will increase with ageing, see Fig. 1.
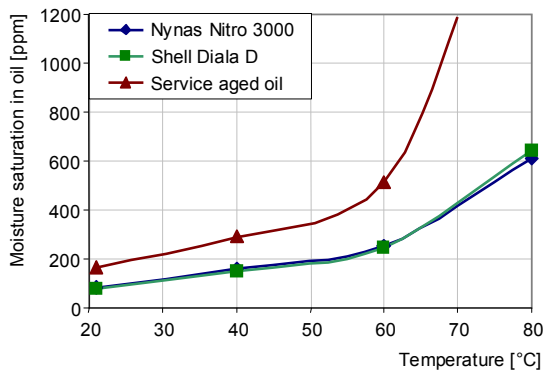

Fig. 1. Moisture saturation level for new Nynas Nitro 3000, new Shell Diala D and a 25 years serviceaged oil

D. Water Solubility in Cellulose

Pressboard and paper used as insulation material consists to 90 % of cellulose, to 3-7 % of lignin and of pentosan. In the following explanations cellulose should be the collective name for insulation materials such as pressboard, Transformerboard (made by Weidmann), Kraft paper (insulation paper) and thermally upgraded paper. Cellulose consists of polar glucose chains and is therefore able to dissolve high quantities of water in the following states:

- Strongly bound to OH-groups of glucose chains by hydrogen bonds
- Weakly bound by Van Der Vaals bonds, water molecules may form multiple layers attracted to glucose chains
- Held by capillary forces
- As free water in capillaries

The ability to dissolve water is, depending on temperature, some thousand times higher compared to oil. Insulation oil thus serves as a transport medium for water, not as a storage medium.

Hydrolysis is assumed to be the dominating ageing process. It decreases the degree of polymerisation (DP, number of joint glucose rings per cellulose chain, see Fig. 2) from 1000-1500 to 200-400 at the end of the cellulose life span.
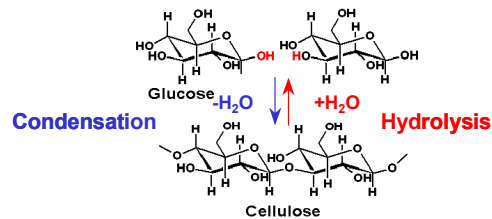

Fig. 2. Chaining through condensation and scission through hydrolysis of glucose rings

Water in power transformers comes from residual moisture in bulky construction elements, out of the atmosphere (breathing of open conservator systems, through leaky seals, during repair) and from ageing reactions [1]. The atmosphere is considered to be the main source of water.

III. MOISTURE MEASUREMENTS

A. Moisture Related to Weight - Karl Fischer Titration

The water content of any material can be related to the weight of the dry material or to the moisture saturation level. In transformers the moisture content is conventionally related to the weight i.e. per cent of weight for cellulose (%) and parts per million of weight for oil (ppm). For this measurement mostly the coulometric Karl Fischer titration KFT is used. At coulometric titration the titre is added by a generator electrode. Water content calculates equation (5). The detection limit of coulometric titration reaches down to some μg of water.

$$2\,H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + 2\,HI \qquad (5)$$

Three methods may bring the moisture of the material could into the reaction vessel:

Firstly direct injection into the reaction vessel, e.g. oil through a syringe.

Secondly the water can be extracted by another medium, e.g. methanol. Methanol and water will then be injected into the reaction vessel.

Thirdly the sample can be heated in an external oven and a gas stream with water vapour is lead into the reaction vessel. Advantageously the reaction vessel remains clean from pollutions and also from ageing byproducts,

depending on their boiling point. The blank value of the gas stream and the heating vial decreases the sensitivity compared to the direct injection method.

