A Comparative Test and Consequent Improvements on Dielectric Response Methods

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Abstract: This paper starts with a systematic benchmark test of the three commercialised dielectric diagnostic methods RVM (recovery voltage method), PDC (polarisation and depolarisation currents) and FDS (frequency domain spectroscopy), performed on a large transformer model. The water content as analysed by the specific software was compared under three parameters: insulation geometry, insulation temperature and oil conductivity. It was found, that for the RV method the interpretation scheme based on the central time constant is too simplistic. The other two methods PDC and FDS compensate much better for the mentioned parameters but nevertheless analyse a drier cellulose with increasing temperature and a wetter cellulose for increasing oil conductivity. Actually the moisture in cellulose remained constant at 1 % during all the tests. Starting from these weaknesses a more sophisticated software was developed. The new software called “Dirana” bases on a new data pool, measured at new and aged pressboard with various moisture contents, temperatures and oil impregnation. The analysis algorithm works in frequency domain and features weighting of low frequency data and an extended XY-model for analysing oil-paper-insulations. Results obtained from this software show especially a much better compensation for varying oil conductivities and insulation geometries. The new software was successfully utilized for a on-site measurement in comparison to other measurement methods.

1 INTRODUCTION

Aging of power transformers evolved into a frequently discussed problem because of the cost pressure in the liberalized energy market. Power companies try to suspend the investment into new devices and shift maintenance from time based to condition based strategies. Therefore the demand for new diagnostic methods arose, methods which reliably evaluate the actual condition of the equipment.

Water in oil-paper-insulations goes hand in hand with transformer aging, it decreases the dielectric withstand strength, accelerates cellulose decomposition and causes the emission of bubbles at high temperatures.

State of the art for moisture measurements are equilibrium diagrams, where one tries to derive the moisture in the solid insulation (paper, pressboard) from moisture in oil. This method fails for several reasons, at what aging of oil and paper has the major impact [1].

Beyond this the Karl Fischer titration suffers from moisture ingress during transportation to the laboratory, different procedures releasing water from the sample leading to unsatisfying comparability of the results [2].

Therefore dielectric diagnostic methods were developed, which deduce the moisture in paper or pressboard from dielectric properties like return voltage, charging currents and dissipation factor. These methods promise to give higher accuracy and are designed for onsite moisture determination. Unfortunately controversial discussions arose, where one of the interpretation principles was called “not correct” [3], whereas others attested it to be “sensitive to aging and moisture” [4].

This paper systematically investigates the competing methods, reveals their strengths and weaknesses and shows subsequent improvements.

2 MEASUREMENT AND ANALYSIS PRINCIPLES

The multilayer insulation of power transformers consisting of oil and paper shows polarization and conductivity phenomena. Dielectric diagnostic methods measure the interfacial polarization effect, that originates from the interfaces between cellulose and oil. Polarization is superimposed by the DC conductivity of cellulose and oil. Moisture, temperature and conductive aging products influence these phenomena. Obviously the analysis of dielectric measurements has to discriminate moisture from the other parameters, this is an elementary quality feature (Fig. 1).

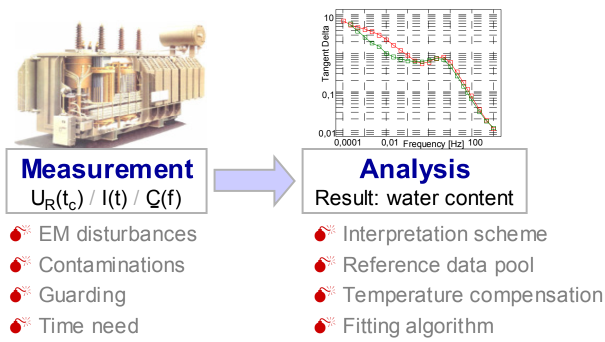


Fig. 1: Influences on measurement of the dielectric response and demands for its analysis

DC voltage, DC current or AC voltage and AC current display the properties of the dielectric. DC voltage measurements are applied as recovery voltage measurements after charging of the insulation with a DC voltage. The derived diagnostic method is the Recovery Voltage Method (RVM). A series of recovery voltage measurements with increased charging time leads to the so called "Polarisation Spectrum" which is commonly used to evaluate the moisture content in cellulose, Fig. 2. For this measurement and its interpretation a Recovery Voltage Meter RVM 5462 by Haefely Tettex with analysis software SWRVM 2 V.3.0 was used [5].

