DIELECTRIC MODELLING AND DIAGNOSIS OF THE OIL-PAPER-INSULATION SYSTEM IN POWER TRANSFORMERS

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Abstract: Frequency domain measurements of oil-paper insulation systems provide novel diagnostic methods for assessing the aging and moisture content in the insulation layers of power transformers [1]. The first step is to measure and to analyse the dielectric behaviour of oil-paper insulation systems and their dependence on temperature, moisture content and ageing products in oil and pressboard among others. This paper describes the conductivities of insulating oil and pressboard with different values of parameters like temperature and moisture content. These conductivity dependences were then incorporated into the dielectric model of the insulating medium which were then put together to replicate mathematically the main insulation of power transformers. The geometrical layout of power transformers is taken into account and hence a basic model for power transformers is obtained. The model is then compared and verified with FDS (Frequency Domain Dielectric Spectroscopy) measurements obtained from power transformers in service.

1. INTRODUCTION

The modelling of the insulation layers of a power transformer is just like any other model bound to some form of simplification and assumptions. One could try to model the main insulation in a 3-dimensional perspective, but a 2-dimensional modelling in the form of parallel plate capacitors is sufficient to adequately model a transformer's main insulation [2].

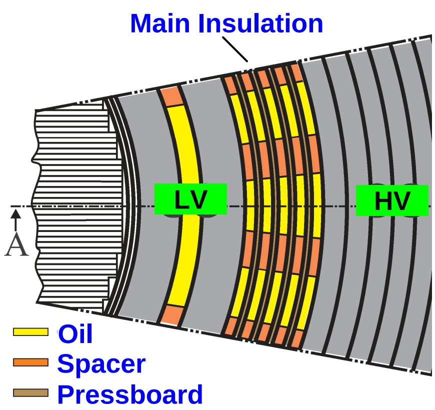

Figure 1: Main insulation duct of a power transformer

The main simplification is that the main insulation between the HV-Coils and LV-Coils is considered to be formed from a 2-layer insulation consisting of oil and cellulose based paper. Furthermore it is assumed that the dielectric spectrum of insulation paper can me adequately modelled using only three terms – conductivity, Cole-Cole dielectric relaxation model and its relative dielectric constant. The dielectric spectrum of insulation oil on the other hand can be replicated with its conductivity and its relative dielectric constant. In the frequency range taken into consideration below 1 kHz the dielectric spectrum of oil does not show any polarisation behaviour. Laboratory results have verified the assumptions mentioned above to be sufficiently accurate.

The electrical field between the HV-Coils and LV-Coils is also assumed to be homogenous. This assumption can be made when coil radius is significantly larger then the main insulation length. The planes of the insulation materials are all assumed to be perpendicular to the electrical field. The surface conductivities of the insulating materials are also assumed to be negligible. With the mentioned assumptions one obtains a 2-dimensional model of the insulation shown in the figure below which is very similar to a double layer capacitance.

