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Issue: „Modelling of Oil-/ Paper Insulation Layers in the Frequency Domain with Cole-Cole-Functions (Part II)“

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# Modelling of Oil-Paper Insulation Layers in the Frequency Domain with Cole-Cole-Functions (Part II)

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**Abstract:** The measurement of oil-paper insulation systems in the frequency domain provides novel diagnostic methods for quality control of materials and high-voltage power transformers. The first task is to measure and to analyse the dielectric behaviour of oil-paper insulation systems and their dependency on material quality, moisture content and ageing products in oil, paper and pressboard. Furthermore, the geometrical layout of power transformers and the type of modelling are very important for the diagnostic.
Every medium has its own special complex capacitance $\underline{C}_{Medium}$ in frequency domain that can be simulated with a Cole-Cole function with conductivity.
The behaviour of the power transformer can be calculated from the parallel connexion and the series connexion of the individual microscopic capacitances $\underline{C}_{Medium}$.
The quantitative usage of the insulation layer model requires small parasitics on the boundaries, homogeneous materials of the individual layers and a uniform field.
The paper describes the models of oil, paper and pressboard with different values of parameters like temperature and moisture. This is the basic model for the power transformer. It describes a method of generating the different power transformer models with parameters like temperature, moisture etc. and a technique to control and show the error of measurement.

## INTRODUCTION

The aim of this work is to improve the diagnostics of power transformers to optimise the cost-effectiveness and to increase the operational reliability. To identify the state of a power transformer, knowledge about the operating conditions, the measurands and their effects on the insulation system is necessary. The measurands can be measured online or offline.
Measurements in frequency domain and time domain, like FDS and PDS measuring methods, are offline diagnostic methods. If the geometric data and the behaviour of the measurands through changes of the insulation system are known, it is possible, with either of the measuring methods, to draw conclusions about the insulation system of the power transformer [6].
Due to the different insulation arrangements, it is important to have a model that simulates the insulation arrangement for the respective measuring method accurately enough to achieve more accurate diagnostics of the different transformer types. As an alternative, the model can also be used to separate individual insulation behaviours, e.g. the approximate insulation behaviour of the whole transformer board. For that, the geometry and the behaviour of the other insulations must be known.
The basics for the diagnostic method were introduced in detail in the paper [3]. This paper is an extension and a refinement of the model so far.
For a better understanding, the chapter "Theory" discusses briefly the basic approach of the model necessary for this paper.
After that, the insulation models for oil, paper and transformer board are introduced, followed by a transformer model constructed with the individual insulation models. Here, firstly, the insulation between high and low voltage in the cylinder field is seen as a homogeneous field and secondly, some of the fringe fields can be considered.

## THEORIE

The model for measurements in frequency domain is based on the complex dielectric function (1). This function has two important advantages. Firstly, the capacitance and the conductivity are a part of the function, which makes the transformer modelling easier. The second advantage lies in the order of magnitude of the complex permittivity. The conductivity of insulation systems is seen as an imaginary part and is perceivable in low frequencies with higher numerical values.
The complex permittivity $\underline{\varepsilon}$ can be determined using the following formula and an impedance measurement [5]:

$$\underline{\varepsilon}_{(\omega)} = \varepsilon' + j\varepsilon'' = \frac{-j}{(\omega \cdot \underline{Z}_{(\omega)})} \cdot \frac{1}{C_0}, \qquad (1)$$

with $C_0$ as the capacitance of the empty capacitor. The real part $\varepsilon'$ indicates the permittivity of the capacitor material and the imaginary part $\varepsilon''$ indicates the ratio of current in the same phase with the voltage, i.e. the electric loss. The loss factor or $\tan\delta$ can be determined as follows:

$$\tan\delta_{(\omega)} = \frac{-imag(\underline{\varepsilon}_{(\omega)})}{real(\underline{\varepsilon}_{(\omega)})} \qquad (2)$$

For oil-paper insulation systems it was shown that the dielectric function, also known as Cole-Cole Function with conductivity (3), consists of different behaviours, like conductivity $\sigma$, instantaneous polarisation $\varepsilon_\infty$ and relaxations.
For oil-paper insulations used mainly in transformers, it was experimentally shown that the Cole-Cole function with conductivity is an appropriate form for modelling. Having this function as a basic form the oil and the paper can be emulated in the transformer behaviour. The Cole-Cole function assumes a distribution of time con-

stants $G(\tau)$ - the so-called relaxation. Expanding the function with the specific conductivity $\sigma$ and other distributions of time constants results in the following equation [1] [4] [5]:

