Onsite, Online and Post Mortem Insulation Diagnostics at Power Transformers

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SUMMARY

This paper investigates new approaches to determine water in oil-paper-insulated power transformers and conforms diagnostic parameters to post mortem investigations.
The first part of this paper presents a new methodology to measure and characterize moisture in oil-paper-insulations. 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 adsorption 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 moisture determination as relative saturation 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. A practical example illustrates moisture assessment in a power transformer comparing four different methods.
In the second part of the paper some results of post mortem investigations are shown. Material samples have been taken from the winding insulation during scrapping of several transformers. The Degree of Polymerization (DP) and the results of the DGA have been determined and evaluated. This contribution tries to close the gap between the findings during the visual inspection of the active part just before scrapping, the results of the material analysis and parameters which can easily be measured during the life time of the transformer such as DGA und Furanes.

KEYWORDS

Power transformer, moisture, equilibrium, degree of polymerisation, furanes, DGA

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1 INTRODUCTION

Reliable assessment of the actual condition of high voltage power transformers allow for time- and cost-saving maintenance actions. Moisture in cellulose and oil is an ageing indicator and accelerator, decreases the dielectric withstand strength and may generate gaseous bubbles in the liquid insulation. Aging gains importance since utilities keep transformers in service even if the estimated life cycle is exceeded. Hence the number of wet transformers because of aging or even inadequate maintenance increases. Notwithstanding the harmful effects of moisture, the present measurement method based on moisture equilibrium often leads to too high results. Therefore a new onsite and online approach to access moisture in oil, paper and pressboard is introduced in section 2 of this article.
The degree of polymerisation constitutes one of the most important parameters of the insulation condition. The number of joined glucose rings forming a cellulose molecule determines the mechanical strength of an insulation with cellulose materials. The degree of polymerisation decreases from 1000-1500 under new conditions to 200-400 at the end of the cellulose life span, where nearly all the mechanical withstand strength gets lost. Unfortunately an online assessment of this parameter is impossible, but post mortem investigations impressively illustrate the transformers condition and may even judge, whether scrapping was justifiable or not. Comparisons of service to post mortem diagnostics are done in section 3 of this article.
Dissolved gas analysis DGA enables for an integral condition assessment by fault gases dissolved in oil. Even ongoing electrical or thermal errors can be detected. Also here the comparison to post mortem inspections correlate this analysis to the real condition of a transformer.
Furane analysis was introduced in the last decade as a promising method to assess the degree of polymerisation by the furan content in oil. However moisture in cellulose and operation temperature of the special transformer influences the furan production greatly, making general limits subtle. Post mortem investigations can prove here the relevance of this parameter.

2 MOISTURE MEASUREMENT THROUGH MOISTURE EQUILIBRIUM

2.1 Moisture Equilibrium

Moisture equilibrium bases on three conditions: thermal equilibrium (temperature), mechanical equilibrium (e.g. pressure) and chemical equilibrium. Thermodynamic equilibrium is reached, if the macroscopic observables do not change with time *and* place. An equilibrium regarding the time aspect is possible during a constant load period of a transformer. Still the observables will change with place. Equilibrium for time *and* place can be reached only in locally limited areas, e.g. between cellulose and the surrounding oil at high temperatures and slow oil flows.
Moisture equilibrium means, that the no migration of water molecules inside materials and between oil and cellulose occurs. Moisture migrates until the water vapour pressure p gains the same value, thus differences in the moisture vapour pressure are the driving force for moisture migration, (1).

$$p_{Cellulose} = p_{Oil} = p_{Air} \qquad (1)$$

Supposed the same temperature and pressure rules, moisture exchange can be described in terms of relative saturation. The moisture content relative to saturation level in adjacent materials becomes equal (2). The material might be cellulose, oil, air or even a plastic.

$$RS_{Cellulose} = RS_{Oil} = RH_{Air} \qquad (2)$$

2.2 Conventional Equilibrium Diagrams

It is a standard procedure for operators of power transformers to derive the moisture by weight (%) in cellulose from the moisture by weight in oil (ppm). This approach consists of three steps: (1) Sampling of oil under service conditions, (2) Measurement of water content by Karl Fischer Titration and (3) Deriving moisture content in paper via equilibrium diagrams (e.g. [1], [2]) from moisture in oil.
Unfortunately this procedure is affected by crucial errors:

- Sampling, transportation to the laboratory and moisture measurement by Karl Fischer titration,
- Equilibrium conditions are rarely achieved (depending on temperature after hours/days/months),

- A steep gradient and high uncertainty in the low moisture region compounds the accuracy,
- Diagrams from various literature sources lead to different results,
- The temperature gradient in windings (up to 30 K) causes a uneven moisture distribution,
- Equilibrium depends on moisture solubility in oil and moisture adsorption capacity of cellulose.

