RELIABILITY AND INFLUENCES ON DIELECTRIC DIAGNOSTIC METHODS TO EVALUATE THE AGEING STATE OF OIL-PAPER INSULATIONS

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Dielectric measurements and diagnostic methods are established procedures to evaluate moisture as an ageing indicator in commonly used oil-paper insulations of power transformers. Both the measurements themselves as well as the analysis of collected data contain several uncertainties and sources of error. This investigation discusses the sources of error and gives a further insight to the influences of transformer insulation design (geometry), insulation temperature, moisture equilibrium in oil and paper and other aspects regarding practical measurements. The dominating impact on dielectric analysis is related to the insulation temperature rather than insulation geometry. Limits and influences on linear modelling of multilayer insulations by equivalent circuits are described too. The investigation includes all the common dielectric diagnostic methods for oil-paper insulations: Recovery Voltage Method (RVM), Polarisation and Depolarisation Currents (PDC) and Frequency Domain Spectroscopy (FDS).

Dielectric diagnostic, oil-paper insulation, polarisation, moisture equilibrium, RVM, PDC, FDS

1 DIELECTRIC DIAGNOSTIC METHODS

1.1 INTRODUCTION

Reliable assessment of the ageing state of high voltage power transformers is a basic condition for a failsafe and cost-saving service. One ageing indicator is the water content in the solid part of the insulation (paper, pressboard). Water is an ageing product and accelerates the further deterioration of cellulose through depolymerisation (for details see [1]). In addition an increased water content in oil may cause bubble formation and lead to an electrical breakdown. To access the insulations water content some dielectric diagnostic methods were widely discussed and occasional used during the last decade. This article discusses general influences on dielectric measurements and regards in detail insulation geometry and insulation temperature.

The multilayer insulation of common power transformers consists of oil and paper and therefore shows *polarisation* and *conductivity* effects. Dielectric diagnostic methods work in a range dominated by interfacial polarisation at the boarders between cellulose and oil, cellulose conductivity and oil conductivity. Moisture influences these phenomena. Temperature and the insulation construction has a strong impact too, [3], [4], [9].

1.2 DIELECTRIC MEASUREMENTS

To evaluate dielectric phenomena one may measure DC voltage, DC current or AC voltage and AC current. Figure 1 depicts a basic circuit diagram for dielectric measurements.

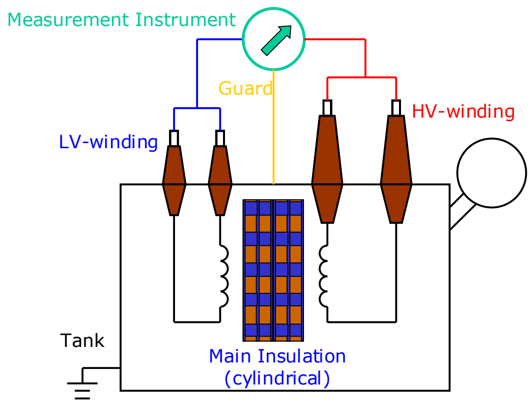

Figure 1: Basic circuit diagram for dielectric measurements

DC voltage measurements are applied as recovery voltage measurements after charging the insulation with a DC voltage. The derived diagnostic method is 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 of cellulose, [5], [6], [7].

A DC current measurement will record the charging and discharging currents of an insulation. They are also known as Polarisation and Depolarisation Currents (PDC), [3], [4].

AC voltage and current measurements could be led back to the old known Tangent Delta measurements. However the frequency range is much enhanced especially to low frequencies (e.g. 0,1 mHz). The derived measurement method is called Frequency Domain Analysis (FDS), [3], [8].

2 INFLUENCES ON DIELECTRIC MEASUREMENTS

Research and development on dielectric diagnostic methods substantially improved the reliability of analysis results. Nevertheless there are still several influences and sources of error.

(1) Insulation temperature

The strongest influence on the dielectric behaviour causes the insulation temperature (20-90°C), induced through the operating current. The related problems are:

- Its absolute value, since the common capillary thermometer shows the temperature of the hot oil at the transformers cover, but the polarisation processes are mostly influenced by the main insulation between HV and LV winding.
- The vertical temperature distribution among the windings can lead to a difference of 25 K, especially at naturally cooled transformers, see Figure 2.
- Increasing temperature changes the DC conductivity of the dielectric materials as well as the polarisation phenomena.

Section 3.3 shows the influence of temperature on RVM, PDC and FDS measurements and analysis results.