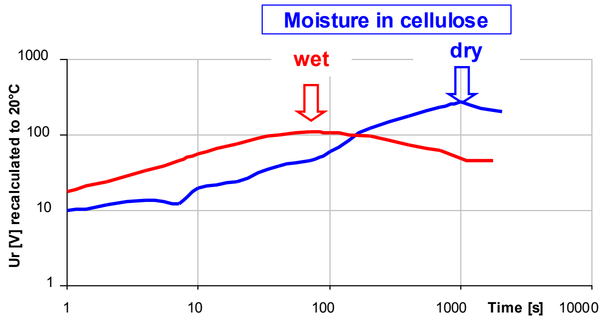


Fig. 2: The RVM interpreted by the "polarisation spectrum"

A DC current measurement records the charging and discharging currents of the insulation (Fig. 3). They are also known as Polarisation and Depolarisation Currents PDC, here measured by the Polarisation Depolarisation Currents Analyser MOD1 from Alff Engineering with analysis software PDC Evaluation Software V.3.0, [6].

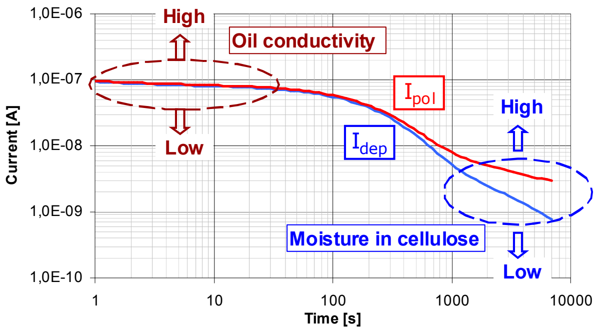


Fig. 3: Influences of oil conductivity and moisture in cellulose at the PDC method

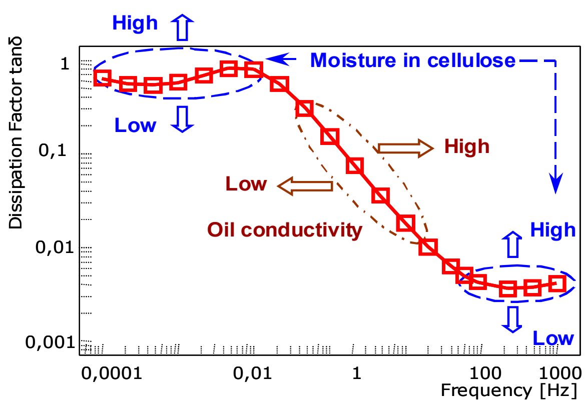


Fig. 4: Interpretation of dissipation factor measurements

AC voltage and current measurements are derived from the old known Tangent Delta measurements. Yet the frequency range is much enhanced especially to low frequencies (Fig. 4). The derived measurement method is called Frequency Domain Spectroscopy FDS, used by the Insulation Diagnostics System IDA 200 from GE Energy Services (now Pax Diagnostics) with analysis software MODS V.1.5, [7], [8].

3 COMPARATIVE STUDY AMONG RVM, PDC, AND FDS

3.1 Description of the Model

A large insulation model called "Pancake Model" served to benchmark the three commercialised instruments. The following parameters were investigated: insulation geometry, insulation temperature and oil conductivity. In the ideal case the analysis methods should be able to compensate for these three parameters. During all investigations the moisture content in cellulose remained constant at 1,0 %, measured at paper and pressboard samples with coulometric Karl Fischer titration at 160°C heating temperature.

