Abstract: If the insulation system is considered as a linear system, transformation of data from one domain to another domain is possible. In this paper transformation of data from time to frequency domain for impregnated pressboard will be presented. Both frequency and time domain measurements are carried out on impregnated pressboard. The accuracy of different transformation methods and their limits are studied. Several methods for transformation of PDC data are investigated in details. The first method is considered as an approximated analytic function using the general relaxation response. The second method is based on extended Debye model for the impregnated pressboard to obtain FDS data. The last method is a numerical integral form of transformation. All methods show similar results. However non-linearity exists in the insulation system caused small errors in some cases, which have to be analyzed in order to demonstrate the limits of the used methods.

Review of Theory

Some approaches for describing a dielectric medium exist. It can be defined in time domain or frequency domain. In time domain, the dielectric material is characterized in low frequency with dielectric response function $f(t)$, DC conductivity $\sigma_0$ and high frequency component of relative permittivity $\varepsilon_\infty$ [2].

In frequency domain, it can be described with real and imaginary part of complex permittivity $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ respectively. Also Debye extended model can be used for this purpose. If the dielectric material is a linear system, all models give the same information, and a transformation of data from one model, to the other model is possible.

Dielectric response function

The electrical polarization $P(t)$ in a dielectric material can be divided into two parts, one part representing "rapid" polarization and one part representing "slow" polarization processes [3].

$$P(t) = \varepsilon_0(\varepsilon_\infty - 1)E(t) + \Delta P(t)$$
$$= \varepsilon_0(\varepsilon_\infty - 1)E(t) + \varepsilon_0 \int_0^t f(\tau)E(t-\tau)d\tau$$

(1)

The "rapid" part follows the applied electric field whereas "slow" part is built up from a convolution integral between the applied electric field and a function called the dielectric response function $f(t)$. Equation 2 shows the relation between $f(t)$ and depolarization current.

$$i_{dep}(t) = -C_0 U_c \int f(t) dt + T_c$$

(2)

$C_0$ is the geometric or vacuum capacitance of test object and $U_c$ the charging voltage. As $f(t)$ is a monotonically decaying function, the second term in (2) can be neglected for large values of $T_c$ and the depolarization current becomes proportional to the dielectric response function [4].

$$f(t) = -\frac{i_{dep}(t)}{C_0U_c}$$

(3)

The complex dielectric susceptibility $\chi(\omega)$ is related to $f(t)$ with Fourier transform as (4).
\[ \chi'(\omega) - j\chi''(\omega) = \int_0^\infty f(t)e^{-j\omega t} \, dt \quad (4) \]

If \( f(t) \) is an analytic function, which has a Fourier transform, the transform can then analytically be calculated [3]. However, a numerical integration can perform the transformation [5,6].

\( \epsilon'(\omega) \) and \( \epsilon''(\omega) \), real and imaginary part of the complex relative permittivity are measurable values and with (5) and (4) are related to dielectric response function.

\[ \begin{align*}
\epsilon'(\omega) &= \epsilon_\infty + \chi'(\omega) \\
\epsilon''(\omega) &= \frac{\sigma_0}{\epsilon_\infty \omega} + \chi''(\omega)
\end{align*} \quad (5) \]

**Extended Debye Model**

Figure 1 shows an extended Debye model for oil-pressboard insulation. \( R_\infty \) is the insulation resistance of the insulation between the electrodes for long time. Each series circuit represents a relaxation process in the insulation, shown as \( R_1 - C_1, R_2 - C_2, \ldots, R_n - C_n \).

![Extended Debye Model Diagram](image)

**Figure 1: An extended Debye model**

Referring to Figure 1, it is clear, that the full depolarization current is composed from different components of relaxation current expressed by (6):

\[ i_{dpol} = \sum_{k=1}^{n} a_k e^{-t/\tau_k} \quad (6) \]

Where \( \tau_k \) is the relaxation time constant \( (R_k C_k) \) and \( a_k \) (7) is the coefficient related to charging voltage, charging duration and relevant relaxation branch parameters.

\[ a_k = \frac{(U_c e^{-t_j/\tau_j})}{R_k} \quad (7) \]

To obtain the parameters of equivalent circuit from PDC data, several methods can be used: e.g. a method with fix time constants [4], a nonlinear least square optimization technique [7,8] or consideration of exponential functions which each function is fitted on a part of depolarization current [9]. After dielectric modeling of test object, dielectric parameter of specimen from equivalent circuit can be calculated.