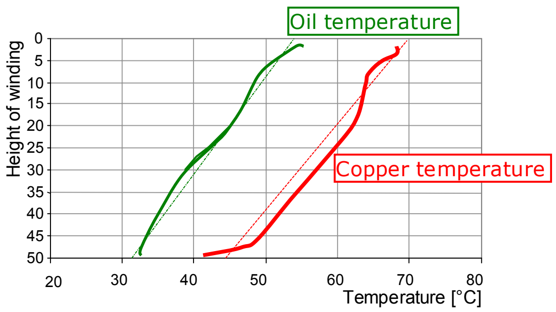

Figure 2: Measured vertical temperature distribution on a winding cooled by natural oil convection

(2) Migration processes

At increasing temperature the relative water saturation of oil increases too. Thus water penetrates from cellulose into oil until an equilibrium state is reached. With decreasing temperature the water migrates back into the solid parts of the insulation. Particularly at ambient temperature (20°C) this water migration process takes a long time of 14 days per millimetre (water migration into oil-impregnated pressboard referring to [1]). An example for an Onsite measurement: The transformer is switched off at an operating temperature of 60°C, the dielectric measurement starts at 55°C and in the end of the measurement the transformer is at 40°C. Thus at Onsite measurements the water migration is commonly running, the transformer is in a nonequilibrium state. Section 3.4 deals with the influence of moisture equilibrium in oil-paper insulations.

(3) Decreasing oil conductivity

Depending on ageing state, ion mobility, width of oil duct and electric field strength the conductivity of oil decreases with increasing polarisation time, see Figure 3. This leads to a nonlinear behaviour of multilayer oil-paper insulations. In [2] is described a way to quantify this influence at PDC measurements. Section 4 shows measurement data with nonlinear behaviour of oil-paper insulations.

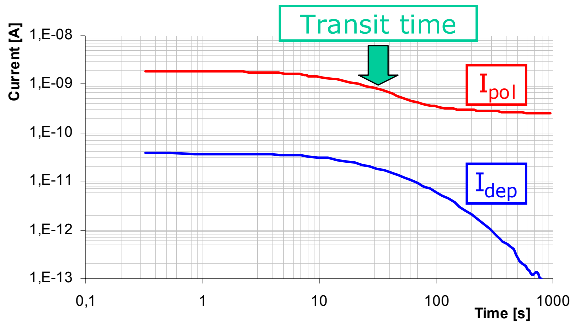

Figure 3: Transient time constant at decreasing oil conductivity

(4) Parallel current paths

Beside the current path through the multilayer oil-paper insulation the measurement current may flow in parallel paths consisting only of oil, see Figure 4. Even though this parallel path may be small, it will have an influence on the measurement because of the high conductivity of oil compared to the low conductivity of pressboard barriers.

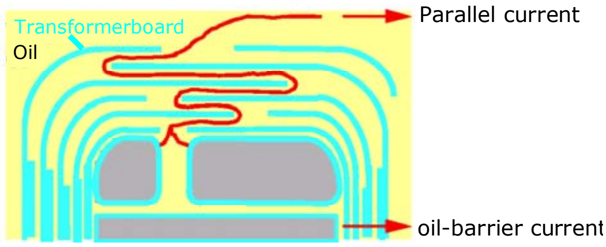

Figure 4: Current paths in a multilayer insulation, [2]

(5) Temperature compensation in analysis software

Measurements under different insulation temperatures should lead to the same analysis result of moisture diagnosis. Therefore a reliable temperature compensation is necessary. Although water migrates into oil with increasing temperature, the prevailing amount of water is always in the cellulose (water content of cellulose is 0,5-4 10^{-2}, of oil 5-80 10^{-6}). The temperature compensation of the commonly used dielectric diagnostic methods RVM, PDC and FDS was proved and the results are presented in section 3.3.

(6) Interpretation of measurement data

The interpretation scheme must allow a separation between influences of moisture in cellulose and other influences (e.g. oil conductivity). This is possible with the common scheme for the methods PDC and FDS (see Figure 5 and Figure 6) but not for the Recovery Voltage Method RVM. CIGRE Task Force 15.01.09 has already reported the interaction of different effects on the "Polarisation Spectrum", which is used to evaluate RV measurements. The "Polarisation Spectrum" and its "Central Time Constant" is mainly a mirror of interfacial polarisation. The moisture content of pressboard influences this "Spectrum" too, but it can't be separated from oil conductivity, see [6], [7], [9].