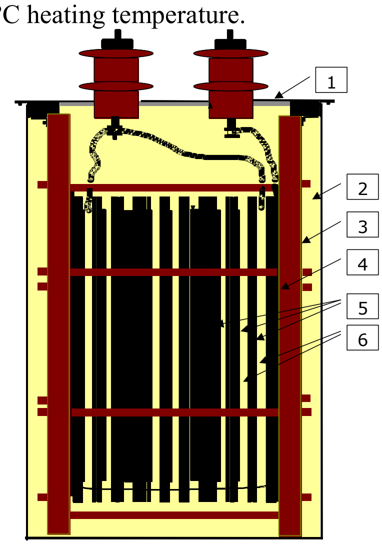


Fig. 5: Sectional view of the insulation model: 1 – Tank, 2 – Insulating oil, 3 – Bakelite, 4 – Copper plate, 5 – Pressboard Kraft Thermo 70, 6 – Spacers

The model consists of eight pancake shaped coils with oil ducts between them (Fig. 5). The ratio of barriers and spacers to oil ranged from 15 to 100 % as described in the following table. This simulates the main insulation of different transformers. The dielectric response was measured at 21-50-78°C insulation temperature and once again at 21°C. During the temperature investigations a new insulation oil type Shell Diala D (conductivity 1,57 pS/m) filled the model tank. This oil was exchanged by a 25 years service aged transformer oil (conductivity 16,5 pS/m) and the measurements were repeated at 21°C.

Tab. 1: Ratio of oil to cellulose in the insulation model

Connection	Oil / Barriers	Oil / Spacers
CH – B	83 / 17	85 / 15
DG – CH	72 / 28	72 / 28
E – DG	50 / 50	45 / 55
F – E	0 / 100	0 / 100

Although the pancake model has conditions similar to power transformers, there is still a remarkable difference. The insulation geometry is constructed in the shape of disks, but at power transformers in the shape of cylinders. This might increase the influence of parallel currents on the measurement results. Beside this the geometrical condition F-E (100 % pressboard) contains small oil ducts close to the paper-wrapped conductors.

3.2 Analysis Results of RVM, PDC and FDS

Fig. 6 to Fig. 8 display the moisture content analyzed by the software programs of the three commercialised instruments. The dotted line marks the moisture content as measured by Karl Fischer titration.

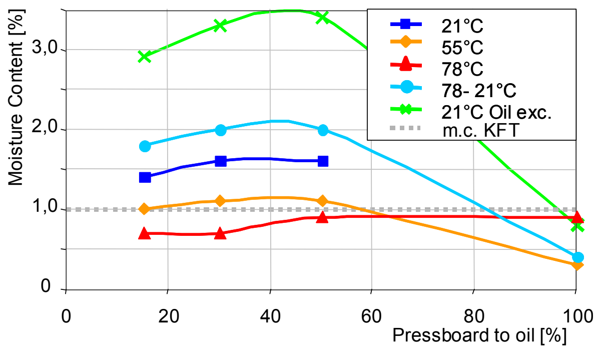


Fig. 6: Moisture analysis results with SWRVM 2 V.3.0

The results of the RV analysis software depend strongly on oil conductivity. Also temperature and insulation geometry influence the results, although the moisture content of paper was constant during the measurements. Hence the software SWRVM 2 V.3.0 using the "polarization spectrum" can't clearly evaluate moisture in oil-paper-insulations, it does not regard oil conductivity and owns a poor temperature compensation.