Although KFT is counted as a reliable measurement method, it is effected by some influences: (1) There is always a moisture ingress from atmosphere during sample preparation. (2) Sometimes direct injection and heating method lead to different results for moisture in oil. This might be due to the influence of oil additives and ageing by products. It is known, that aldehydes and ketones react with the methanol of the reagent to acetales and ketales with water as a byproduct. (3) Cellulose binds water with chemical bonds of different strengths. It is unsure, if the thermal energy releases all the water. (5) Heating temperature and time strictly changes the released water. According to IEC 60814 it should be 130-140°C. The authors of [5] found, that at pressboard samples only a temperature of 180°C leads to results comparable to the methanol extraction method, see Fig. 3.
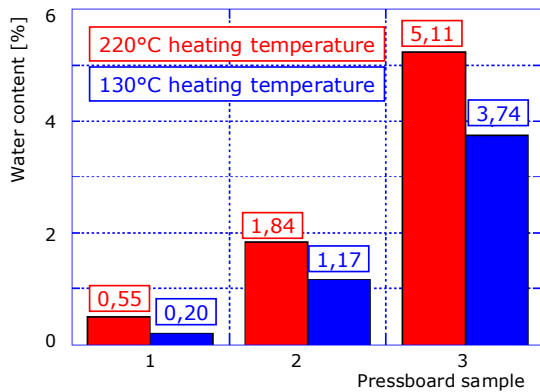

Fig. 3 Moisture content analysed by KFT with heating temperatures of 220°C and 130°C, [5]

In this investigation a coulometric KFT instrument with heating oven and methanol vapour circulation called Aqua 40.00 made by Elektrochemie Halle was used. Water in cellulose is measured by the heating method with temperatures of 160°C for paper and 180°C for pressboard. For water in oil determination the oil was directly injected into the reaction vessel by a syringe. Using the described procedures the repeatability of moisture determination in cellulose was then ± 10 % of the measurement value in the range 0,3-8 % moisture by weight. For moisture in oil the repeatability is about ± 7 % in the range of 15-90 ppm moisture by weight.

B. Moisture Related to Saturation - Capacitive Probes

Capacitive probes consist of two electrodes with a dielectric made by a hydroscopic polymer, see Fig. 4. Water molecules penetrate into the polymer depending on the water content *relative to saturation level* of the ambient material, see section II. B "Equilibrium and Relative Moisture Content" of this article. Water penetration c then changes the capacity C because of the high relative permittivity of water $\varepsilon_r = 80$, see equation (6). A RC-oscillator measures the change of capacity by a change of frequency.

$$C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot A}{d} \quad \text{and} \quad \varepsilon_r = \varepsilon_i + \varepsilon_w \cdot c \qquad (6)$$
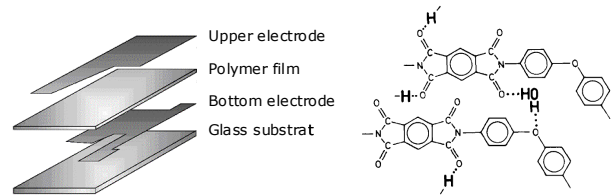

Fig. 4. Schematic drawing of a polymer thin film probe (left) and water in the dielectric attached to polyimide molecules by hydrogen bonds (right)

Other molecules than water may likewise diffuse into the polymer and thus change the capacity, leading to a measurement error. This influence is considered to be small, since e.g. ageing byproducts have a low permittivity compared to water. Beside this it is very easy to calibrate capacitive probes with saturated salt solutions ("Greenspan table").

In this investigation two HMP 228 sensors by Vaisala were used. The average value of both sensors was used for moisture determination. Moisture content relative to saturation level is the intrinsic measurement parameter of this sensor. However the moisture by weight in ppm could be delivered too by an arithmetic equation containing two constants A and B. These constants depend on water saturation level of the oil (e.g. ageing state, pollutions, kind of oil). Therefore to obtain reliable ppm-values the sensor must be calibrated for each oil-paper-system. Because of the different measurement techniques and values there is no direct comparability given to KFT. In this setup only the original measurement value, the moisture content relative to saturation level, that is independent on oil ageing etc. was used.