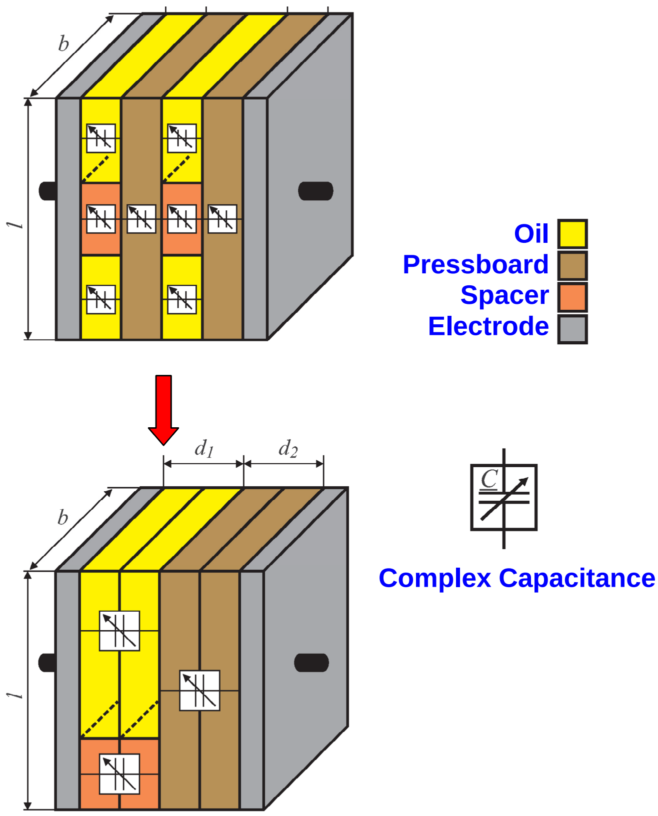

Figure 2: Insulation model in homogenous electrical field

$$\frac{1}{\underline{C}_{total}}=\frac{1}{\varepsilon_0\cdot A}\left[\frac{d_2}{\underline{\varepsilon}_{Pb}}+\frac{d_1}{k_1\cdot\underline{\varepsilon}_{Sp}+\left(1-k_1\right)\cdot\underline{\varepsilon}_{Oil}}\right] \quad (1)$$

ε_0	*vacuum permittivity*
A	*surface area*
$\underline{\varepsilon}_x$	*complex permittivity of medium x*
d_x	*thickness of medium x*
k_1	*surface factor of medium 1*

Equation 1 is used to calculate the equivalent capacitance of the main insulation duct. The complex dielectric function of pressboard $\underline{\varepsilon}_{Pb}$ is modelled using the Cole-Cole dielectric function and its conductivity as below:

$$\underline{\varepsilon}_{Pb}=\frac{\Delta\varepsilon}{1+\left(j\omega\tau\right)^n}+\frac{\sigma_{Pb}}{j\cdot\varepsilon_0\cdot\omega}+\varepsilon_{r_{Pb}} \quad (2)$$

The spacers were also modelled using the same dielectric function of Pressboard $\underline{\varepsilon}_{Pb}$ as the spacers and pressboard are in the most cases formed from the same basic substance cellulose. The dielectric function of insulating oil doesn't show polarization effects in the considered frequency range and can therefore be modelled with the following function:

$$\underline{\varepsilon}_{Oil}=\frac{\sigma_{Oil}}{j\cdot\varepsilon_0\cdot\omega}+\varepsilon_{r_{Oil}} \quad (3)$$

The conductivity of both oil and pressboard fluctuates according to moisture content and temperature. Many researchers have observed Arrhenius-type temperature dependence of the conductivity of insulation oil as shown in equation 4 [3]. This dependence has also been noticed from our laboratory measurements (refer to figure 3).

$$\sigma_{Oil}=\sigma_{Oil_0}\cdot e^{\left(\frac{-E_A}{R_m\left(\vartheta+273{,}15\right)}\right)} \quad (4)$$

With E_A being the activation Energy and R_m the universal gas constant.

2. EXPERIMENTAL RESULTS

2.1. Oil-Conductivity

The conductivity of insulating oils sampled from power transformers in service was measured in our indoor laboratory with the temperature as a variable. The tests were carried out with DTL-C from BAUR Prüf- und Messtechnik GmbH. The oil temperature was increased beginning from 20° C in 10° steps till 110° C. The conductivity was measured with a direct current of 500 V for positive as well as negative polarity. As there were not significant discrepancies between the measurements with different polarities, only the results from the positive polarity measurements are shown in figure 3.

The results verify the Arrhenius-type temperature dependence of the conductivity. The Arrhenius representation of the specific conductivity measured shows curves whose slopes differ from each other for different measuring fluids and viscosities. For the same measuring fluids with different state of ageing the curves show parallel shifts. The figure 3 illustrates the behaviour of the specific conductivity of the different oil samples over the reciprocal temperature. As stated above, the activation energy depends mostly on the medium and is related to the dynamic viscosity. The correlation of the specific conductivity with the temperature of the oil is based on the fact that a high viscosity and a low temperature result in a higher resistance against the charge carriage of the ions than a low viscosity and a high temperature would. The ions can be considered as spherical charges moving with the electric field in the measuring fluid.

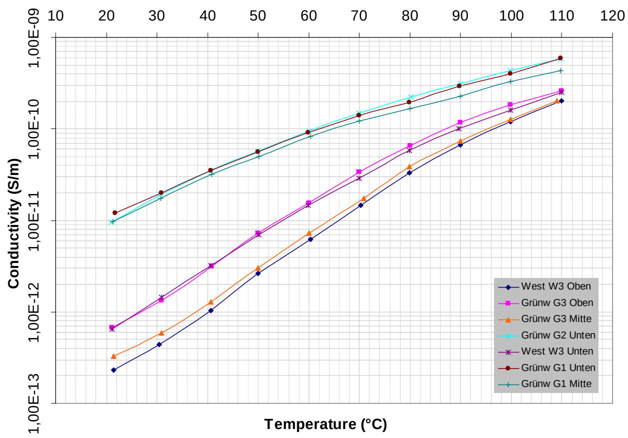

Figure 3: Thermal dependence of the specific conductivity of insulating mineral oil sampled from power transformers in service