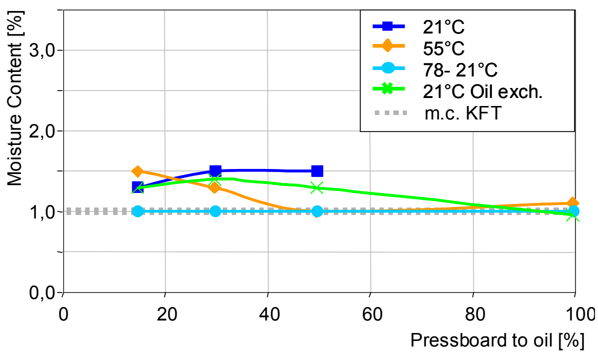


Fig. 7: Analysis results with PDC Evaluation Software V.3.0

PDC analysis results show a small influence of insulation geometry and a slight temperature dependence. With increasing oil conductivity the evaluated moisture content increases, although in reality it remained constant. Nethertheless the analysis results are very close to the moisture content measured by Karl Fischer titration.

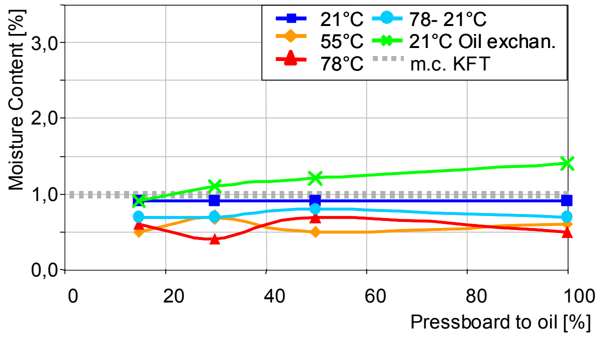


Fig. 8: Analysis results obtained with software MODS V.1.5

FDS analysis provides the best compensation of insulation geometry. However with increasing temperature the cellulose seems to dry, that actually happens because of moisture diffusion, but not in this dimension. This tendency rather reveals an imperfect temperature compensation. Similarly to the other methods the increased oil conductivity increases the moisture analysis results too, although indeed the moisture content in cellulose remained constant.

4 NEW ANALYSIS SOFTWARE

Based on the experiences gathered from the benchmark test a new software for moisture analysis called "Dirana" was developed.

4.1 Data Pool

The data pool for the analysis of the dielectric response constitutes of measurements on new and aged pressboard at various temperatures. A reliable moisture analysis of onsite measurements bases on an exact data pool (Fig. 1). An insulation diagnostic system IDA 200 [8] measured the dielectric response of pressboard in the frequency range 0,0001-1000 Hz. Four parameters were investigated: moisture content in cellulose (0,5-4,0 % by weight), pressboard temperature (21, 50 and 80°C), impregnation with three oils of different conductivity and finally aging of pressboard (1534 h at 130°C in a closed container). Moisture determination in the pressboard samples is very important for a later comparability of the obtained results to them from other research groups. In this work a coulometric Karl Fischer titration system EC Halle Aqua 40.00 measured the moisture content in paper at a heating temperature of 160°C and oil extraction with heptane [2].

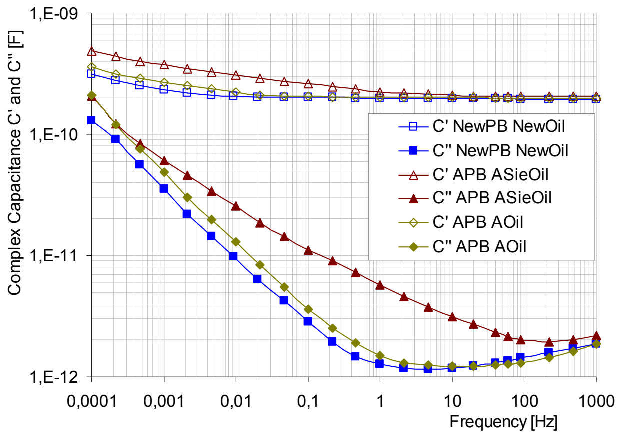


Fig. 9: Complex capacitance *C(f)* of new pressboard in new oil (1,5 % moisture content) compared to artificially aged pressboard (1,05 % moisture content) in service-aged oil (ASieOil) and artificially aged pressboard (1,05 % moisture content) in artificially aged oil (AOil)

As an example of the extensive measurement data Fig. 9 illustrates the complex capacitance of new pressboard compared to that of aged pressboard at 21°C. Obviously aging products increase the losses and therefore pretend a high moisture content. Besides the kind of oil used for impregnation of pressboard plays an important role. To ensure the reliability of the achieved data base the results were compared to previous investigations, e.g. [9], [10].