The validity of equilibrium diagrams is restricted to the original materials that were used to establish the diagrams. Especially aging changes the moisture adsorption capacity substantially. The following Figure 1 (left) displays the graphs for equilibrium of new Kraft paper with new oil at 20, 40, 60 and 80°C. Additionally for 60°C it shows moisture equilibrium for new pressboard in new oil and for aged Kraft paper and aged pressboard in aged oil. Assumed the moisture content in oil is 20 ppm these curves lead to a moisture content in new paper of 2,9 %, in new pressboard of 2,6 %, in aged paper and aged oil it is 2,1 % and for aged pressboard and aged oil 1,5 %. Thus equilibrium diagrams not adapted to the specific materials are inapplicable to calculate moisture in paper from moisture in oil.

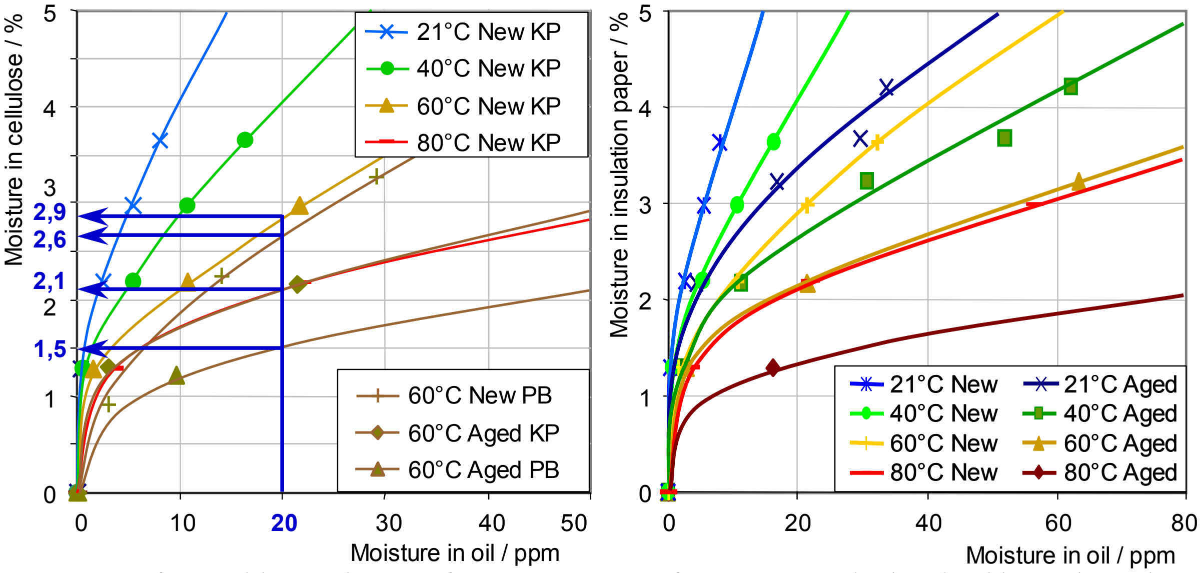


Figure 1. Left: Equilibrium diagram for moisture in Kraft paper KP and oil with additional graphs for new pressboard PB and aged kraft paper and pressboard
Right: Equilibrium diagrams adapted to the moisture adsorption capacity of new Kraft paper in new oil and of thermally degraded Kraft paper in aged oil

2.3 Diagrams Adapted to the Moisture Adsorption Capacity

The first step to improve equilibrium diagrams is to adapt them to the water adsorption capacity of the materials involved [3]. Diagrams as Figure 1 (right) might be used to determine the "true" water content in cellulose, since they are adopted to the moisture adsorption capacity of the materials. They still have the essential drawback, that their validity is restricted to the involved materials. For other materials and ageing conditions they have to be redrawn, that is, a correction is necessary for every transformer with its special materials and aging conditions. Because of this disadvantage the following subsection describes the next step to more universal equilibrium diagrams.