2.2. Pressboard Measurements

For the Pressboard testing, a climate chamber WK from Weiss Umwelttechnik GmbH was used. As the dielectric function is known to be very sensitive to moisture content and temperature, conditioned testing environment as provided by the climate chamber was necessary. The climate chamber was used to moisturize the pressboard samples as well as to maintain a constant temperature during testing. The moisture content of the pressboard samples were measured using Karl-Fischer-Titration method according to IEC 60814 but modified according to [4] using AQUA 40.00 from Analytik Jena AG.

The pressboard samples were moisturized and then impregnated with new dried insulating mineral oil (Shell DIALA D). Moisture contents of 0.7, 1.2, 2.5, 3.5 and 7 % were prepared for the testing. As the measurements on the 7% samples were still running at the time of writing, its results will not be presented in this paper. The dielectric measurements were performed with an ALPHA-A Dielectric Analyser from Novocontrol Technologies.

The obtained dielectric measurements of Pressboard samples were then matched to equation 1 using non-linear complex curve fitting methods in MATLAB. An example of the fitted curve is shown in figure 4 to exemplify the accuracy of the curve fitting. The red curve in Figure 4 is the fitted model curve and the blue points are the measured points with the upper figure showing the real and imaginary parts of the complex capacitance and the lower figure its dissipation factor tan δ. It can be observed that the proposed model does fit very nicely with the measured curve. Hence the conductivities of Pressboard at different discreet moisture content and temperatures were obtained. The results are shown in Figure 5.

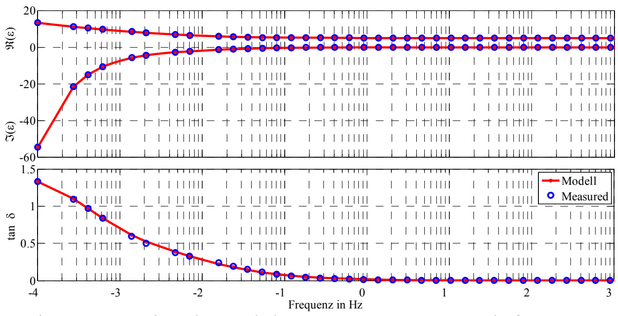

Figure 4: Fitted model curve to measured frequency domain dielectric function of oil-impregnated pressboard (x-axis in logarithmic scale)

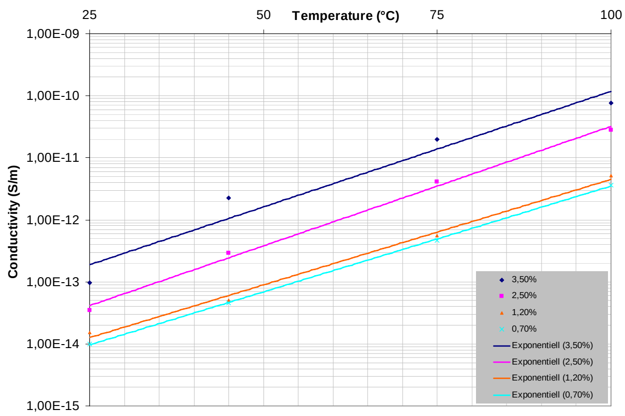

Figure 5: Thermal dependence of the specific conductivity of oil-impregnated pressboard with variations in moisture content [5]

As shown in Figure 5 the conductivity of oil-impregnated pressboard is strongly affected by the changes in moisture content and temperature. Figure 5 presents the variation of conductivity (logarithmic scale) with temperature and moisture content. Similar to insulation oil in Figure 3, it can be safely assumed that it's a thermal process and as such follows Arrhenius's equation similar to equation 4. The derived trend lines are also included in the figure. It is noticeable that the gradient of the curves in figure 5 are very similar and are shifted parallel to each other according to its moisture content. This somewhat confirms that the conductivity of pressboard increases with an increase in moisture content. It also implies that two exponential functions of temperature and moisture content could be used to model their respective influence on the conductivity of pressboard. These dependencies will be used as a diagnostic approach for power transformers as described in section 3.1.