4.2 Analysis Algorithm

The moisture analysis bases on a comparison between the measured dielectric response from a real transformer and the modeled dielectric response derived from the data base. At first the insulation temperature T from the measured dielectric response *C(f)* is taken and the corresponding permittivity record $\varepsilon_{PB}(f)$ from the extra- and interpolated data base. Formula (1) from the so called XY-model combines this permittivity record $\varepsilon_{PB}(f)$ with the complex oil permittivity $\varepsilon_{Oil}(f)$ from equation (2). The XY-model allows for the computation of the dielectric response of a linear multi-layer-dielectric [11], where X represents the ratio of barriers to oil and Y the ratio of spacers to oil.

$$\underline{\varepsilon}_{tot} = \frac{(1-Y)}{\frac{1-X}{\varepsilon_{oil}} + \frac{X}{\varepsilon_{PB}}} + Y \cdot \varepsilon_{PB} \quad (1)$$

$$\underline{\varepsilon}_{Oil} = 2{,}2 - j\frac{\sigma_{Oil}}{\varepsilon_0 \omega} \quad (2)$$

The obtained modeled permittivity $\varepsilon_m(f) = \varepsilon_{tot}(f)$ is converted into a modeled capacitance $C_m(f)$ and then compared to the measured dielectric response *C(f)*. The modeled capacitance $C_m(f)$ with the best fitting to the measured capacitance *C(f)* gives the moisture content in cellulose and the oil conductivity of the real transformer. Fig. 10 depicts the programming flowchart of the newly programmed analysis algorithm.

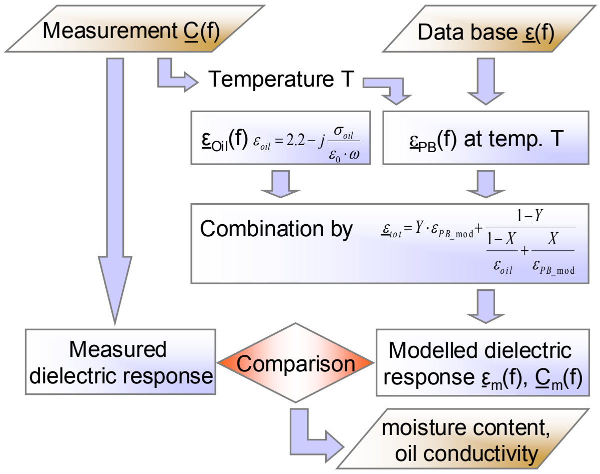


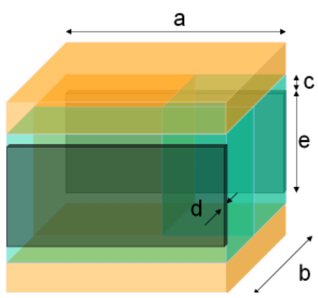
Fig. 10: Programming flowchart of the analysis algorithm

4.3 Weighting of Low Frequency Data

The fitting error detection algorithm regards especially the low frequency range, since water influences this region. Fig. 9 illustrates the connection between losses and frequency range. Water increases the dielectric losses below 1 Hz. Thereby the sensitivity of water analysis to a varied oil conductivity decreases substantially (Fig. 13).