$$\underline{\varepsilon}(\omega,T) = \underbrace{-j\left(\frac{\sigma_{(T)}}{\varepsilon_0\omega}\right)}_{\text{Conductivity}} + \varepsilon_\infty + \underbrace{\frac{\Delta\varepsilon_{\alpha(T)}}{1+(j\omega\tau_{\alpha(T)})^{n_\alpha}}}_{\alpha\text{-Relaxation } G(\tau)} + \ldots \quad (3)$$

parameter:

| | | |
|---|---|---|
| $\sigma$: | $0 \leq \sigma$; | specific conductivity [S/m] |
| $\varepsilon_\infty$ | $0 \leq \varepsilon_\infty$; | instantaneous polarisation |
| $\omega$ | $=2\cdot\pi\cdot f$; | angular frequency [1/s] |
| $T$ | | temperature [K] |

$\alpha$-relaxation:

| | | |
|---|---|---|
| $n_\alpha$ | $0 < n_\alpha \leq 1$; | |
| $\Delta\varepsilon_\alpha$ | $0 \leq \Delta\varepsilon_\alpha$; | $\alpha$-dielectricity change |
| $\tau_\alpha$ | $0 < \tau_\alpha$; | $\alpha$-relaxation time [s] |

The advantage of this function lies in the exact mapping of the time constant distributions to the respective relaxation and the considering of the specific conductivity.
The multiplication of the complex dielectric function $\underline{\varepsilon}(\omega,T)$ with the capacitance of the empty capacitor $\underline{C}_0$ results in complex capacitance $\underline{C}$.

# MODEL

## Insulation-Oil Model

The paper [3] shows a typical temperature-dependant permittivity graph of new insulation oil (Shell Diala D) with a distance of 0.25 mm. Such a small distance is applicable only for material analysis. For the diagnostics of transformers, the distances between the individual oil ducts are multiples of that and influencing parameters like state of ageing, thermal behaviour, moisture, field strength etc. are of importance.

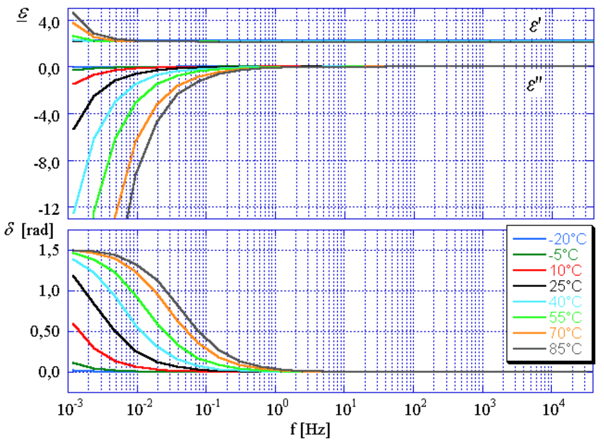


**Figure 1:** Curve run of the complex permittivity of new mineral oil in different temperatures

Examining first the mineral oil in the transformer on the FDS and the PDC measurements, experimental studies show that the conductivity changes strongly and the permittivity weakly. The relaxation behaviour decreases with growing distances. The influence of the field strength is small here, as it was significantly below 10V/mm during all measurements.
In the following are shown measurements performed with a distance of 1-2mm and the more exact analysis of the parameters temperature moisture content and the state of ageing.
The figure 2 shows a typical curve run of the mineral oil permittivity in frequency domain and a temperature range between 10 °C and 85 °C. In this case it is Shell Diala D with approx. 10 ppm moisture. The distance between the electrodes was 1 mm.
The imaginary part of the complex permittivity shows a significant dependence on the temperature and thus an increase in the conductivity. From the phase angle $\delta$ it is discernable, after which barrier frequency the conductivity outweighs capacitance behaviour.
As the relaxation behaviour shows itself only in frequencies below 5 mHz and with higher temperatures, it can be neglected in most cases. Using the simplified oil model that models the behaviour of mineral oil with a parallel connexion of capacitance and resistor, the following equation is the result:

$$\underline{\varepsilon}(\omega,T) = -j\frac{\sigma_{(T)}}{\varepsilon_0 \cdot \omega} + \varepsilon_\infty$$
$$with \quad \sigma_{(T)} = \sigma_0 \cdot \exp\left(\frac{-E_a}{(R\cdot T)}\right) \quad (4)$$