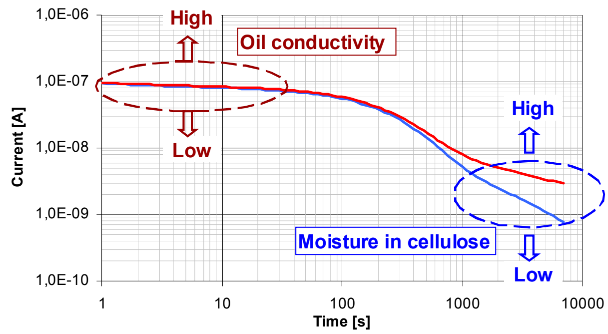

Figure 5: Separate impacts of oil conductivity and moisture in cellulose on Polarisation / Depolarisation Currents

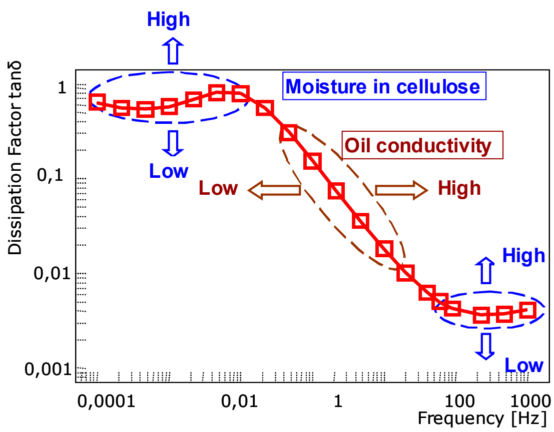

Figure 6: Separate impacts of oil conductivity and moisture in cellulose on Frequency Domain Spectroscopy FDS

(7) Verification by chemical analysis

Coulometric titration by Karl Fischer represents a credible method to access the moisture content of insulation oil and paper/pressboard. The user still has to solve some constraints:

- The heating temperature and time influence the measured moisture content at material samples. In [10] is recommended a heating temperature of 190-220°C in stead of 130-140°C according to IEC 60814. The higher temperature releases also the water absorbed or bounded in cellulose, see Figure 7.
- Oil additives and ageing products may interact with the Karl Fischer Reagent, especially if direct titration is used [10].

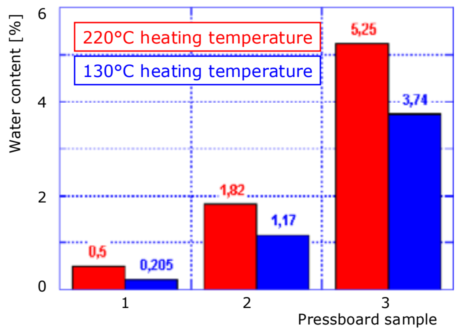

Figure 7: Moisture content analysed by Karl Fischer Titration with heating temperatures of 220°C and 130°C, [10]

(8) Comparison to moisture equilibrium charts

Moisture equilibrium charts as presented in [1] might lead to the moisture content of paper via the moisture content of oil, measured at an oil sample. Those equilibrium charts are only valid under some conditions:

- The water migrations process must be completed. Especially at ambient temperatures its time constant might be weeks (referring to [1]). In most cases this condition won't be fulfilled at an transformer in service.
- Basis for the equilibrium charts is the relative moisture saturation of oil and paper. This value is only valid for the specific oil and paper and will change during the ageing process. Hence one ought to use a specific chart for each oil and paper depending on the degradation process.
- The curves in the moisture equilibrium charts have a steep gradient in the area of low moisture content (up to 15 ppm). This complicates the reading. Moreover there are several equilibrium charts with different values, some of them are depicted in [1].

(9) Measuring time

Moisture in cellulose effects the long time or low frequency information in dielectric measurements. The claimed high operational availability of power transformers limits the time for *Onsite* but *Offline* dielectric measurements. The necessary time to obtain valuable data depends on ageing state, insulation temperature and measuring method. A brief comparison: The duration to get *time domain* information up to 2000 s lasts 3,5-4,5 h with RVM, 1,2 h with PDC and 2-2,5 h with FDS. Figure 10 shows the influence of measuring time on FDS analysis results.