4.4 Extended X-Y-Model

The original XY-model was extended to regard the influences of parallel current paths. Parallel current paths provide a direct connection through oil between paper-wrapped conductors. Their influence seems to be extensive, since oil conductivity exceeds that of cellulose up to a thousand fold [12]. To regard these influences the original XY-model was extended by five geometrical parameters as depicted in Fig. 11.



$$\varepsilon_{tot} = \frac{(1-Y)}{\frac{1-X}{\varepsilon_{Oil}} + \frac{X}{\varepsilon_{PB}}} + Y \cdot \varepsilon_{PB} + \frac{2 \cdot b \cdot d / e}{\frac{b + 2 \cdot c - 2 \cdot f}{\varepsilon_{Oil}} + \frac{f}{\varepsilon_{PB}}}$$

Fig. 11: Extended X-Y-model as a schematic (left) and the corresponding formula (right)

This approach improves especially the analysis results for measurements with a ratio of pressboard to oil of more than 50 %. Below 50 % the influence of parallel current paths vanish because of the large oil volume which is already implicit in the analysis. The main insulation of power transformers owns a ratio of pressboard to oil of 17-45 %, thus parallel current paths can be neglected in practical cases.

4.5 Transient Oil Conductivity

Since the conductivity of oil decreases with time, an approach was made to consider this phenomenon in the analysis software. Various research groups found out, that particularly aged oils feature a decreasing oil conductivity with increasing measurement time. A field strength above 10 V/mm enhances this behavior, Fig. 12 and [10], [12].

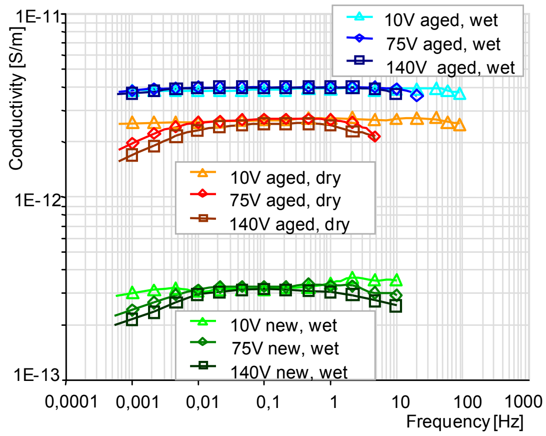


Fig. 12: Oil conductivity as a function of frequency, measurement voltage, aging and humidity

To implement this property into the analysis software, vectors of $\sigma(f)$ were used instead of equation (2). Unfortunately this did not improve the moisture analysis result, on the contrary the results got worse. One possible explanation gives the field strength dependence of oil conductivity, which might be low enough during onsite measurements. Beside this at measurements on real transformers it is hardly possible to regard the unknown transient properties of the specific insulation oil.

4.6 Verification on the Pancake Model

The new software "Dirana" was verified on the pancake model (see section 3.1) under three parameters: insulation geometry, insulation temperature and oil conductivity. As for the commercially available software the new one should be able to compensate for these parameters.

Fig. 13 proves the advantages of the newly developed software in comparison to the analysis results of the available software as depicted in Fig. 6, Fig. 7 and Fig. 8. Especially the compensation for different oil conductivities works very well because of weighting of the low frequency data, likewise the compensation for insulation geometry. Thus the error influence because of oil exchanges at real transformers reduces. Still the moisture content apparently decreases at increasing temperatures. This might be due to a different temperature behaviour or nonlinearities of the pressboard material in the model compared to that in the data base. Altogether the new software shows the smallest sensitivity to the investigated influences or in other words the best capability to compensate for them.