For the new mineral oil and for the temperature range $T\in$[283K, 385K] the following coefficients are resulting: $\sigma_0$ = 5, 9626E – 6 S/m, $\varepsilon_\infty$ = 2, 15 and $E_a/R$ = 5005.
If the specific conductivity is laid on the temperature (Fig.:3) $T$ [K], the new mineral oil shows an exponential dependence. This exponential behaviour was confirmed by all the measuring fluids measured during this work and examined during the dissertation works of Mr. Fichtner [2]. One way to emulate the dependency is to use the theory of Arrhenius equation and the activation energy (see Eq. 4). Another possibility is the exponential function $\sigma(T) = a \cdot exp(-b \cdot T)$. Both functions can emulate the thermal behaviour exactly enough only partly, i.e. in sections. It could be shown that especially the Arrhenius equation is the best model for the thermal behaviour in temperature range between 10°C and 85°C. This form of modelling has two significant advantages: the compressing of the measured data and the gaining of information about the material characteristics through the activation energy $E_a$, which is independent of systematic measurement errors. A constant systematic error of the impedance measurement has thus no effect on the calculation of the activation energy [2].
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 new oil shows a sharp bend below 15°C, this run could be de-

scribed with two activation energies. The figure 3 illustrates the behaviour of the specific conductivity of the different oil samples over the reciprocal temperature.

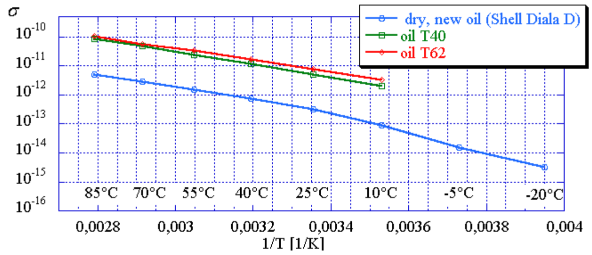


**Figure 2:** Thermal dependency of the specific conductivity of mineral oils with a moisture content of approx. 11ppm (Arrhenius representation)

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 seen as spherical charges moving with the electric field in the measuring fluid. For a constant velocity, the result is a balance of forces between the charge in the field and the Stokes' drag.

The samples T40 and T62 are original mineral oil samples of a transformer. The higher specific conductivity compared to new mineral oil is mainly caused by the acid content. The moisture content has also an effect on the conductivity, however, only for mineral oils, whose acid number and thus the acid content are small. The figure 4 shows, as an example, the moisture content in dependence of the specific conductivity of the new oil and of the oil sample T40 for a constant temperature of $T=298\ K$. A representation independent of the temperature would be the usage of the parameter $\sigma_0$ yielding more or less the same result.

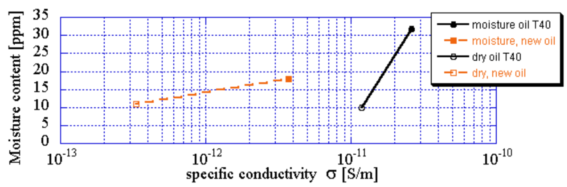


**Figure 3:** Specific conductivity in dependence of the moisture content of new mineral oil and the oil sample T40 at a temperature of 40°C

## Transformer board Model

Parameters like e.g. the state of ageing, thermal behaviour, moisture content, field strength are also of importance for cellulose based systems. However, experimental measurements showed that the model (3) consisting of the terms conductivity, instantaneous polarisation and relaxations could emulate the individual parameters affecting the measurements.

The variation of the results of the measurements can so far only partly be assigned to the individual parameters.

In the following part, to make the changes of the measured data clearer in frequency domain, only transformer board (TIV) with thickness of 1 mm is used in frequency domain between 1 mHz and 40 kHz. The following material samples were used:

**Table 2:** Description of the material samples

| Name | Description |
|---|---|
| TPb-1 | Dry, non-impregnated transformer board TIV |
| TPb-2 | impregnated transformer board TIV with a moisture content under 0,3% |
| TPb-3 | impregnated transformer board TIV with a moisture content of 0,7% |
| TPb-4 | impregnated transformer board TIV with a moisture content of 1,8% |
| TPb-5 | impregnated transformer board TIV after 600h artificial ageing at 120°C |

The figure 5 shows all four material samples at 40°C. The curve run of the sample TPb-1 shows a near to ideal behaviour of capacitance and can be approximated with the equation

$$\underline{\varepsilon}(\omega) = -j\frac{5E-15}{\varepsilon_0 \cdot \omega} + 2.78 \qquad (5)$$

for a temperature range of T∈[283K, 385K].

The thermal behaviour of the specific conductivity could not be determined exactly, as the specific conductivity lies below $\sigma$ = 5E–15 S/m. To determine the conductivity more exactly, it should be measured with smaller frequencies, thus leading to longer duration of the measuring. In comparison to TPb-1, the impregnated sample TPb-2 shows an increase of the instantaneous polarization to $\varepsilon_\infty$=3.8 and of the specific conductivity (see Fig. 6). In addition to that, both samples show the first, minor $\alpha$, $\beta$-relaxations which can be modelled with the equation (3). The exact modelling is at the moment interesting only for the material analysis.