3 INVESTIGATIONS ON A PANCAKE-SHAPED INSULATON MODEL

The following comparative measurements and analyses were performed with the known instruments:

- Recovery Voltage Meter RVM 5462 by Haefely Tettex with analysis software SWRVM 2 V.3.0
- Polarisation/Depolarisation Currents Analyser MOD1 by Alff Engineering with analysis software PDC Evaluation Software V.3.0
- Insulation Diagnostics System IDA 200 by GE Energy Services (former Programma) with analysis software MODS V.1.5

3.1 THE INSULATION MODEL

An insulation model, called “Pancake Model”, with a large oil volume allows for studies on the factors (1) insulation geometry, (2) insulation temperature, (3) test voltage level and (4) oil conductivity. The model was build using commonly used paper Kraft Thermo 70 and is filled with insulation oil type Shell Diala D. The model contains eight pancake shaped coils (connected to bushings A-H) with oil ducts between them in a different ratio of oil to pressboard, see Figure 8.

The different ratios of pressboard barriers/spacers to oil shall simulate the main insulation of different transformers (see following table and Figure 9).

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

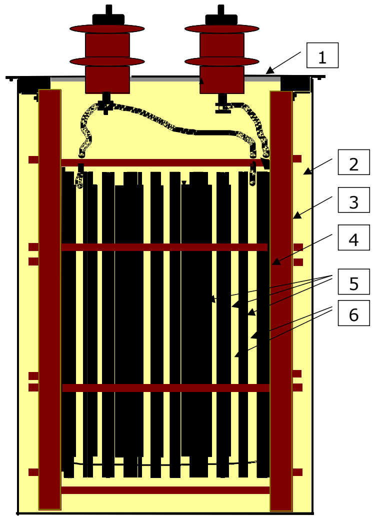

Figure 8: Sectional view of the insulation model: 1 – Tank, 2 – Insulating oil Shell Diala D, 3 – Bakelite, 4 – Copper plate, 5 – Pressboard Kraft Thermo 70, 6 – Spacers

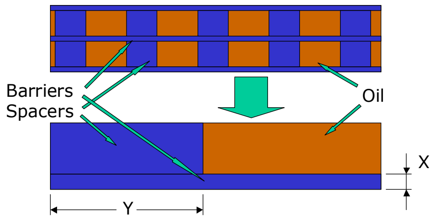

Figure 9: Modelling a multilayer insulation by X-Y values

Although the pancake model has conditions comparable 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 (see section (4) “Parallel current paths”). Furthermore the geometrical condition F-E (100 % pressboard) contains very small oil ducts close to the paper-wrapped conductors.

3.2 INFLUENCE OF GEOMETRY

The influence of insulation geometry on the dielectric diagnostic methods was investigated at 21°C insulation temperature. The measurement voltages were below 200 V to avoid nonlinear effects. The goal is an analysis result of moisture content *independent* on different geometrical conditions. The measurement conditions were for RVM: Charging voltage $U_C = 100$ V, charging time up to $t_C = 10'000$ s, for PDC: $U_C = 50$ V and $t_C = t_D = 10'000$ s, for FDS: $U_{RMS} = 75$ V, frequency range 1 kHz to 1 mHz and 1 kHz to 0,1 mHz.

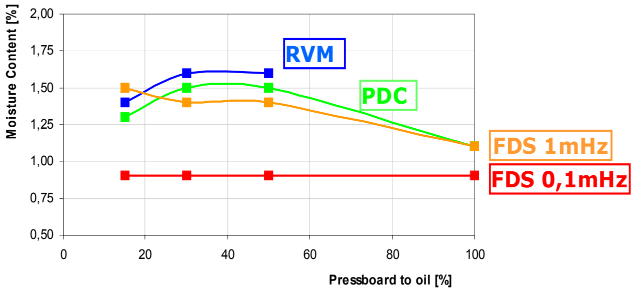

Figure 10: Analysed moisture content in cellulose at different geometry conditions and analysis methods

The analysis results of the Recovery Voltage measurements, depicted in Figure 10, show a rather small dependence on insulation geometry. At configuration F-E (100 % pressboard) occurred no "central time constant" and therefore no analysis result for the moisture content.

The analysis of the Polarisation/Depolarisation current measurement bases on a *visual* comparison between calculated and measured PDC. The programmers of this evaluation software decided to use this superposition of PDC to enable the user for a wider range of interpretation of measurement results. However this superposition leads to a subjective impact by the user. Moreover there is always a difference between measured and calculated PDC. The analysis results, depicted in Figure 10, show still a rather small influence of geometry.