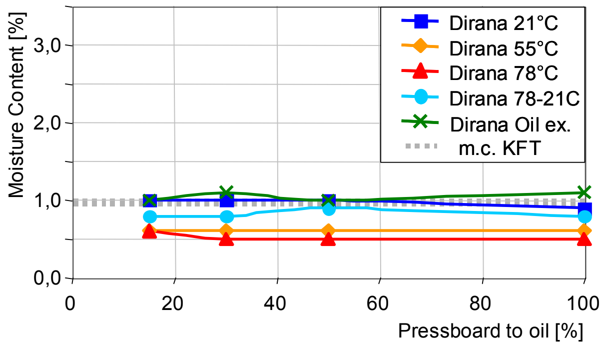


Fig. 13: Moisture analysis with the new "Dirana" software

5 ONSITE MEASUREMENT

Various moisture measurement methods were applied on an aged transformer to estimate its moisture content onsite. The transformer was manufactured in 1967, had a rated power of 133 MVA, a transformation ratio of 230 / 115 / 48 kV and OFAF cooling. Two meters measured the dielectric response of the insulation as polarization and depolarization currents *i(t)* and as complex capacitance *C(f)* between HV-winding and MV-winding, MV-winding and LV-winding and LV-winding and tank.

The new program and Mods 1.5 [8] analyzed the measurements and came to the results in Fig. 14. A capacitive probe measured onsite the relative moisture saturation in oil, the moisture in cellulose was derived via advanced equilibrium diagrams [1]. Beside this coulometric Karl Fischer titration determined the moisture by weight (ppm) in an oil sample and an conventional equilibrium diagram served to derive the moisture in cellulose from this result [13]. Ideally all the methods should come to a similar moisture content in cellulose.

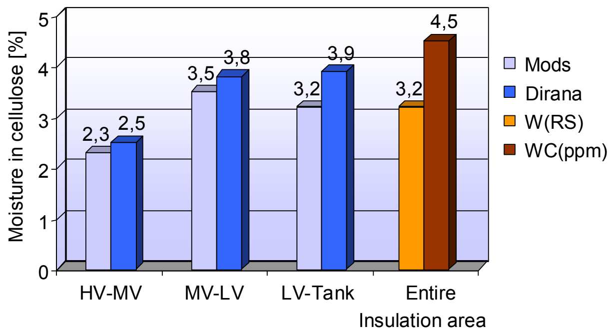


Fig. 14: Moisture content in the solid insulation as obtained from MODS, the new analysis software (Dirana) and via equilibrium diagrams from the relative saturation of oil (W(RS)) and from the moisture by weight in oil (WC(ppm))

Indeed the analysis software Mods 1.5 and the new software came to similar results (Fig. 14), minor discrepancies arise from the different data pools. The higher moisture content in the LV insulation agrees well 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 localisation of wet areas in the insulation. Contrary to this the moisture content in cellulose as derived from oil samples gives an average value. The result obtained from the relative saturation in oil by advanced equilibrium diagrams [1] agrees well with the dielectric analysis. However the conventional method of deriving the moisture in cellulose from moisture by weight in oil (ppm) gives a too high result. Aging of oil and paper makes the application of equilibrium diagrams from literature sources (e.g. [13]) impossible in most cases.

6 SUMMARY AND CONCLUSIONS

The three commercialised dielectric diagnostic methods RVM with analysis software SWRVM 2 V.3.0, PDC with PDC Evaluation Software V.3.0 and FDS with analysis software MODS V.1.5 were systematically benchmarked. Based on the achieved results a new software was developed, likewise benchmarked and applied for an onsite measurement.

1. The commercial evaluation software for PDC and FDS are able to compensate for the influences of insulation geometry, insulation temperature and oil conductivity.
2. The commercial analysis software for the RV method based on the central time constant is too simplistic.
3. All methods show an apparently *decreasing* moisture analysis result for *increasing* temperature and an *increasing* moisture result for *increasing* oil conductivity.
4. A new software "Dirana" was developed which bases on a new data pool, measured at new and aged pressboard with various moisture contents and oil impregnation.
5. The new analysis algorithm compares measurements from a transformer to modelled dielectric responses, obtained from the so called XY-model. The new software features weighting of low frequency data and an extended XY-model. A time dependent oil conductivity did not improve the analysis results.
6. Applied on the benchmark test the new software proves the best compensation for oil conductivity and for insulation geometry.
7. The new software was successfully utilized for onsite measurements in comparison to other measurement and analysis methods.

7 ACKNOWLEDGEMENT

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