2.4 Measurement via Moisture Saturation of Oil

In this approach instead of moisture in oil relative to weight (ppm) the relative saturation in oil (%) is used. Additionally the diagrams are adapted to the moisture adsorption capacity of the cellulose. Based on equation (2) via moisture adsorption isotherms the moisture content in cellulose is derived from moisture relative to saturation of the surrounding oil. The advantages are:

- Oil aging and its influence on moisture saturation level becomes negligible, since it is already included into the measurement of moisture saturation.
- With relative moisture on the X-axis the graphs become less temperature dependent compared to moisture by weight on this axis (Figure 2, right)
- Errors due to sampling, transportation to the lab and titration are excluded.

- Continual, accurate measurement and easy implementation into a monitoring systems

Figure 2 (right) shows moisture by weight in thermally degraded Kraft paper as a function of moisture saturation. With thermal aging the ability of cellulose to adsorb moisture decreases. In this example a relative to saturation of 4,1 % at 47°C oil temperature gives in Kraft paper 2,2 % moisture content relative to weight. The approach to use moisture saturation of oil substantially improves moisture determination in transformers, still the diagrams have to be adopted to the moisture adsorption capacity of the specific cellulose material. The next section shows a way to overcome this drawback.

2.5 Measurement and Implementation of Moisture Saturation in Cellulose

Moisture saturation is a critical factor that determines the amount of water available for interactions with materials. The destructive effects of water in power transformers are a decreased breakdown strength of oil, accelerated aging of cellulose and bubble formation. All these destructive effects are caused 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 molecules forming a monolayer. Just water relative to weight, measured by Karl Fischer titration, reflects the bound and less active water too. Moisture relative to saturation - not relative to weight - determines the available water for destructive effects. This approach gives the following advantages:

- Neither oil nor paper aging effects the validity
- Conversion via equilibrium charts unnecessary
- Direct relation to the destructive impacts of water
- Continually, accurate measurement and easy implementation into a monitoring systems

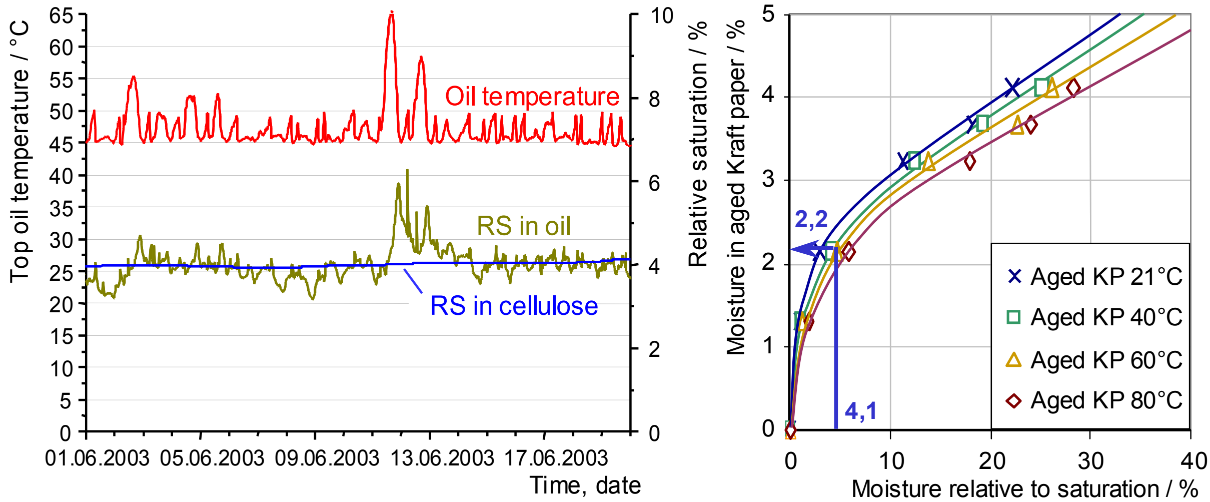


Figure 2. Left: Top oil temperature, relative saturation in oil and in cellulose measured resp. calculated by an online monitoring system
Right: Determination of water content in thermally degraded Kraft paper via a moisture adsorption isotherm

