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Comparing Various Moisture Determination Methods for Power Transformers

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SUMMARY

This paper discusses and compares various methods of assessing moisture in the liquid and solid insulation of power transformers. Water in oil-paper-insulations causes three damaging effects: it decreases the dielectric withstand strength, accelerates cellulose aging and causes the emission of gaseous bubbles at high temperatures. Therefore knowledge about the moisture concentration in a transformer is of great importance for safe operation and for further maintenance actions.

On-line, on-site and off-site moisture determination methods have been compared: Karl Fischer titration applied to oil and paper samples, capacitive probes, equilibrium diagrams and dielectric response methods (Recovery Voltage Method RVM, Polarisation and Depolarisation Currents PDC, Frequency Domain Spectroscopy FDS).

The traditional method of moisture evaluation, oil sampling with subsequent Karl Fischer titration and application of an equilibrium diagram, suffers from severe errors resulting into a poor accuracy. Therefore a new type of equilibrium diagrams based on moisture saturation in the oil (relative humidity) was developed.

For dielectric response methods, the recovery voltage method is now outdated since its interpretation scheme appeared to be unable for compensating the interfacial polarisation effect and oil conductivity. In contrast to this, the new methods polarisation and depolarisation currents and frequency domain spectroscopy feature scientifically founded interpretation schemes and are thus able to reliably calculate water in the solid insulation. In this article a new approach is applied, which combines measurements in time and frequency domain for shortening the time duration. Its software also compensates for conductive aging by-products.

The methods were applied to several transformers for on-site moisture evaluation comparing conventional to new approaches. For new transformers, the analysis of the dielectric response suits best since moisture equilibrium cannot be expected directly after the manufacturing process. However, due to the dry condition particularly the measurement of the low frequencies is of importance (e.g. down to 100 µHz). The study case on oil processing impressively illustrates that most of the moisture is in the solid insulation and for drying purposes the cellulose needs to be treated. Another transformer was dried using on-line oil circulation for 1.5 years, resulting in a decrease of moisture content by about 1.2 % and therefore a longer life expectation. Moisture determination for a heavily aged transformer indicates that the methods and algorithms not taking into account the aging state will overestimate the moisture content. This may lead to wrong maintenance decisions.

Equilibrium diagrams based on moisture saturation in oil delivered credible results in contrast to the conventional use of moisture content (ppm). Within this work the developed dielectric analysis software proved its capability to compensate for conductive aging by-products and provide dependable results for moisture assessment of power transformers.

KEYWORDS

Power Transformer, Moisture Determination, Karl Fischer Titration, Capacitive Sensor, Water Saturation, Dielectric Response, Frequency Domain Spectroscopy

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1 MOISTURE WITHIN TRANSFORMER INSULATION SYSTEMS

Three reasons increased the interest of the international HV community in the moisture contamination of oil-paper-insulated power transformers: the number of aged and possibly wet assets grows, secondly power utilities apply condition based maintenance practices and thirdly new measurement techniques like dielectric response and capacitive sensors became available.
Moisture in the solid and liquid insulation decreases the dielectric withstand strength, accelerates cellulose decomposition and causes the emission of bubbles at high temperatures. Therefore reliable knowledge of the moisture concentration is of high importance for a safe service and long lifespan of power transformers as well as for dependable maintenance decisions. Different approaches are used today to assess this parameter. This article briefly presents these methods, gives comments on application and interpretation and compares them on various case studies where also paper samples were taken.

2 MOISTURE DETERMINATION METHODS

2.1 Karl Fischer Titration

Karl Fischer titration is a method in analytical chemistry that determines trace amounts of water in a sample using volumetric or coulometric titration. Titration basically means to add a reagent of known concentration (titre) to an unknown substance until the concentrations are balanced.
To evaluate the moisture content in the liquid and solid insulation the titration according to Karl Fischer is not only widely used, but also serves as a benchmark for other methods such as dielectric response methods.
However, it is affected by several influences: There is always moisture ingress from the atmosphere during sampling, transportation and sample preparation. Cellulose binds water with chemical bonds of different strengths. It is uncertain whether the thermal energy releases all the water, therefore heating temperature and time certainly changes the released water. Individual laboratories treat differently constraints that are not covered by standards, such as the solvent for oil extraction. Sometimes direct injection and heating method lead to different results for moisture in oil.
For these reasons round robin tests revealed an unsatisfactory comparability of different laboratories [1].
Conclusively, whenever Karl Fischer titration is used to evaluate other methods, their inherent inaccuracy needs to be considered. This particularly applies if paper samples taken from a transformer are used to judge the results of new approaches like dielectric response or equilibrium diagrams, or when comparing between new methods.