IV. MOISTURE EQUILIBRIUM DIAGRAMS

A. Conventional Use of Equilibrium Diagrams

For many operators it is common to determine moisture in cellulose by the following method:

1. Sampling of insulation oil under service conditions
2. Water measurement by Karl Fischer titration
3. Deriving moisture in paper via equilibrium diagrams (e.g. by Oommen, Piper, Du, Zahn [2]) from moisture in oil

This procedure is effected by substantial errors:

- Sampling, transportation to laboratory and moisture measurement by KFT
- Validity of diagrams restricted to equilibrium conditions (depending on temperature established after days/months)
- Steep gradient in low moisture region
- Different results using different equilibrium charts (Oommen, Piper, etc. [2])
- Temperature and therefore moisture distribution in transformer winding with gradient of up to 30 K
- Equilibrium depends on moisture absorption capacity

The validity of equilibrium diagrams is restricted to the original materials that were used to establish the diagrams. Especially ageing changes the moisture absorption capacity substantially. The following Fig. 5 displays beside the graphs for equilibrium of new Kraft paper with new oil at 20, 40, 60 and 80°C additionally the moisture equilibrium for other kinds of cellulose and ageing state. Using these curves, that show the equilibrium at 60°C, a moisture in oil of 20 ppm at 60°C leads to a moisture content in new paper of 2,9 %, in new pressboard of 2,6 %, in aged paper and oil it is 2,1 % and for aged pressboard and oil 1,5 %. Because of this the error using equilibrium diagrams not adapted to the material and its ageing state comes easily up to 100 %! Thus they are not applicable to determine moisture in cellulose.
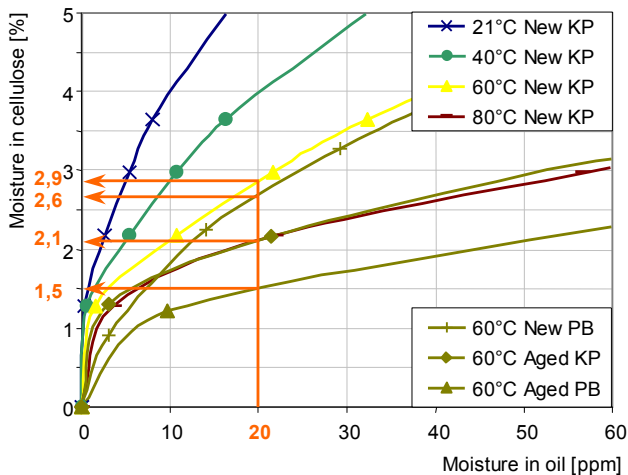

Fig. 5. Equilibrium diagram for moisture in cellulose and oil with additional graphs for different kinds of cellulose and ageing conditions

The changed moisture absorption capacity could easily be explained. Ageing of oil produces alcohols, ketones, aldehydes and acids that *increase* its ability to dissolve moisture. Ageing of paper *decreases* its moisture absorption capacity. During thermal ageing the active parts of the cellulose chains (OH-groups) become attracted to each other. Thus they are no longer able to take up water molecules.

B. Diagrams Adapted to Moisture Absorption Capacity

The first step to improve equilibrium diagrams is to adapt them to the water absorption capacity of the materials involved [6]. The following types of cellulose were explored: pressboard, Kraft insulation paper and thermally upgraded paper. To simulate ageing Kraft paper was thermally degraded by heating at 130-140°C under wet air for 1 week. Beside this service aged pressboard from a transformer manufactured in 1950 was measured. Oil types were new Nynas Nitro 3000, new Shell Diala D and an oil aged by 25 years of service with an neutralization number of 0,13 mg KOH/g oil.

The methodology to establish equilibrium diagrams was derived from the physical law, that the relative moisture content for adjacent materials is equal under equilibrium conditions, see subsection II. B. "Equilibrium and Relative Moisture Content". The ambient medium may

be air or oil, supposed they are at the same temperature and pressure.