Figure 2 (left) illustrates the application of a relative saturation measurement using a capacitive probe in a power transformer equipped with an online monitoring system. The load factor influences the top oil temperature, which follows in diffusion processes changing the relative saturation in oil. A long term average equilibrates the relative saturation in oil with the relative saturation of the surrounding cellulose and comes to 4,1 %. Using a moisture isotherm as Figure 2 (right) one can derive the moisture by weight in cellulose too, that would be 2,2 % in this case. Obviously the obtained results gain in reliability, if the probe is inserted into the hot oil flow before the cooler or as close as possible to the winding.

2.6 Example of an Onsite Moisture Evaluation

The practical example of a net coupling transformer from 1967, having 133 MVA, OFAF cooling and 230/115/48°kV shall demonstrate the moisture assessment procedure. Based on the moisture content in cellulose the transformer should be dried and transported to another substation or even scheduled for scrapping. Three measurement methods were applied: firstly moisture equilibrium based on relative moisture in oil, secondly moisture equilibrium based on moisture by weight (ppm) in oil, thirdly the dielectric response method frequency domain spectroscopy FDS with evaluation software "Dirana" [4]. The relative saturation of the oil was directly measured onsite in the transformer oil by a capacitive probe showing 10,1 % at 29°C. By applying the equilibrium diagram of Figure 2 (right) this leads to a moisture in paper of 3 %. Karl Fischer titration in the laboratory gave 19 ppm, the equilibrium diagram of [1] lead to 4,4 % moisture in the solid insulation. The dielectric measurements with "Dirana"-analysis came to 2,5 % for the HV-LV insulation, 3,8 % for the LV-TV insulation and 3.9 % for the TV-tank insulation. A possible explanation for the high moisture content in the tertiary winding insulation is, that this winding was not in service and accumulated more water than the other insulation structures. The result obtained from relative saturation in oil gives a good average of both dielectric measurements, since it represents an integral moisture parameter (Figure 3). The far too high result given by the conventional equilibrium diagram [1] points out the incapability of this approach to assess water in the solid insulation.

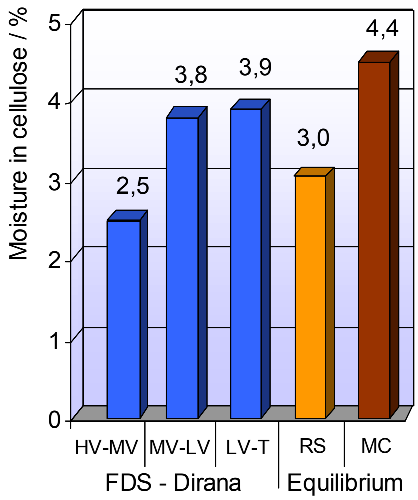


Figure 3. Moisture analysis results obtained from dielectric response method, moisture saturation (RS) and moisture relative to weight (MC)

3 POSTMORTEM INVESTIGATIONS

3.1 Investigation of material samples from aged power transformers

In a cooperate research project of the IEH Karlsruhe, utilities, power stations and a manufacturer material samples of the paper insulation and transformer board have been taken out of the active part of power transformers during scrapping. Main aim of the investigation of aged material samples is the establishment of a correlation between DP (Degree of Polymerization) and the content of furanes in the oil. Another aim is to get some information about the ageing behaviour of individual transformer populations e.g. for generator transformers.
Taking material samples requires keeping the costs for analysing the material samples as well as the effort required for taking the samples within reasonable limits. For that reason, the number and location of samples must be chosen with care and reasonably limited.

One of the results of the research project was the development of a method for the evaluation of the DP values. Thereby, some basics of statistics must be considered. The following equations are used for the calculation of estimates x_m for the mean value. The empiric mean value is x_m the arithmetic mean value of the N individual DP values x_k.

$$\mu \approx x_m = \frac{1}{N} \cdot \sum_{k=1}^{N} x_k \qquad (3)$$

Now, a method for choosing the location for sampling has to be defined. For example, if more samples from the upper winding end in comparison to the rest of the winding are used for the calculation of the statistical quantities, then the low DP values are over-proportionally weighted. This results in a shift of the mean value x_m towards lower values. Thus, only those samples are taken into consideration for the calculation of statistical quantities which are taken in equidistant locations along the winding, e. g. at 0, 25, 50, 75 and 100 % of the winding length. Basically, in the case of a layer winding material samples should be taken from each layer at these equidistant heights. However, this might be difficult. Especially if there are more than 4 layers, the access to the inner layers is usually very difficult. Thus, sometimes only at the inner and the outer layer material samples can be taken.