3. FDS-MODEL COMPARISON ON POWER TRANSFORMERS

The model of the main insulation duct in a power transformer shown in Figure 2 is admittedly a simplified model. This model is nevertheless adequate to conduct dielectric diagnostics on power transformers if the geometrical construction of the transformer is known. These data can be obtained from the technical design sketches normally archived by the manufacturer. Knowledge about the insulation material for example oil type and pressboard/paper type is also very useful for diagnostic purposes. These data are then „fed" into the model described by equation 1 which is then fitted using non-linear least squares complex curve fitting methods to a frequency domain dielectric measurement (FDS) carried out on a power transformer. With a sufficient fit one obtains the parameters found in equations 1, 2 and 3 which also mirror the condition of the main insulation duct.

In this paper, results from three generator transformers will be presented. Generator transformers were selected for the diagnostics as they are normally run under constant high load and as such are more susceptible to aging as compared to substation transformers which normally undergo extreme load fluctuations.

The electrical and geometrical design parameters of the mentioned transformers are shown in Table 1. It must also be mentioned at this point that the three transformers are from three different manufacturers whose names will not be revealed in this paper. As such variations in pressboard and oil parameters are bound to be present because of the different materials used by different manufacturers. Curve fitting methods similar to the ones performed on pressboard samples as shown in figure 4 were also performed on the FDS measurements on the transformers. The fitting results are shown in figure 6. For clarity only the dissipation factor tan δ is shown. Table 2 shows the extracted oil and pressboard parameters.

Table 1: Electrical and geometrical data of three generator transformers which were measured with FDS measurements

	T1	T2	T3
Rated Power (MVA)	500	190	600
Rated Voltage (kV)	245/21	236/21	400/30
Manufactured	1971	1969	-
Total Spacers	72	40	36
Spacers width (mm)	25	25	15
Radius HV-Coil (mm)	845	754	1028
Radius LV-Coil (mm)	760	684	932
Coil Height (mm)	2200	1615	2170
Total Pressboard (mm)	36	42	31
Total Oil duct (mm)	49	28	65

Table 2: Extracted model parameters from curve fitting according to equations 1, 2 and 3

	T1	T2	T3
C_0 (nF)	3.2	2.923	3.182
$\Delta\varepsilon_{Pb}$	21.98	35.46	78.72
ε_{Pb}	4.812	4.273	4.9
ε_{Oil}	2.2	2.2	2.2
n	0.4962	0.4381	0.44
σ_{Oil} (pS/m)	6.76	6.736	106.2
σ_{Pb} (fS/m)	40.8	95.69	1349
τ_{Pb} (s)	1715	4384	2023