2.2 Capacitive Probes

Capacitive probes have been in use since the mid-nineties and indicate moisture relative to saturation. They consist of two electrodes with a hydroscopic dielectric, e.g. a polymer, see Fig. 1. Water molecules penetrate into the polymer and change the capacitance depending on the relative saturation of the ambient material. This change of capacitance correlates with the surrounding relative humidity. Advantages of capacitive probes are very easy application even on-site and on-line, continuous measurements and high accuracy compared to sampling and transportation to laboratory with subsequent Karl Fischer Titration.

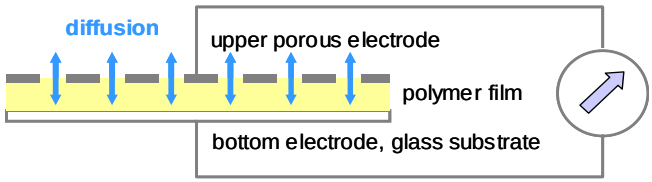

Fig. 1: Polymer thin film probe

In the last years discussions frequently flared up about the reliability of Karl Fischer titration in comparison with capacitive probes. Some transformer operators listed significant differences between the moisture by weight (ppm) results from Karl Fischer titration and capacitive probes or other instruments based on moisture equilibrium. However, due to the different measurement principles (chemical reaction vs. moisture deposition) a comparison is impossible without calibrating one method to the other.

2.3 Moisture Determination by Equilibrium

Deriving the moisture content (%) in cellulose from the moisture content in oil (ppm) is a standard procedure for operators of power transformers. 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.[2]) from moisture in oil.
Unfortunately this procedure is affected by crucial errors, which are, firstly, sampling, transportation to the laboratory and Karl Fischer titration. Secondly, equilibrium conditions are rarely achieved (depending on temperature after hours/days/months). Thirdly, a steep gradient and high uncertainty in the low moisture region compounds the accuracy. Finally, 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. Particularly aging of oil changes its moisture adsorption capacity substantially. This is shown in Fig. 2 (left), where beside the graphs for moisture equilibrium of new Kraft paper the curves for aged Kraft paper and aged pressboard are depicted. Assuming 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 material and its aging state are inapplicable to calculate moisture in paper from moisture in oil.

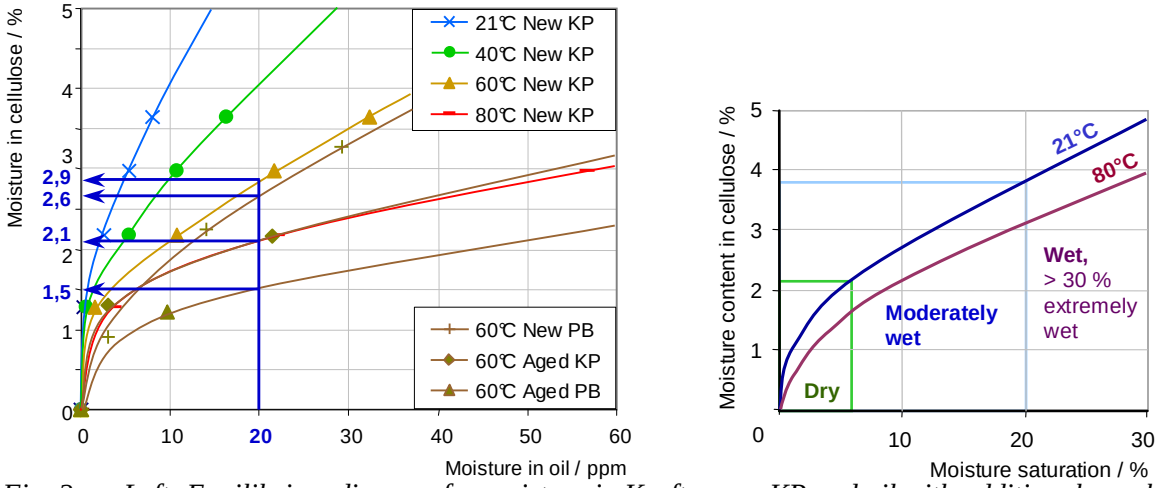

Fig. 2: Left: Equilibrium diagram for moisture in Kraft paper KP and oil with additional graphs for new pressboard PB and thermally degraded Kraft paper and aged pressboard
Right: Equilibrium diagram based on relative saturation in oil with limits of IEC60422

A new approach of equilibrium diagrams uses the relative saturation (relative humidity) in the oil instead of the moisture content (Fig. 2, right). As a major advantage the aging of oil becomes now negligible and the measurement can be performed on-line, leading to much more accurate results [3].

