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Thema: „Modelling of Oil-Paper Insulation Layers in the Frequency Domain with Cole-Cole Functions“

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Modelling of Oil-Paper Insulation Layers in the Frequency Domain with Cole-Cole-Functions

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Abstract:
Modern impedance analyzers offer the possibility to measure the frequency related conductivity and the complex permittivity $\underline{\varepsilon}(\omega)$ of a sample from a few mHz up to some MHz. Impedance measurements are relatively easy to accomplish and deliver very precise results over a wide range of conductivity and capacitance. Using the measured spectra from oil-paper-confining-layer, inference can as well be made on the mobility of ions & molecules and also regarding the transport-mechanisms. It could be proved that impedance measurements with dry and moist oil-paper-confining-layer-systems show a distinctive permittivity function $\underline{\varepsilon}(\omega)$. For modelling the dielectric performance of pure oil and pure paper systems the Cole-Cole-function approach for dielectric systems was applied.
The modification of the relative permittivity is on one hand caused by polarization processes within the confining-layer-system and on the other hand by lamination on the boundaries between oil and paper. The moisture and temperature have a great impact on the results. One reason is the high relative permittivity of water, the other the heat convection which disturbs the lamination and the polarization.
This paper supplements the theoretical model with experimentally measured data permitting better understanding of complex processes in insulation systems. The model of Oil-Paper Insulation Layers in the Frequency Domain could be used for transformers diagnosis.

1. Introduction

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 aging products in oil, paper and pressboard. Furthermore, the geometrical layout and the type of modelling are very important. To characterise the dielectric behaviour a suitable measuring system and a model to identify the dielectric behaviour is needed.
Initially, this paper describes the theory of impedance measurement and two kinds of models, e. g. the equivalent circuit with RC elements and the Cole-Cole function with conductivity.
The next section explains briefly the measuring setup and the process of data acquisition.
Emphasis is on the relevant properties of the measuring cell, which are necessary to measure insulation materials in frequency domain.
The Cole-Cole function was applied to experimentally measured data of Shell-Diala D and papers at different temperatures and the function parameters were determined.
Eventually, the insulation-layer model with Cole-Cole-function is presented. This model permits the description of the behaviour of insulation layers in the frequency domain.
The goal is to use frequency measurement to make qualitative statements about a power transformer, using the layer model to derive the macrostructural effect from the microstructural properties.

2. Theory

This chapter describes the theory of impedance measurement and two kinds of models like the equivalent circuit with RC elements and Cole-Cole function with conductivity.

2.1. The Complex Permittivity

For the dielectrical measurement the sample material is fixed between two electrodes in a sample container, the so-called sample capacitor. A sinusoidal voltage $u(t)$ with a fixed frequency $f=\omega/2\pi$ and a maximum amplitude U_0 is applied to the sample capacitor. $u(t)$ produces a current $i(t)$ with the amplitude I_0 and the same frequency as the voltage. In general, there will be a phase shift between the sample current and the input voltage. This phase shift can be described with the angle φ. The ratio between $u(t)$, $i(t)$ and the phase angle φ is determined by the electric properties of the sample, for example the permittivity, conductivity and the sample geometry.
Hence, the impedance of the sample capacitor can give by:

$$Z = Z' + jZ'' = U / I \qquad (1)$$

If the capacitance of the empty sample capacitor corresponds to an ideal capacitor, the impedance of the sample capacitor correlates directly with the complex permittivity $\underline{\varepsilon}$ of the sample material. The permittivity can be determined with the formula [1, page 13]:

$$\underline{\varepsilon}_{(\omega)} = \varepsilon' + j\varepsilon'' = \frac{-j}{(\omega \cdot \underline{Z}_{(\omega)})} \cdot \frac{1}{C_0}, \qquad (2)$$

with C_0 as the capacity of the empty sample capacitor. The real part ε' indicates the permittivity of the capacitor material and the imaginary part ε'' indicates the ratio of current in the same phase with the voltage, i.e. the electric loss.
The dissipation factor or $tan\ \delta$ can be calculated from:

$$tan\ \delta_{(\omega)} = \frac{imag(\underline{\varepsilon}_{(\omega)})}{real(\underline{\varepsilon}_{(\omega)})} \qquad (3)$$

For a homogeneous material with a relaxation, the real capacitor can be presented as an equivalent RC circuit.