Thereto in a first step the relative moisture of air $C_{W,rel,Air}$ in equilibrium with cellulose is measured at different temperatures. The second step comprises in the measurement of the relative moisture in oil $C_{W,rel,Oil}$ at different temperatures. The third step is the combination of both diagrams under the fulfilled requirement, that the relative moisture in air is equal to the relative moisture in oil $C_{W,rel,Air} = C_{W,rel,Oil}$ under equilibrium conditions. This method was firstly used by T.V. Oommen [4].
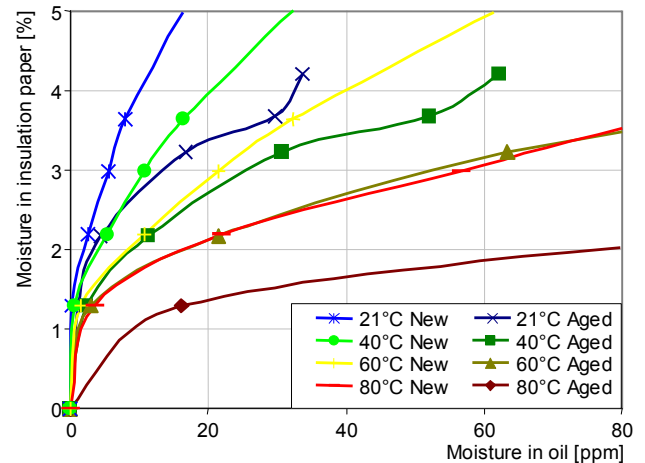

Fig. 6. Adapted equilibrium diagrams for new Kraft paper and new oil and for thermally degraded Kraft paper and aged oil

Fig. 6 shows equilibrium diagrams with insulation temperature as parameter for new Kraft paper and new oil and for thermally degraded Kraft paper and service aged oil. Under new conditions there is no difference in the moisture saturation level for Nynas Nitro 3000 and Shell Diala D (see Fig. 1.), thus one set of curves is valid for both oils together with new Kraft paper. Ageing shifts the curves to the right, since moisture absorption capacity of oil increases hugely. The following figure displays the same behaviour for service aged pressboard and service aged oil.
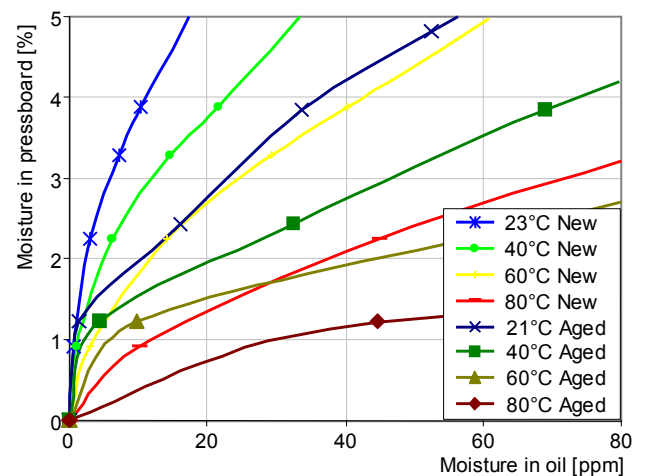

Fig. 7. Adapted equilibrium diagrams for new Pressboard and new oil and for service aged Pressboard and aged oil

Using the equilibrium diagrams depicted above it is possible to determine the "true" water content in cellu-

lose, since they are adopted to the moisture absorption capacity of the materials. They still have the essential drawback, that their validity is restricted to the involved materials. For other materials and ageing condition they have to be adapted. Thus the next step to advanced equilibrium diagrams is described in the following subsection.

C. Advanced Adapted Equilibrium Diagrams

Advanced diagrams derive moisture in cellulose from the *relative* moisture in oil and are adapted to the moisture absorption capacity of cellulose. The following advantages arise:

- Oil ageing and its influence on moisture saturation level becomes negligible, since it is already included into the measurement value.
- Errors due to sampling, transportation to the lab and titration are excluded.
- Capacitive sensors measure the relative moisture in oil continually and are easy to integrate into a monitoring system.