**Hamon Approximation**

An alternative for fast calculation of the frequency domain data from the time domain is the Hamon approximation if the measured depolarization current can be approximated with \( Ar^n \) function (a line in log-log scale) [10]. According to the Hamon approximation only the imaginary part of the complex susceptibility \( (\chi') \) will be considered. If \( n \) is in the range 0.3 < \( n \) < 1.2, it can be written as [11]:

\[ \chi''(\omega) = \frac{-i_{dpol}}{2\pi fC_0 U_c} \left( \frac{0.1}{f} \right) \quad (8) \]

**Experiments and Results**

Figure 2 shows the electrodes arrangement for experimental setup. Before the test began, the specimen remained in short circuit case until very low-level detectable current was achieved in order, to ensure similar condition for the measurements. A sealed vessel has been used for oil-press board samples.

![Electrodes Arrangement](image)

**Figure 2: Arrangement of electrode and test object**

Figure 3 shows PDC of unaged 2 mm impregnated pressboard. Charging Voltage is 200 V and charging period 25000 s.

![PDC of new impregnated pressboard](image)

**Figure 3: PDC of new impregnated pressboard**

For transformation of PDC data to frequency domain also these data are used. Geometrical capacitance is 22.2 pF, calculated from electrode configuration and the relative permittivity at 50 Hz is
chosen as $\varepsilon_r$. Figure 3 shows that consideration of depolarization current curve as universal curve [11] with two slopes has a limitation. The change of the depolarization curve over some decades makes difficulties for the fitting methods. Relative error of small values becomes high but it has no effect on the total error. However in the very low frequency range the conduction loss is the major part of the total losses and therefore the behavior of dielectric function of very long time has no important effect on the loss curves.

Figure 4 shows the results of transformations method and measured values for real part of complex capacitance of test object. Application of relative permittivity at 50 Hz causes a shift between models and measured value. But this error is less than 5 percent of measured value and the curves are approximately parallel.

![Figure 4](image1.png)

Figure 4: Measured and calculated models of real part of complex capacitance as function of frequency for an impregnated pressboard

The imaginary part of complex capacitance is shown in figure 5. The sampling rate of PDC is 0.33 sample/s and the first sample is taken at 2 s after switching (supply or short circuit), then the maximum frequency for transformation 0.1 Hz is selected. The difference between calculated models and measured values in higher frequency range is justified with loss of dielectric function data before 2 s. Universal dielectric functions have more error compared to another methods, due to already mentioned limitation. Figure 6 shows results of PDC measurement on 2mm impregnated pressboard, with a 3mm oil duct. In this case the geometrical capacitance is reduced to 8.88 pF. The transformation results are shown in figure 7 and 8.

![Figure 6](image2.png)

Figure 6: PDC of new impregnated pressboard with oil duct

The agreement of multi exponential method and integral method is good. Universal dielectric response has in this case more error in the very low frequency range as already explained.
Figure 8 shows the imaginary part of complex capacitance. The error of Hamon approximation at 0.1 mHz which is transformed from depolarization current at 1000s is relatively high. The slope of depolarization curve at this time is approximately 2. For a successfully application of Hamon approximation it must be smaller than 1.2. In the very low frequency range, these models are similar because conduction loss is an important part of total loss.

![Figure 8: Measured and calculated models of imaginary part of complex capacitance as function of frequency for an impregnated pressboard with oil duct](image)

**Conclusion**

In this paper it is shown that transformation of dielectric time domain measurement to frequency domain with the good accuracy is possible, however the accuracy is limited by the accuracy of calculation of geometrical capacitance of the test object and different behaviors in conduction and polarization in DC and AC electric field as a result of non-linearity of dielectric medium.

Universal dielectric response can be used for this reason, but if the curve of depolarization current has more than 2 slopes in log-log diagram, accuracy of fitting result and as consequence accuracy of transformation is reduced.

Direct numerical integral method has a good ability to transformation of data especially in the lower frequency range.

Decomposition of depolarization current to some exponential function is another successfully applied method. The obtained parameters should be positive, as physically basis.

The results of Hamon approximation show the ability of this method for transformation of PDC data of impregnated pressboard to frequency domain, although the depolarization current of impregnated pressboard has more than 1 slope in log-log diagram. However if the slope of curve is not within the limitation of approximation, the accuracy of transformation will be reduced.

**Acknowledgment**

We wish to thank Deutsche Forschungsgemeinschaft for their support and GE Energy Management Services GmbH and Programma Electronic AB for letting us to use the IDA 200 Insulation Diagnostic System for the frequency domain measurements.

**References**


**Author address:** Amir Abbas Shayeangi Akmal, Institute of Electric Power System, Division of High Voltage Engineering (Schering-Institut), University of Hannover, Callinstr. 25A, D-30167, Germany

Email: shayeangi@mbox.s1.uni-hannover.de.