3.2 Investigation of a 110 MVA generator transformer

The investigated generator transformer manufactured in 1970 was scrapped in 2005. During the visual inspection, a severe thermal stress of the LV winding could be observed. Paper layers in the main insulation channel which were in direct contact to the winding as well as the paper insulation of the copper conductors have been totally blackened. The enamel of the copper conductors was burned at the upper third of the LV winding and split easily when the paper insulation was removed from the conductor (Figure 4). The copper itself showed a yellow colour indicating a high thermal stress of the conductors at the upper part of the LV winding. The paper insulation was extremely brittle and crumbled at the slightest touch, especially in the upper part of the winding. Obviously, the transformer was extremely loaded and thermally stressed and has reached the end of its life-time some time ago at the date of scrapping.

The paper insulation of the outer layer of the HV winding was in a much better condition. Blackening could be observed only at the upper cooling ducts. This gives some evidence that the inner layers of the HV winding have been stronger thermally stressed. The copper of the HV winding showed its typical colour and also the enamel coating was in good condition. Obviously, the HV winding was not so heavily stressed in comparison to the LV winding.

The result of the DP analysis of material samples is shown in Figure 4b. The lowest DP value occurs at about 75 % of the winding length and not at the top of the winding in the case of the LV as well as of the HV winding. Obviously, the hot spot does not occur at the top of the winding. The DP values of the first barrier consisting of several paper layers are somewhat higher than those of the paper insulation of the winding itself. This is confirmed by the light-brown color of the barrier paper. The DP value of 440 determined for the mid of the barrier is with high probability incorrect, a more trustable value can be determined by interpolation between 300 and 160.