Fig. 8 shows the moisture by weight in new and thermally degraded Kraft paper as a function of relative moisture. With thermal ageing the ability to absorb moisture decreases, as described in section IV.B. The same behavior shows service aged pressboard in Fig. 9. Thermally upgraded paper is not displayed in Fig. 8 since its moisture absorption capacity is similar to that of thermally degraded paper [6].
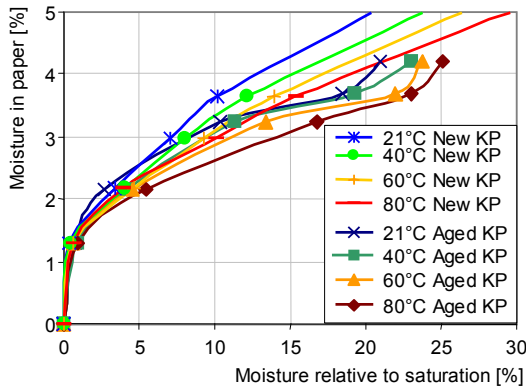

Fig. 8. Moisture in new and thermally degraded Kraft paper at different temperatures
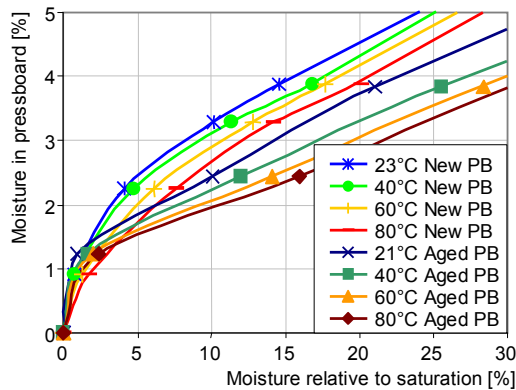

Fig. 9. Moisture in new and service aged pressboard at different temperatures

If relative moisture is displayed on the X-axis (Fig. 8), the graphs are less temperature dependent compared to

moisture by weight on the X-axis (Fig. 6). Furthermore it is obvious, that the relation of relative moisture to moisture by weight in cellulose is not linear but steep for low moisture contents and then rather flat for an increasing moisture content. This behavior is explainable by the way water is attracted to cellulose. The steep gradient is caused by strong chemical bonds, i.e. hydrogen bonds, that attract water molecules in a mono layer. Weaker bonds like Van Der Waals and capillary absorption determine the flat increase above 5 % relative moisture content with multiple layers of water molecules. Fig. 10 gives a qualitative illustration.
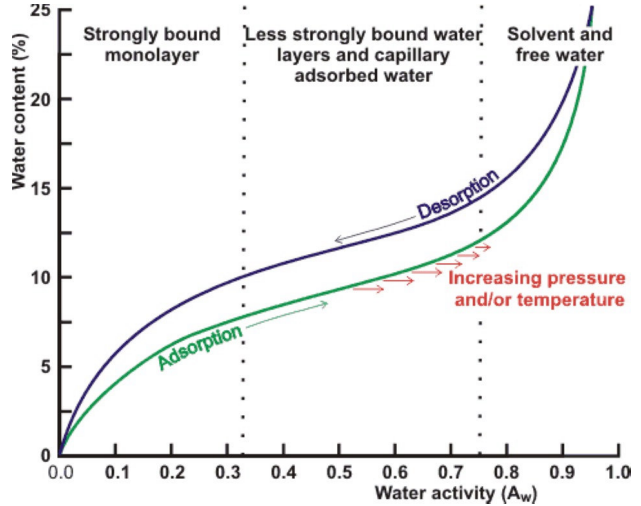

Fig. 10. General moisture adsorption and desorption isotherms with influence of water bonding [7]

D. Application in Online Monitoring Systems

Some transformers are already equipped with capacitive moisture sensors that measure relative moisture and temperature. The progression of temperature could be used to estimate whether equilibrium exists or not. Analytical equations fit the moisture sorption isotherm for different temperatures like depicted in Fig. 8. As an example the following equation fits the isotherm for new paper

$$MW_{20} = 1,22 \ (1 - e^{-RH/0,0745}) + 5,56 \ (1 - e^{-RH/18,06}) \qquad (7)$$

The use of moisture relative to saturation level in oil (%) instead of moisture relative to weight in oil (ppm) in equilibrium diagrams gives some advantages, but the diagrams still have to be adopted to the moisture absorption capacity of the involved cellulose. The next subsection shows the exceptional advantages of active water measurements.