2.4 Dielectric Response Methods

Dielectric diagnostic methods deduce moisture in paper or pressboard from dielectric properties like return voltage, polarisation and depolarisation currents and dissipation factor. Primary motivations for the development of dielectric response methods were the lack of methods for on-site moisture assessment in power transformers and the disappointing results of the hitherto used conventional equilibrium approach.

2.4.1 Recovery Voltage Method RVM

Here a voltmeter determines the recovery voltage after charging the insulation with a DC voltage. By subsequent relaxation and repeated charging for varied times the so called “polarisation spectrum” can be created [4]. The CIGRÈ TF D1.01.09 concluded in 2004: "For the RVM technique, the old interpretation based only on simple relationship between the dominant time constant of the polarisation spectrum and the water content in cellulose is not correct", [5]. Subsequently two improved dielectric response methods were developed: the polarisation and depolarisation currents PDC [6] and the frequency domain spectroscopy FDS, and [7].

2.4.2 Polarisation and Depolarisation Currents PDC

A time domain current measurement records the charging and discharging currents of the insulation. They are usually called Polarisation and Depolarisation Currents PDC. Fig. 3 (left) depicts the shape and common interpretation of a PDC measurement.

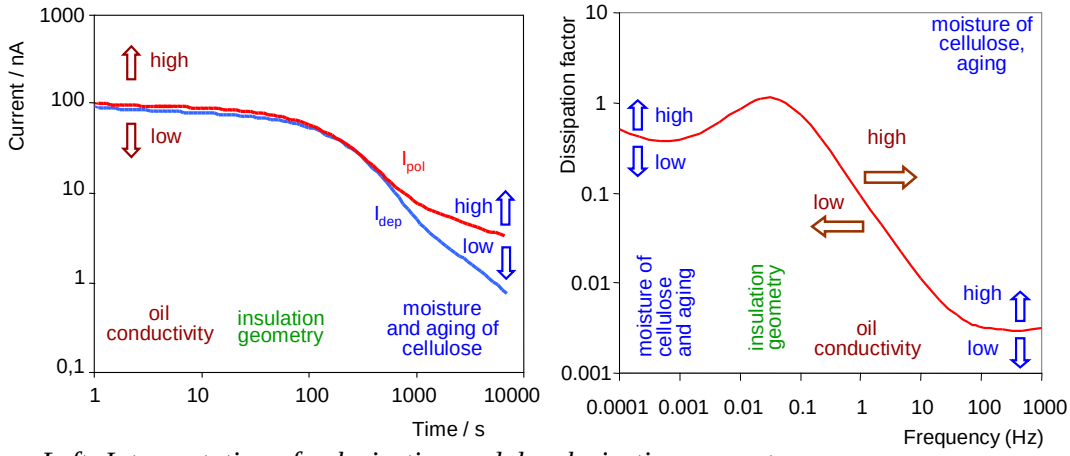

Fig. 3: Left: Interpretation of polarisation and depolarisation currents, Right: Interpretation of the dissipation factor vs. frequency of an oil-paper-insulation

2.4.3 Frequency Domain Spectroscopy FDS

Frequency domain measurements are derived from old known dissipation factor measurements, yet with a frequency range particularly enhanced for low frequencies. The derived measurement method is called Frequency Domain Spectroscopy FDS. Fig. 3 (right) shows the typical s-shaped curve of the dissipation factor via frequency and the scientifically agreed interpretation scheme for a power transformer.

2.4.4 Combining Time and Frequency Domain Measurements

A new approach combines the advantages of the polarization current measurement method in time domain with the frequency domain spectroscopy and thus significantly reduces the testing time compared to existing techniques [8]. Essentially, time domain measurements can be accomplished in a short time but are limited to low frequencies. In contrast, frequency domain measurements are feasible for high frequencies but take very long time at low frequencies. Combining both methods reduces the measuring duration by 50-75 % compared to exclusive frequency domain measurements. Fig. 4 compares the required time duration and acquired frequency range for the measurement techniques in frequency and time domain and their combination.