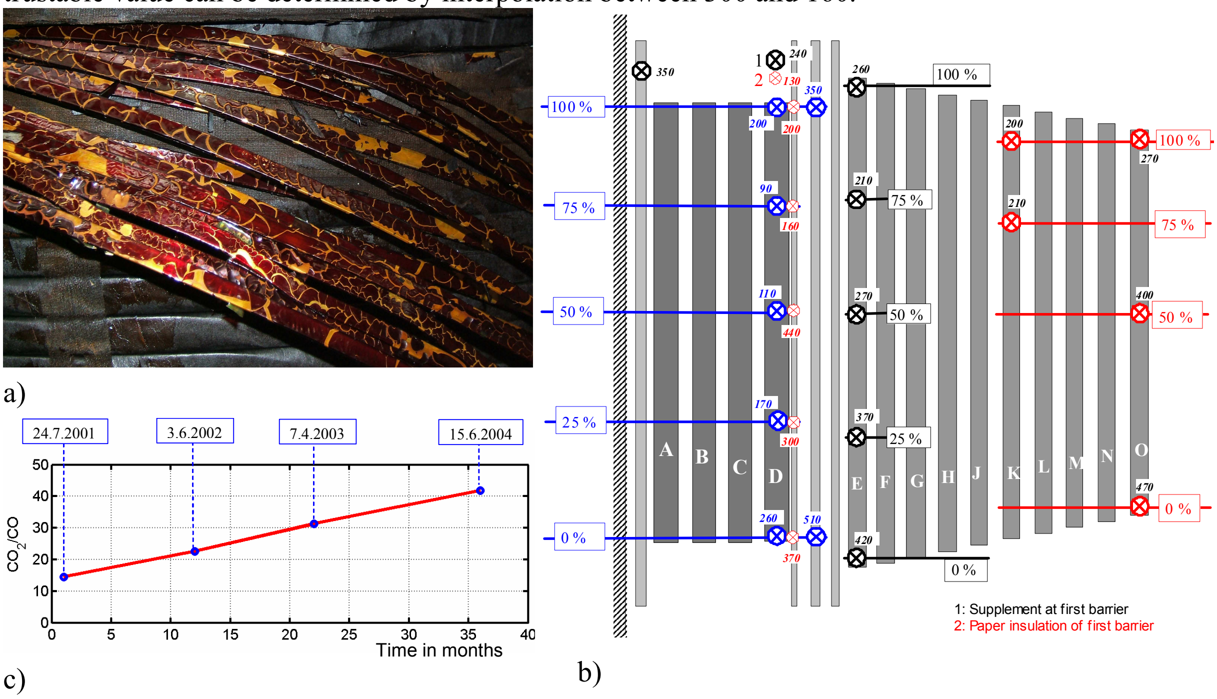


Figure 4. a. Conductor with crumbled enamel coating at the LV winding of a 110 MVA generator transformer
b. Winding assembly of the investigated 110 MVA generator transformer and DP values determined at the locations given in the sketch
c. Development of the ratio CO_2/CO during the last years of service of the 110 MVA generator transformer

The following limits can be used for the evaluation of DP analysis:

- DP ≥ 1000: Cellulose is as good as new
- DP ≤ 200: Cellulose is unusable due to ageing processes

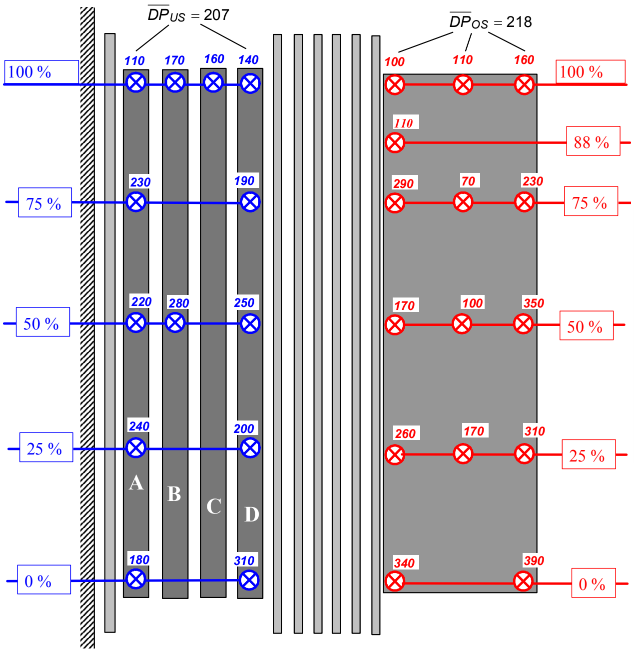
Some of the DP values taken from samples of the LV winding are below the limit of 200. Obviously, at the time of decommissioning of the transformer, the paper insulation was already heavily aged. The DP values at some locations at the upper end of the HV winding are also not much higher than the limit. The maximum DP (510) was found at the lower end of the transformer board barrier between HV and LV. Using the described method for the calculation of mean DP values the following results are obtained for the mean values of LV and HV winding and the paper insulation in total:

$$\overline{DP}_{LV} = \frac{1}{N} \cdot \sum_{Layer\,D} DP_{LV,j} \approx 166 \qquad \overline{DP}_{HV} = \frac{1}{N} \cdot \sum_{Layers\,E,O} DP_{HV,j} \approx 334 \qquad \overline{DP}_{Windings} = \frac{1}{2} \cdot \left(\overline{DP}_{HV} + \overline{DP}_{LV}\right) = 250$$

The minimum DP value of 90 was found at the outer Layer of the LV winding (layer D).
The DGA and the analysis of Furanes in the oil provided the following results. The ratio CO_2/CO showed an almost linearly increase during the last year of service. According to the standards a value above 10 for the ratio CO_2/CO indicates noteworthy ageing of the cellulose. In the present case the ratio has been increased up to about 40 (Figure 4c). This seems to be a clear indicator for severely aged or even burned cellulose.
The analysis showed also an increasing tendency during the last years of service. An oil sample taken on 8.10.2000 gave a 2-FAL content of 1.28 ppm whereas the analysis 4 years later on 13.9.2004 provided 2.2 ppm.
Aim of the further research activities is to establish a correlation between DP and content of Furans in the oil. Such a correlation would open the possibility to assess the solid insulation material by a simple method, since taking an oil sample from the transformer is relatively easy and cheap compared with other methods.