Working with Frequency Domain Spectroscopy the analysed results of moisture content depend on the measured frequency range. If this range reaches from 1 kHz to 1 mHz, the analysis is influenced by insulation geometry. Changing the lower frequency to 0,1 mHz leads to analysis results independent from insulation geometry, see Figure 10. This increases the measurement time from 1,1 h to 12 h, mostly improper for Onsite measurements.

Comparing the used dielectric diagnosis methods obvious differences in the analysed results of moisture content are apparent. While RVM and PDC show a value of 1,4 %, the result of FDS is 0,9 %. The "true" moisture content is unknown, but around 1 % is probable at this relatively new and unused oil-paper insulation.

3.3 INFLUENCE OF TEMPERATURE

The influence of insulation temperature on the analysed results was proved at 21, 55 and 78°C. The goal is an analysed moisture content *independent* on insulation temperature. Also at higher temperatures only a negligible part of water migrates out of cellulose into oil. The measurement conditions U_C, t_C and frequency range were the same as under 3.2, but the frequency range for FDS was limited from 1 kHz to 0,2 mHz at 55 and 78°C because of temporal restrictions.

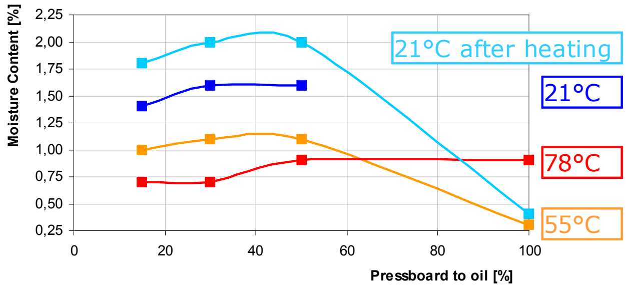

Figure 11: Results of RVM analysis at different temperatures

Figure 11 depicts the moisture content in paper analysed by the RVM software with a very strong influence of temperature. Beneath the difference in the results at variable temperatures there is a notable difference at 21°C insulation temperature before and after heating. Its cause may be the migration of water from pressboard into oil at higher temperatures and the uncompleted migration back into pressboard after heating.

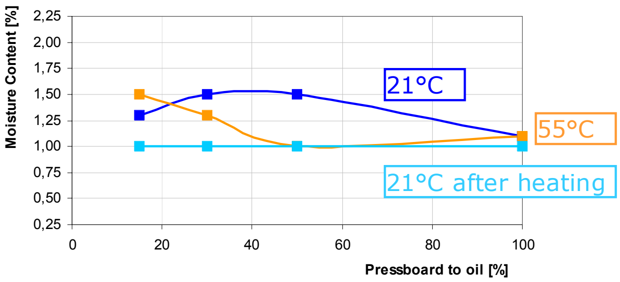

Figure 12: Results of PDC analysis at different temperatures

The results of moisture analysis by PDC shows an influence of temperature too (see Figure 12). It wasn't possible to obtain results at 78°C because the temperature compensation is restricted to lower values.

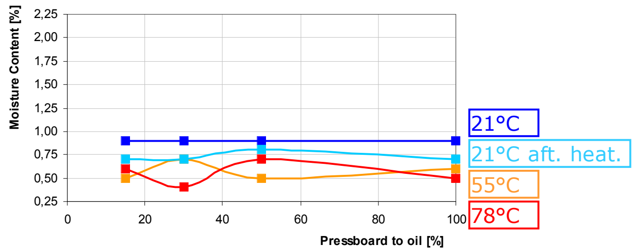

Figure 13: Results of FDS analysis at different temperatures

The analysed results calculated by the software MODS for FDS measurement data show only a slight difference at variable temperatures. Therefore these are the best results at different temperatures and different geometrical conditions too.

3.4 NONEQUILIBRIUM STATE

The moisture distribution between oil and paper is determined by the relative water saturation of oil (as described in (2) "Migration processes"). At the pancake model the first measurements were performed after several years at ambient temperature. A moisture distribution near to equilibrium state may be assumed. After heating to 78°C the model is in a nonequilibrium state, more water is dissolved in oil as under equilibrium conditions. The influence of nonequilibrium state on analysed results is always presented at Figure 11 to Figure 13, see results at 21°C before and after heating to 78°C. There the dielectric diagnosis method RVM obtains a much wetter cellulose, while PDC and FDS obtain a drier insulation. Those results are wrong, because the moisture content of cellulose is almost constant. The reason for the difference will be the higher conductivity of oil after heating and a drying of the pressboard surface because of moisture migration during the heating. The following Figure 14 compares the measurement data of FDS at 21°C before and after heating to 78°C as an example of measuring under equilibrium and nonequilibrium conditions.