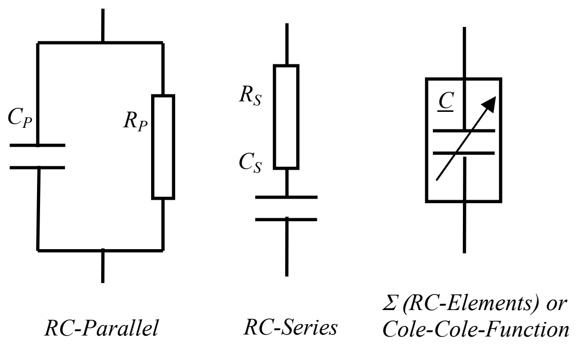

Figure 1 – Equivalent circuit diagrams for lossy capacitors

Many materials consist of different molecules and molecule chains! These molecules can differ significantly from each other in structure, composition and size. Depending on then micro structure, the molecule chains have different properties. Hence, they cannot be described by a simple time constant, but require a set of time constants. To describe a set of clearly separate time constants, the equivalent circuit must be built up with several RC elements [4, page 19]. The sum of RC elements can be represented with a Cole-Cole-function with conductivity as well.

2.2. The Cole-Cole-function with Conductivity

The Cole-Cole-function assumes a distribution $G(\tau)$ of time constants – the so-called relaxation. The following function is obtained through adding the conductivity σ and an additional distribution of time constants to the Cole-Cole-function [1, page 19]:

$$\underline{\varepsilon}(\omega, T) = \underbrace{-j\left(\frac{\sigma_{(T)}}{\varepsilon_0 \omega}\right)}_{\text{Conductivity}} + \varepsilon_\infty + \underbrace{\frac{\Delta\varepsilon_{\alpha\,(T)}}{1 + (j\omega\tau_{\alpha\,(T)})^{n_\alpha}}}_{\alpha\text{-Relaxtion } G(\tau)} + \ldots \qquad (4)$$

Parameters:

σ:	$0 \le \sigma$;	conductivity
ε_∞	$0 \le \varepsilon_\infty$;	permittivity for $\omega \to \infty$
ω	$= 2 \cdot \pi \cdot f$;	angular frequency
T		temperature
α-Relaxation:		
n_α	$0 \le n_\alpha \le 1$;	
$\Delta\varepsilon_\alpha$	$0 \le \Delta\varepsilon_\alpha$;	change of α-permittivity
τ_α	$0 \le \tau_\alpha$;	α-relaxation time

Table 1 – properties of Cole-Cole-Function with conductivity

The advantage of this function is that it attributes the distribution of the time constants more exactly to the corresponding relaxation and takes into account the conductivity.

2.3. Temperature dependency

Knowing the permittivity depends on the temperature permits the temperature-dependant modelling of the capacitance in frequency domain. This is necessary for the analysis and evaluation of individual materials and the diagnosis of power transformers out of serve, where the temperature depends on the environmental conditions.
With the changing temperature T the polarisation mechanisms change as well. This leads e.g. to decreasing relaxation time τ_α of the dipoles. In addition to that, the conductivity and partly also the dielectric constants $\Delta\varepsilon_\alpha$ and ε_∞ change. The influence of the temperature depends on the parameters defined in Table 1, being in most cases constant, linear or exponential for oil and transformer board or paper.

2.4. Measuring Setup and Process

Determining the dielectric properties of liquid and solid insulation material in frequency range between 1 mHz and 40 kHz and temperatures between 10°C and 120°C is demanding: Firstly, the medium must be kept in a stable state, the pressure and the moisture must not change during the measurement. Secondly, the exactness of the measurement must not be influenced by thermal expansion or disturbances.

Moreover, the conductivity of the oil-paper insulation system is very small. This means that the measuring cell must be a good approximation of an ideal capacitor, not affecting the medium and being insensitive to environmental influences.

When measuring liquids, a distance piece is mostly used to keep the measuring plates apart. The distance piece influences the measurement through changes of the electric field and the surface conductivity. Because of this, a metric fine thread was attached to the shield of this measuring capacitor; thus the distance between the plates can be varied and the negative effects caused by the distance piece don't affect the measuring. The measuring cell was conceptually designed as follows:

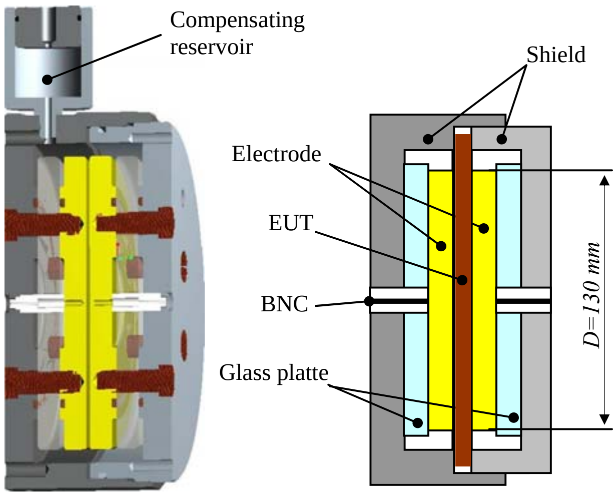

Figure 2 - measuring cell and the schematic setup of the cell

When choosing the material for the measuring cells attention was paid to ensure that no material does emit moisture to the medium or react with it. The shield and the electrodes consist of X8 Cr Ni 18 9 (V2A). They are kept apart by a glass plate. For caulking, thermally and chemically resistant O-ring seals were used. For the filling of the container with liquid material, several bolls were attached to the shield.

The impedance is measured with the impedance analyzer by *Novocontrol*. The climatic exposure test cabinet and the measuring equipment are operated through a PC and monitored and controlled by a temperature sensor attached to the shield of the measuring cell.

The PC controls the measuring process, during which the temperature is kept constant and the complex impedance in the frequency range between 40 kHz and 1 mHz is measured in logarithmic steps.

The measuring results consist of the complex impedance $\underline{Z}$, which is used to calculate the complex permittivity $\underline{\varepsilon}$ using formula (2). The complex permittivity is fit with the Cole-Cole function (4).

During Curve Fitting the imaginary and the real part of the complex permittivity and the dissipation factor (3) were separately fit with the method of least square. After the Kramers-Kronig transforms all the parameters of the imaginary and the real part must be identical, if the system is linear, time-invariant and causal [2, page 154].

3. Model

The following model considers the temperature effect on complex capacitance of two different media: Shell-Diala D and insulations paper. The influences by the quality of the material, deterioration and moisture are not considered here, but can be modelled as well, if the Cole-Cole function or the measured data is known. Extending the model towards several layers with varying thicknesses will be examined more carefully, enabling, for example, a qualitative statement about the states of the power transformers.

It is basically possible to use measured data for the insulation-layer model. Fitting to the Cole-Cole function has proven its value in keeping the amount of data small and making the analysis more effective.

Eventually, the parameters of the Cole-Cole function can be better attributed to microscopic properties, e.g. thermal behaviour, influences due to moisture and mechanisms of deterioration (aging).

3.1. Insulation Oil (Shell-Diala D)

Figure 3 shows a typical permittivity graph of new oil in the frequency domain at temperatures between 40 °C and 110 °C. In this case Shell-Diala-D was used with approximately 10 ppm moisture. The distance between the electrodes was 0.25 mm.

The behaviour of the ε'' curve and the $\tan\delta$ curve show that the conductivity σ of oil is depends strongly on the temperature. An α- and β-relaxation on the curve run of the real part and $\tan\delta$ are also discernible. In temperatures below 40 °C the α-relaxation disappears slowly from the measuring range. The reason for the α-relaxation is barrier layer on the electrode formed by the ions and dipoles and increasing the capacitance in low frequencies [3]. Both relaxations change when the moisture is increased. If the moisture is below 5 ppm no β-relaxation is discernible. This correlation will still be studied more carefully.