3.3 Investigation of a 380 MVA generator transformer

The core-and-coil assembly of the 380 MVA power transformers manufactured in 1971 showed no mechanical deformations or other highlights. The paper insulation of the conductors was dark-brown coloured and had mostly a firm structure. The area around the HV and LV winding leads was blackened due to a high thermal stress. Further sludge was found around the winding leads. Figure 5 shows a cross-section of the winding arrangement with the locations from where the material samples have been taken and the DP values of the material samples.



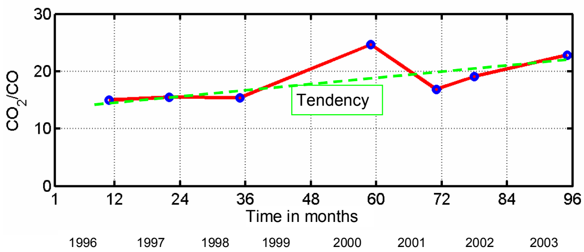


Figure 5. Principle winding arrangement of the 380 MVA generator transformer manufactured in 1971 with the locations of the material samples and their DP values

The LV winding was a 4 layer winding. Due to the thickness of the conductors only the outer layers were accessible. The HV winding was a disc winding. Samples could be taken at the inner and outer diameter as well as in the middle of the winding. The lowest DP value of 70 was found in the middle of the HV winding at 75 % of the winding length. This seems to be plausible since the disc winding had only axial oil ducts. Thus, the cooling of the HV winding, especially in the middle was not as effective as the cooling ducts of the LV winding. Again, the hot spot did not occur at the top of the winding but at about 75 % of the winding length. Using the described method for choosing the locations of the material samples the results are

$$\overline{DP}_{LV} = \frac{1}{10} \cdot \sum_{Layers\,A,D} DP_{LV,k} = 207 \qquad \overline{DP}_{HV} = \frac{1}{14} \cdot \sum_{k=1}^{14} DP_{HV,k} \approx 218 \qquad \overline{DP}_{Windings} = \frac{1}{2} \cdot \left(\overline{DP}_{HV} + \overline{DP}_{LV} \right) \approx 212$$

Obviously, the windings of the 380 MVA transformer were aged equally. This proves the good thermal design of the transformer. The mean DP values of both windings lie only a little beyond the limit of 200. The minimum DP found in the transformer of 70 as well as the mean values give clear evidence that the transformer has reached the end of its life-time at the time of decommissioning.
The 380 MVA transformer shows again the increasing tendency of the CO_2/CO ratio. However, the values of the ratio are maximum at about 20 compared with 40 for the 110 MVA transformer. Furthermore, the rate of rise is much smaller for the 380 MVA transformer. The insulation paper of the 380 MVA transformer was not carbonized. Obviously, it was not as heavy thermally stressed as the 110 MVA transformer. Maybe it is possible to use the CO2/CO ratio and its development over the time for the assessment of the paper condition, especially for the detection of heavy thermal stresses.
In the case of the 380 MVA transformer a content of Furanes of 4.41 ppm was detected in a sample taken on 13.11.2003 (operation with full load) and of 4.63 ppm in a sample from 25.7.2005 (directly after decommissioning).

4 SUMMARY AND CONCLUSIONS

The conventional application of equilibrium diagrams to derive moisture in cellulose (%) from moisture in oil (ppm) is effected by substantial errors. To exclude the interference due to oil aging the moisture in oil relative to saturation level (%) is more appropriated instead of moisture in oil in ppm. Online monitoring systems can derive moisture in paper from relative moisture in oil using equilibrium diagrams adapted to the moisture adsorption capacity of paper. One step forward constitutes the use of moisture relative to saturation in oil *and* cellulose. This measure is easy, continually and accurate measurable. Moreover it directly reflects the destructive potential of water.

Main aim of investigations of insulation material samples taken from aged power transformers is the establishment of a correlation between DP (Degree of Polymerization) and the content of furanes in the oil. A method for the systematic material sampling was developed. The DP values of aged power transformers show a behaviour which is in good correlation with the thermal stress in the winding. The CO_2/CO quotient could be used as a quantity which allows to detect the degree of carbonization of the insulation paper.

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