E. Active Water Measurements

Water activity a_w is a critical factor that determines the amount of water available for interactions with materials. A value of unity indicates pure water whereas zero indicates the total absence of water molecules. It is directly related to the relative moisture content, see equation (2). The destructive effects of water in power transformers are:

- Decreased dielectric strength of oil (breakdown voltage, PD inception level)
- Accelerated ageing of cellulose
- Bubble formation at elevated temperatures and wet insulation materials

All the destructive actions of water in power transformers are effected by water molecules, that are available for interactions with materials. This is not the case for molecules that are strongly bound, e.g. by hydrogen bonds to OH-groups of cellulose chains. Unfortunately moisture related to weight, measured by Karl Fischer titration, reflects the bound and inactive water too. Thus the water relative to saturation - not water relative to weight - determines the available water for destructive effects. Using the relative moisture content of oil and of cellulose gives the following advantages:

- Continually, accurate measurement with capacitive sensors
- Easy implementation in monitoring systems
- Neither oil nor paper ageing effects the validity
- Conversion via equilibrium charts unnecessary
- Direct relation to the destructive impacts of water

The following Fig. 11 illustrates the application of the active water measurement in a power transformer equipped with an online monitoring system. The load factor changes the top oil temperature. Because of this diffusion processes change the relative humidity in oil. A long term average equilibrates the relative humidity in oil with the relative humidity in cellulose and comes to $C_{w,rel}$ = 2,6 %. Thus the relative humidity and therefore the active water in the oil-paper-insulation is determined.
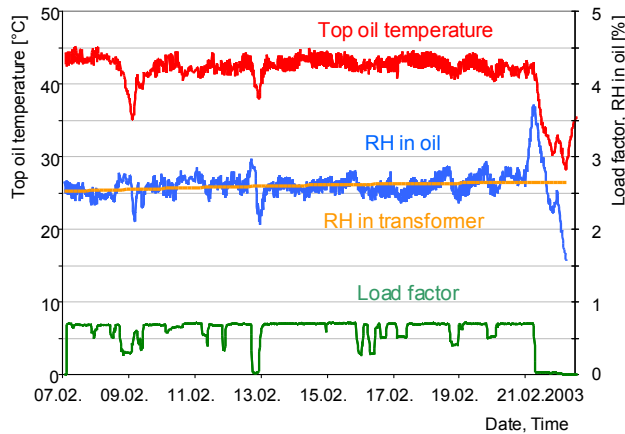

Fig. 11. Load factor, top oil temperature, relative humidity in oil and in cellulose measured resp. calculated by an online monitoring system

V. SUMMARY

Main motivation for this investigation was to determine water in oil-paper-insulated transformers accurate and continuously using equilibrium processes.

- Moisture diffusion and equilibrium depends on the highest possible entropy. This leads to the simple rule, that the *relative* moisture content $C_{W,rel}$ in adjacent materials becomes identical.

- The ability to dissolve water changes especially with ageing of oil. Ageing products such as alcohols, aldehydes, ketones and acids are able to coalesce with water and therefore increase water solubility.
- Ageing shifts the array of equilibrium curves towards oil because of its intense increased water solubility thereby that of cellulose decreases slightly.
- The old method to derive moisture in cellulose (in %) from moisture in oil (in ppm) via equilibrium diagrams is effected by substantial errors.
- Better results can be obtained, if moisture in oil relative to saturation level (in %) is used instead of moisture in oil by weight (in ppm).
- Moisture relative to saturation or water activity is easy, continually and accurate measurable. Online monitoring systems can derive moisture in paper from relative moisture in oil using equilibrium diagrams adapted to the moisture absorption capacity of paper.
- Active water or relative humidity directly reflects the destructive potential of water. It is therefore much more meaningful than the conventionally used water related to weight. Thus water activity is a sufficient indication for water in oil paper insulations. Water activity in paper and pressboard is immediately derivable from relative moisture in oil.

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