The material samples TPb-2, TPb-3 und TPb-4 differ from each other only through moisture content. Here, the $\alpha$-relaxation gets stronger and the conductivity increases with increasing moisture content.

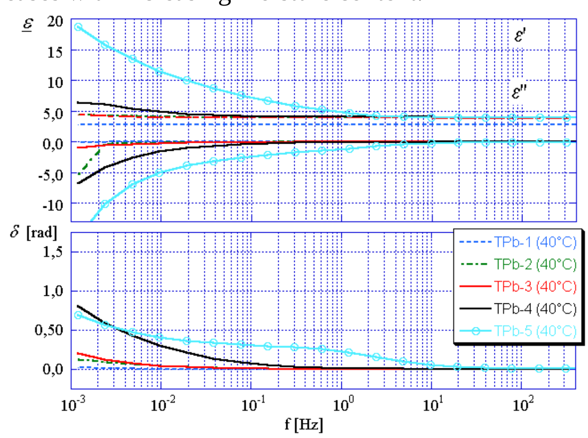


**Figure 4:** Curve run of the complex permittivity of transformer boards TPb-1-5 at 40°C

The sample TPb-3 was artificially aged at 120°C for 600 h. It can be assumed, that the moisture content did not increase significantly, as the water vapour could leave the measuring cell. The run of the curve over the frequency shows two clear $\alpha,\beta$-relaxations and an increase of the specific conductivity. The relaxation and conductivity parameters depend on the temperature and show an exponential behaviour being examined more carefully at the moment.
The temperature-dependent changing of the conductivity can be illustrated with the Arrhenius representation as was done with the mineral oil. As can be seen in the figure 6, the samples show different gradients. The gradient describes the activation energy and is a measure for the state of the cellulose system.

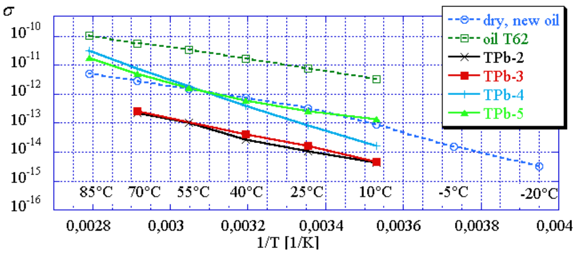


**Figure 5:** Thermal dependency of the specific conductivity of the material samples TPb-1-5 and oils

What comes to the reason for these strong variations, there are basically two possibilities: Firstly, the decomposition substances of the mineral oil and secondly, an increase of the moisture content unable to leave the measuring electrodes. When determining the moisture content, the sample does not show a significant increase after 1000 h.
The general model for the samples TPb-1-4 can be constructed with the equation (3). So far, the specific conductivity can be simulated depending on the temperature. The relaxation times seem to show exponential behaviour.
To be able to determine the model parameters, some time and experience is necessary. A computer algorithm that minimizes this effort through determining the parameters automatically was developed. With these model parameters the amount of data can be decreased and the power transformer with different insulation layers modelled in a simple way. This is briefly described in the next section.

### Power Transformer Model

The power transformer model shall represent the behaviour of the insulation layers between low and high voltage windings, so as to enable proper diagnostics using FDS. The model must:

- consider the power transformer temperature
- enable a simple modelling of the insulation geometry
- enable a simple changing of the insulation parameters

Essentially, every power transformer is an individual. Having measured data, knowledge about the geometrical data and about the behaviour of the insulation geometry in form of the Cole-Cole model, the complex capacitance of the whole transformer can be approximated. Here, the individual insulation capacitances are added like in a capacitance circuit. For a homogeneous field, this approach was described in the paper [3].
At the moment the first transformer models are being examined respective to inhomogeneous fields like a cylinder field and edge fields to improve the accuracy of the model.

## CONCLUSION

As a summary it can be said that it is possible to characterise all basic behaviour of oil-paper insulation systems with the Cole-Cole model with conductivity (3). The conductivity can be determined with a form of the Arrhenius equation in which the so-called activation energy describes the relative change of conductivity respective to the temperature. The parameters of the relaxation are partially constant over the temperature or show exponential behaviour as does the relaxation time $\tau$.
It is difficult to identify the parameters affecting the measurement. Particularly, the effects from moisture content and the acid content of the transformer board can not be exactly enough separated from each other.
So far, the dry impregnated transformer board and the mineral oil can be well emulated over a temperature domain with the equation (4).
At the moment, the transformer model can emulate the transformers only in a simplified way. Inhomogeneous fields, field strength and effects due to the border layers influence the model as well. Now it is attempted to improve the accuracy of the transformer model.

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