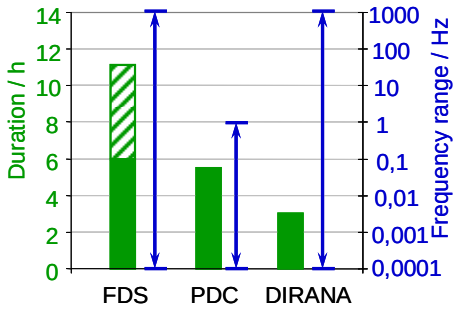

Fig. 4: Time duration and frequency range in frequency and time domain and their combination (FDS, PDC, Dirana)

3 STUDY CASES OF VARIOUS TRANSFORMERS

3.1 Assessment of New Transformers in the Factory

With the awareness of the hazardous effects of moisture the demand to receive new transformers in dry condition increases. Therefore the moisture content in the solid insulation of two new transformers was evaluated with dielectric response measurements in the factory. Fig. 5 (left) depicts the dielectric response in the representation of dissipation factor over frequency. Transformer A shows much lower losses than transformer B, so from a first glance at the dissipation factor one may conclude that the second transformer is in a worse condition. However, a closer look at the dielectric response of transformer B reveals low losses at the very low frequencies below 1 mHz. This is important, since that region is very sensitive to moisture (Fig. 3). Moisture analysis software actually determined the moisture content in the cellulosic insulation of both transformers to be 0.4 %, which is a very low value. The difference in the dissipation factor curve comes not from moisture but from different conductivities of the insulation oils (0.05 pS/m for transformer A, 0.94 pS/m for transformer B).

The example illustrates that particularly for new transformers the very low frequencies, which reflect the condition of the solid insulation, are important for moisture analysis using dielectric response methods. Limiting the frequency range would make the discrimination between the different condition of oil and cellulose impossible.

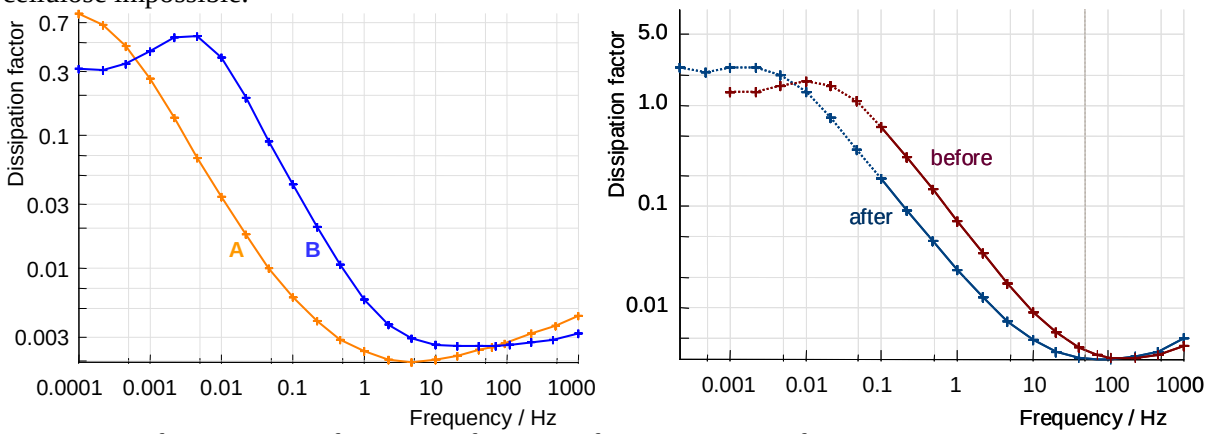

Fig. 5: Left: Dissipation factor over frequency for two new transformers
Right: Dielectric response of a GSU transformer before and after oil processing

3.2 Effect of Oil Processing

For a 480 MVA, 230 kV GSU transformer the oil was processed with heat (50°C) and vacuum. Fig. 5 (right) depicts the dissipation factor versus frequency before and, seven months later, after oil processing, in both conditions for similar temperatures. From automated analysis [8] it appeared, that the oil conductivity decreased from 11 to 2.7 pS/m. However the moisture content remained the same with 1.8 % before and 1.7 % after oil processing. Because of the hydrophilic nature of cellulose, the solid insulation stores 200 times more water than the liquid insulation. Thus oil drying or replacement will not improve the overall moisture condition.

3.3 On-Line Drying of a Power Transformer

A three winding transformer with 150 MVA was dried on-line by continuous oil circulation for a period of 1.5 years and the moisture assessed before and after drying. Three moisture measurement methods were applied before drying: Dielectric response measurement, an equilibrium diagram based on moisture content in oil [2] and an equilibrium diagram based on relative saturation in oil [3]. Fig. 6 depicts the moisture content in the solid insulation as obtained by the various methods before and after drying. The dielectric response method came to a result of 2.5 % for the main insulation.