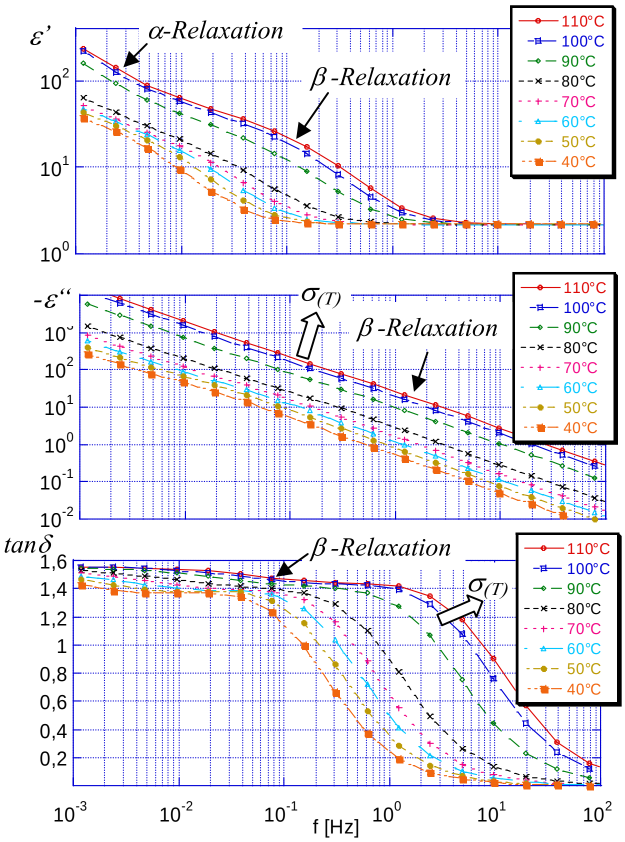

Figure 3 - Dielectric spectra of Shell-Diala D (40°C-110°C)

The following parameters for the Cole-Cole function were obtained as result of the fitting (4):

σ = 3.505 E-13·exp(0,075 · T)+4.55E-12

ε_∞ = 2.1

α-Relaxation:

n_α = 0.84

$\Delta\varepsilon_\alpha$ = 2639 · exp(-0.04058 · T)+311.7

τ_α = 1.522E+004 · exp(-0.04109 · T)

β-Relaxation:

n_β = 0.994

$\Delta\varepsilon_\beta$ = 13.62 · exp(0.00555 · T)

τ_β = 150.8 · exp(-0.04069 · T)

Table 2 – Parameters of Cole-Cole-Functions for Shell-Diala D

The simulation with the Cole-Cole-function (4) made it obvious that the conductivity σ, ε_∞ and the α-relaxation are the dominant parameters.
The β-relaxation can be seen mainly in the *tan δ* curve whereas the α-relaxation does not change the curve noticeably. This means that new oil with ε_∞ and σ from the RC circuit reproduces only coarsely behaviour of the *tan δ* and ε" curves adequately. For a more exact modelling the α- and β-relaxation must also be considered. Furthermore, Table 2 shows that σ, τ_α, τ_β and $\Delta\varepsilon_\alpha$ are temperature-dependant parameters. They were well approximated by the formula y=a·exp(b·T)+c. The other parameters are not influenced strongly by the temperature and can be considered constant.

3.2. Insulation paper

Figure 4 shows a typical graph of the permittivity of new insulation paper in the frequency domain in temperatures between 40 °C and 110 °C. In this case it is insulation paper with approximately 0.7% of moisture. The sample was 0.1 mm thick.
The ε'' curve and the *tan δ* curves shows, that the conductivity of paper does not depend on temperature as strongly as the conductivity of oil. An α- and β-relaxation on the curve run of the real part and *tan δ* are also discernible. In temperatures below 40 °C, the α-relaxation disappears as well from the measuring range and cannot be approximated well anymore. With increasing moisture the α and β relaxations changed remarkably. As for oil, this will be studied more carefully for the insulation paper as well.

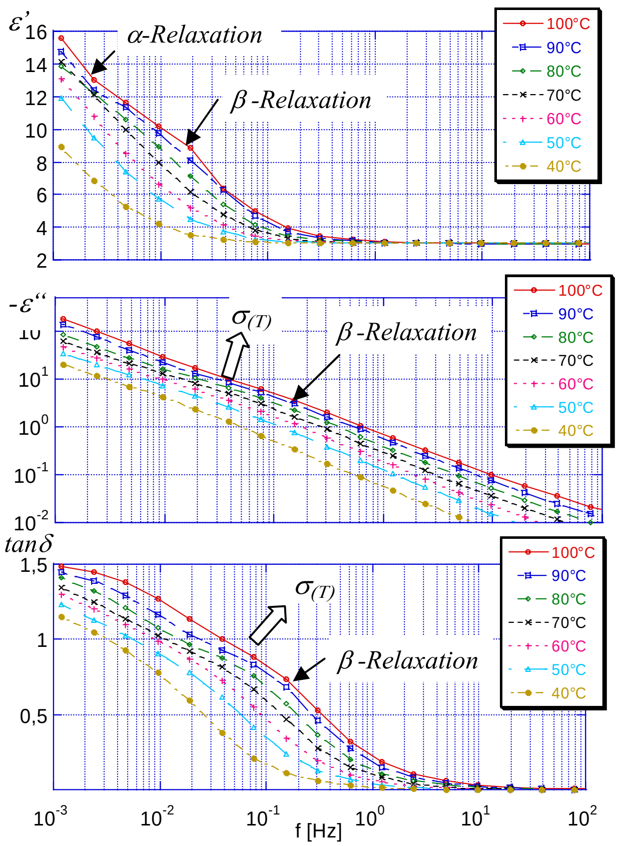

Figure 4 - Dielectric spectra of Paper (40°C-100°C)