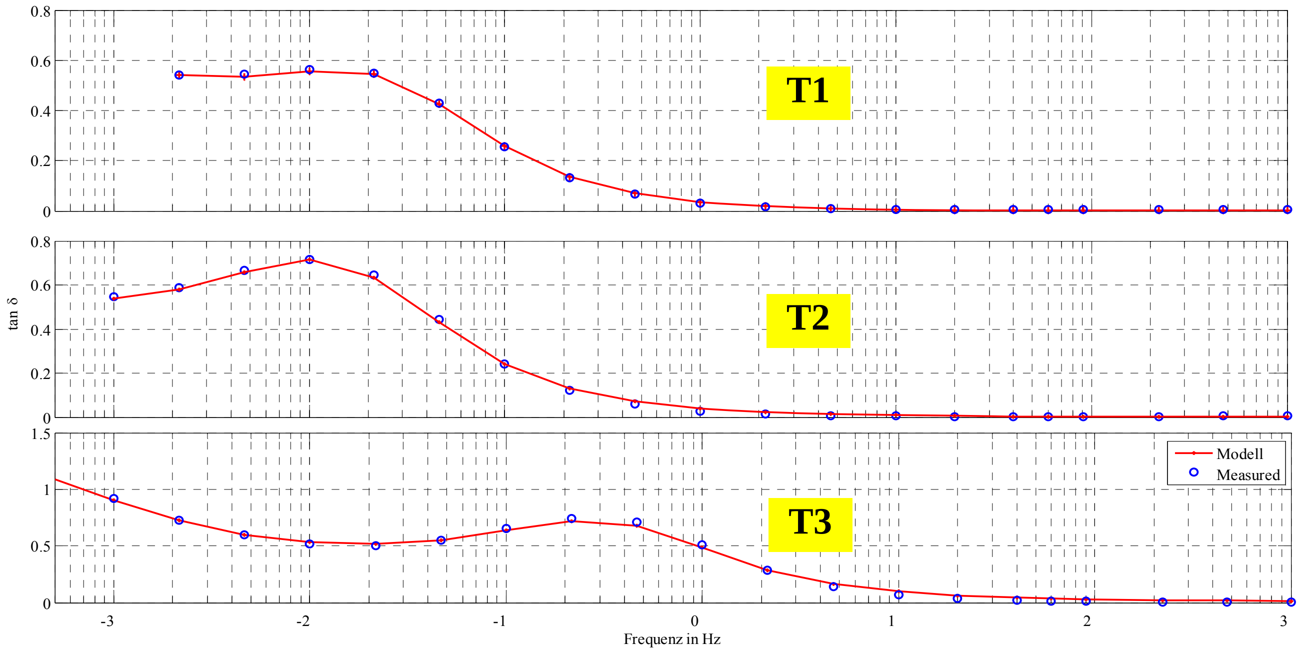

Figure 6: Fitted main insulation model curve from equation 1 to measured frequency domain dielectric function (FDS) of power transformers from Table 1 (x-axis in logarithmic scale)

3.1. Diagnostic approach

The extracted pressboard conductivity is cross-referenced to figure 5 to obtain its average moisture content. However this result needs to be verified with moisture content measurements on pressboard samples from transformers after they have been taken out of service. This opportunity was available with T1 where pressboard samples were taken during the disassembly of the mentioned transformer. Therefore only results from T1 will be discussed in this paper from this point onwards. T2 and T3 are scheduled for disassembly in the near future and their results will be presented in future publications. The moisture content of the pressboard samples from T1 were measured along the height at various positions to obtain the moisture distribution and the results are shown in figure 7.

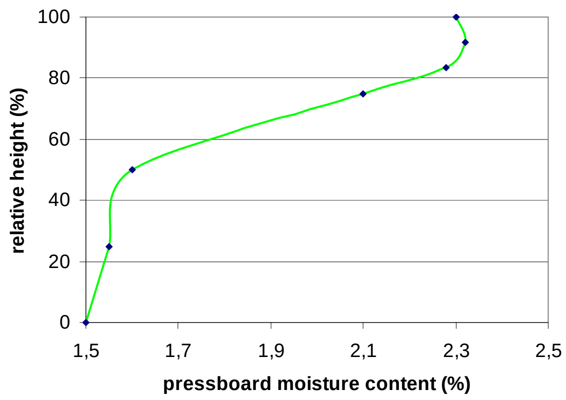

Figure 7: Moisture content distribution of pressboard from T1 sampled at various height points.

The results from figure 7 show that the moisture content is higher at the higher points of the transformer T1. This could be explained with the hot-spot phenomena which occur at the higher points of a power transformer. The increased temperature accelerates the aging process and hence the depolymerization of the pressboard. As mentioned by many authors among others in [6], the aging process leads to an increase in moisture content.

From Table 2 it can be seen that the average specific conductivity of the pressboard from T1 obtained through curve-fitting methods is around 41 fS/m. The average oil-temperature during the FDS measurement was 21° C. The transformer was taken out of service for around 10 days prior to the measurement and hence temperature equilibrium is assumed. When one cross-references this value with a temperature of 21°C in Figure 5, the average moisture content is seen to lie between the curves for 1.2% and 2.5% moisture content and nearer to the larger value. This corresponds very well to the measured moisture content from the pressboard samples. For a more accurate analysis, the parallel shift between the curves must be further investigated which will be done by the author in the near future.

4. CONCLUSION

The main insulation duct model described in this paper is based on the geometrical design which was combined with material parameters. For this purpose the Cole-Cole dielectric model was used which is actually a simplified form of the Havriliak-Negami function. This function was used together with the specific conductivity and the relative permittivity to replicate the dielectric function of insulation materials found in a transformer. The model has been extensively tested with pressboard and oil measurements and has proven to be able to satisfyingly replicate the dielectric functions of insulating oil and oil-impregnated pressboard.

The diagnostic approach shown in this paper has to be verified with pressboard samples from power transformers which have been taken out of service to determine if the approach is wholly applicable.

Another approach which will also be investigated is to conduct FDS Measurements on a brand new power transformer which could be used as a reference or benchmark measurement to determine the aging process. On the other hand, the parameters obtained through curve-fitting could be used to verify the FDS measurements as these are also known to be very sensitive to various disturbances such as atmospheric conditions.

In the future, the effects of acids which are found in pressboard and oil in a power transformer will be investigated. These acids could also behave similarly to moisture as reported in [6] and accelerate the aging process in a similar manner.

5. REFERENCES

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