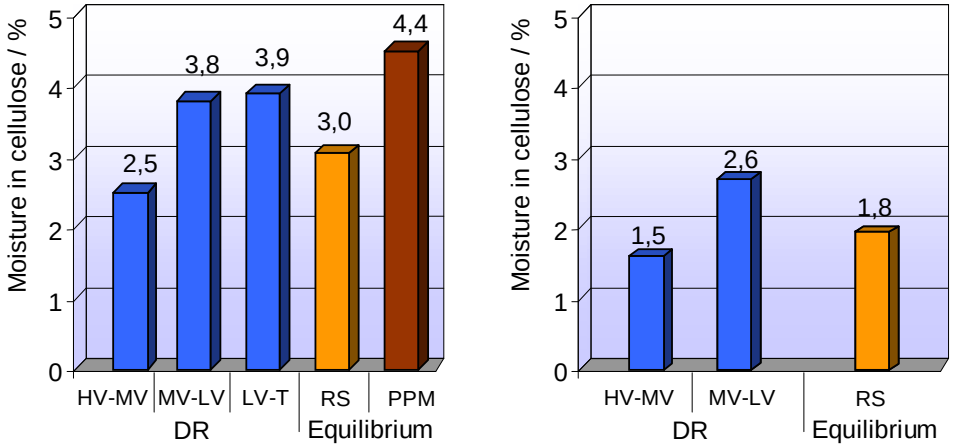

Fig. 6: Moisture content in the solid insulation before drying (left) and thereafter (right), as obtained from dielectric response analysis (DR) and via equilibrium diagrams from the relative saturation of oil (RS) and from moisture content in oil (PPM)

The insulation of the tertiary winding seems to be moister, which agrees with the service conditions of the transformer: the LV winding was not in use. Cellulose at lower temperatures stores the water in a transformer. Thus the dielectric methods allow for an elementary localization of wet areas in the insulation. In difference this; the moisture content in cellulose as derived from oil samples gives an average

value for the all cellulose structures in contact with oil. The result obtained from a relative saturation in oil is 3.0 % and agrees well with the average of the dielectric response analysis. The conventional equilibrium approach based on moisture content in oil (ppm) gives a very high result of 4.4 %. Aging of oil and paper makes the application of equilibrium diagrams from literature sources impossible in many cases.
After moisture assessment an on-line oil circulation for 1.5 years dried the transformer. This process decreased the moisture content in the solid insulation by about 1.2 %, which extends the life span of the solid insulation (Fig. 6, right).

3.4 Moisture Determination for a Heavily Aged Transformer

A heavily aged transformer with 30 MVA, built in 1950, was designated for scrapping. Paper and oil samples were taken out after measuring the dielectric response (polarization and depolarization currents as well as frequency domain spectroscopy).
Fig. 7 compares the results of the moisture determination techniques. Karl Fischer titration on paper samples yielded 2.6 % moisture by weight (KFT). Results of the modelling of the dielectric response measurements by means of different software differ from each other: Two algorithms (DA1, DA2) had no compensation for the influence of conductive aging products and came to 3.8 and 4 % moisture by weight. Another algorithm (DA3) with build-in compensation for conductive aging products [8] indicates 2.9 % moisture relative to weight.
In the oil sample the moisture saturation was measured directly onsite and the moisture content in ppm by Karl Fischer titration in a laboratory. An equilibrium diagram based on relative saturation led to 2.5 % of moisture in cellulose (RS), which well agrees with the KFT analysis of the paper samples and the dielectric response analysis with compensation for conductive aging products. At the same time, direct application of equilibrium curves, based on moisture content in oil in ppm, indicated much too high content of moisture in paper – 6.0 %.

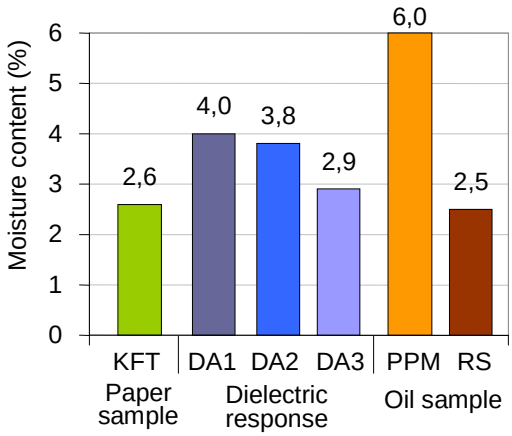

Fig. 7: Moisture content in the solid insulation obtained from Karl Fischer titration of paper samples (KFT), dielectric response analysis (DA1, DA2, DA3) and from equilibrium diagrams for moisture content in oil (PPM) and from the relative saturation (RS).

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