The following parameters for the Cole-Cole function were obtained as result of the fitting (4):

	σ	= 1.196e-013*exp(0.04765*T)
	ε_∞	= 2,99
α-Relaxation:		
	n_α	= 0.84
	$\Delta\varepsilon_\alpha$	= 10370 *exp(-0.06776*T)
	τ_α	= 148.4 *exp(193.3 /T)
β-Relaxation:		
	n_β	= 0.84
	$\Delta\varepsilon_\beta$	= 4.566*exp(0.007364*T)
	τ_β	= 1.556 *exp(148.8/T)

Table 3 – Parameter of the Cole-Cole-Function for paper

The table 3 shows that σ, τ_α, τ_β and $\Delta\varepsilon_\alpha$ are temperature-dependant parameters. The other parameters are not influenced strongly by the temperature and can again be considered constant.

3.3. Insulation-layer model

The insulation layer model describes the macroscopic impedance behaviour produced by the different insulation layers in the homogeneous field. Figure 5 shows the idealized model structure with the mediums in rectangular form.

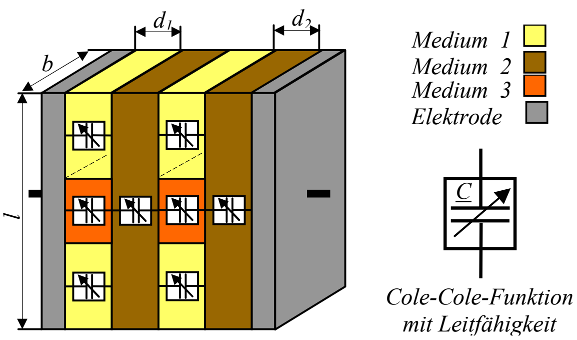

Figure 5 - Insulation layer model

Every medium, like Shell-Diala D, paper or transformer board, has its own special complex dielectric behaviour in frequency domain that can be simulated with a series connection of set of RC elements [4, page 18-21] or with a Cole-Cole function with conductivity. In a uniform electric field the direction of the current is known, which means that the impedance behaviour orthogonal to the electrical field need not be considered.
Figure 5 represents schematically the equivalent circuit of multiple layers with the essential geometric parameters, e.g. the area of the medium $l{\cdot}b$, thickness of the medium d, as well as the number of the layers in the direction of the field, i.e. of the current.
The microscopic complex capacitance $\underline{C}$ of a material contains all the dielectric properties and is determined with the complex Cole-Cole function (4) as follows:

$$\underline{C}_x(\omega,T,..)=\underline{\varepsilon}_x(\omega,T,..)\cdot\varepsilon_0\cdot l\cdot b\,/\,d_x=\underline{C}_{Medium\text{-}x} \qquad (5)$$

The complex capacitance describes the behaviour of a material in the frequency domain $\omega=2\cdot\pi\cdot f$ as a function of temperature T and other parameters, like moisture.
The macroscopic behaviour can be calculated from the parallel connection and the series connection of the individual microscopic capacitances $\underline{C}_{Medium}$ (see Figure 5) from:

$$\underline{C}_{Parallel\text{-}1,3}=\underline{C}_{Medium\text{-}1}+\underline{C}_{Medium\text{-}3} \qquad (6)$$

$$1/\underline{C}_{Reihe}=2/\underline{C}_{Medium\text{-}2}+2/\underline{C}_{Parallel\text{-}1,3}=1/\underline{C}_{Gesamt} \qquad (7)$$

Requirements for the quantitative usage of the insulation layer model are small effects on the boundaries, homogeneous materials of the individual layers and a uniform field. If the effects on the boundaries are not negligible, that behaviour must also be reflected in the model.
In a laboratory test, these conditions are met to a large extent, however not for the diagnosis of power transformers. Nevertheless, it is possible to make qualitative statements about a power transformer by a frequency domain measurement, using the layer model to derive the macrostructural effect from the microstructural properties.
Laboratory studies with simple oil-paper layers showed that the model approximates the measured data well, with variable order of the layers and in different temperatures.

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