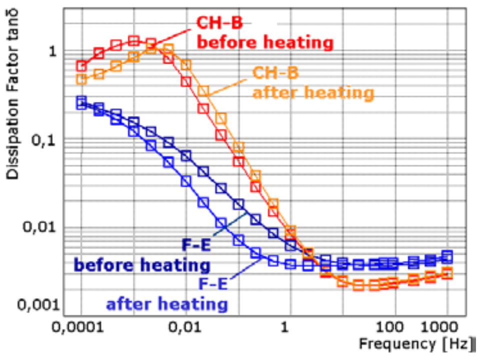

Figure 14: Dissipation factor Tangent Delta measured at 21°C by IDA 200 before and after heating to 78°C

4 MODELLING THE DIELECTRIC RESPONSE

An arrangement of resistors and capacitors can represent a Debye relaxation process over a demanded frequency range [11]. Figure 15 depicts such an arrangement adapted to the multilayer oil-paper insulation.

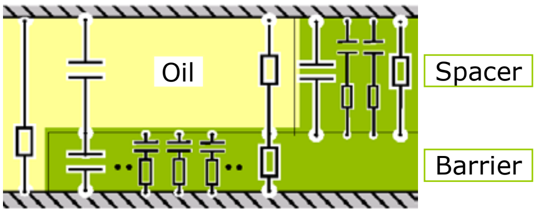

Figure 15: Modelling the dielectric response of a multilayer insulation by means of equivalent circuits

This model has a *linear* behaviour. The linearity of a real multilayer oil-paper insulation is influenced by some circumstances: (1) Electric field strength must not exceed 10 V/mm (2) Insulation geometry (3) Insulation temperature.

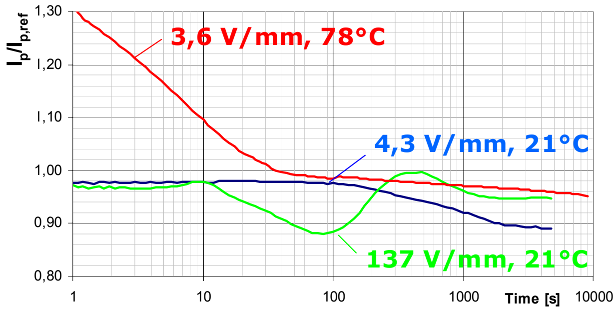

Figure 16: Linearity of polarisation currents under the influence of temperature and electric field strength

Some investigations on linearity were performed at the pancake model with configuration DG-CH (30 % pressboard, see section 3.1). In Figure 16 a ratio of 1 corresponds to a linear behaviour. With increasing measurement voltage (electric field strength) and insulation temperature the behaviour is incrementally *nonlinear*, modelling by means of equivalent circuits as described above is no longer valid.

This nonlinear behaviour may be explained by the time-varying oil conductivity (see (3) "Decreasing oil conductivity"). Further research is needed to insure, whether this explanation is sufficient or a more complex process takes place.

5 SUMMARY

Dielectric diagnostic methods to evaluate the moisture content of oil-paper insulations were subject to a rapid development during the last years and nowadays provide credible results. Nethertheless they are influenced by some conditions and sources of error, as insulation temperature, water migration processes, nonlinear behaviour of insulation materials, parallel current paths and measuring time (see section 2). A verification by chemical analysis called “Karl Fischer Titration” leads to some difficulties too, as the proper titration procedure and the unknown influence of ageing products and oil additives. The usage of moisture equilibrium charts is mostly not possible.

Investigations on the known dielectric diagnostic methods Recovery Voltage Method, Polarisation Depolarisation Currents and Frequency Domain Spectroscopy under the influence of insulation geometry and insulation temperature were performed using a large oil-paper insulation model (see section 3.1). The influence of temperature is much stronger then the influence of insulation geometry. The quality of the temperature compensation made by the different analysis software differs substantially. The instrument for Frequency Domain Spectroscopy called IDA 200 and its software MODS 1.5 offers the best compensation of influences of insulation geometry and temperature.

Future research will give a closer insight to the influence of temperature on polarisation phenomena, the dynamics of moisture migration processes and the implementation of nonlinear elements to model polarisation phenomena.

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