DIELECTROMETRY MEASUREMENTS OF SPATIAL MOISTURE PROFILES IN OIL-IMPREGNATED PRESSBOARD

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Abstract – The dielectric spectrum of pressboard, (i.e. its complex permittivity as a function of frequency), is related to its moisture content and to its temperature. Consequently, it is possible to use dielectrometry measurements to measure a pressboard sample's moisture content. A method of calculating the complex permittivity of pressboard involves interdigitated electrodes, applied only to one surface of the sample. Since the electric field's depth of penetration is dependent on the spatial wavelength of the electrodes, different sensors yield information from different depths in the material, making it possible to measure spatial distributions of the dielectric properties. This can allow the study of the diffusion of water in pressboard.

INTRODUCTION

It is important to monitor the moisture content of the pressboard used as insulation in high-power transformers, because its conductivity increases the dissipated power and the rate of static charge relaxation, which is a crucial factor in static electrification phenomena.

Load transients which transformers undergo, especially upon power-up, cause rapid changes in the insulation's temperature. Temperature affects the solubility equilibrium of moisture between the solid and liquid insulation and also directly influences the insulation's conductivity. Moisture in the oil may under temperature transients result in free water in the oil that can lead to electrical breakdown. A mass transfer process of water results from the equilibrium imbalance, in which at higher temperatures moisture leaves the pressboard to enter the oil. As a result complex dynamic processes take place, such as the formation of interfacial dry zones which are highly insulating, so that surface charge can significantly accumulate to cause spark discharges. Such critical conditions can lead to a high level of static electrification and possibly catastrophic failure of the unit. It is therefore important to be able to monitor the moisture dynamics in such systems, in order to understand the failure mechanism and to prevent critical conditions.

The *dielectric spectrum* of a material is a representation of its complex permittivity, $\epsilon^* = \epsilon' - j\epsilon''$, as a function of frequency. The real component ϵ' gives the dielectric constant while the imaginary component ϵ'' determines the power dissipation (loss) in the material.

Once it is known how the dielectric spectrum of oil-impregnated pressboard varies with temperature and moisture, it is possible to measure the moisture content in a sample by taking a frequency scan and comparing the results to the known calibration mapping. This type of mapping is unique to every type of paper and may depend on the amount of impurities in it.

In this paper we present how a multiple-wavelength interdigitated sensor is used to determine the spatial variations of the dielectric properties of materials. Since the dielectric properties of pressboard are directly related to its moisture content, moisture profiles can be obtained from these measurements.

INSTRUMENTATION

The interdigital flexible sensors probe the material from only one surface via a set of interdigitated electrodes, as shown in Figure 1. The electrodes are deposited on a flexible Kapton (a polyimide) substrate. The entire structure is then coated with 5 μm of Parylene which protects the surface from contamination [1, sec. 6.2.2]. The depth of penetration of the applied electric field is directly proportional to the spatial wavelength of the sensor. A driving AC potential with a magnitude of 1 V is applied to one set of electrodes and the frequency is varied from 0.005 to 10,000 Hz. The three-wavelength (3-λ) sensor, shown in Figure 2, is a combination of three interdigitated flexible sensors placed on the same substrate. It enables simultaneous measurements at three different spatial wavelengths: 5.0 mm, 2.5 mm, and 1.0 mm [1, sec. 6.3.1].

Interpretation of data taken with an interdigital sensor is difficult because the potential distribution is two-dimensional and the driving potential is represented by an infinite number of Fourier modes, each of which sees a *different* complex surface capacitance density at the plane of the electrodes [3, sec. 2.3]. The complex surface capacitance density is used to relate the potential to the sum of conduction and displacement current densities at the electrode surface and thus gives the complex impedance of the sensor. A further difficulty is that the potential is imposed only along the electrodes.

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Figure 1: Imposed ω-k dielectrometry. [1]

Figure 2: Structure of the three-wavelength interdigitated sensor. [1]

Between the electrodes the surface potential must be calculated from conservation of charge at the interface. These complications make it impossible to find an analytical solution even for the *forward problem* of finding the complex impedance of the sensor as a function of the material above it. A numerical method [2] [3] [5] is used to calculate the complex impedance of the sensor from the dielectric properties of the layer structure.

In reality it is seldom necessary to solve the forward problem. Instead, the complex impedance is usually measured, and this information is used to infer unknown properties of the medium. A variety of numerical root-finding one- or multidimensional algorithms can be used for this kind of data processing [3] [5]. They are described under ESTIMATION ALGORITHMS.

The dielectric spectrum of pressboard is a function of the temperature and of its moisture content. This property can be used to estimate the amount of water present in a sample by performing a dielectrometry measurement and comparing the results to an established mapping [4] [5] [6].

EXPERIMENTAL PROCEDURES

In this section we describe the various experimental setups used with the 3-λ sensor to measure spatial profiles. For the data shown in Figure 4 the sensor was simply immersed in a container full of oil, making sure the walls of the container were at a distance greater than the penetration depth of the longest wavelength (about 4 mm) away from the active surface. Since the top plate was well within the reach of the electric fields of the sensor, its presence had to be accounted for in the numerical calculations.

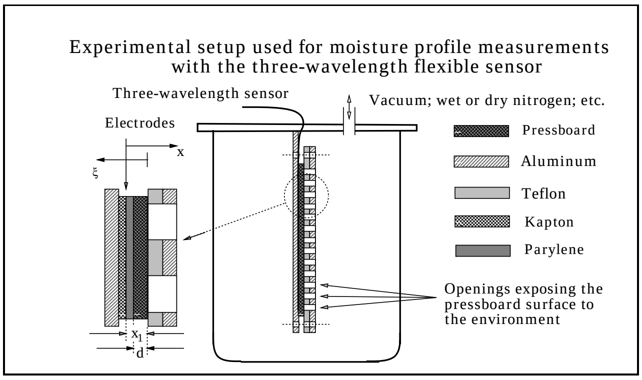

Figure 3: Experimental setup for profile measurements taken with the 3-λ sensor

In order to measure moisture profiles in pressboard, the sample had to be placed in a controlled environment, which allowed moisture to diffuse in and out of the pressboard from one surface. The other surface of the sample was sealed by the sensor itself. For this purpose the experimental setup shown in Figure 3 was created. The stainless steel chamber can be filled with transformer oil, whose moisture content can be varied by bubbling wet or dry nitrogen through it, or the chamber can remain full of air, as was done in the experiments presented in the next section. Since intimate contact between the pressboard and the sensor needs to be maintained, the sample has to be tightly squeezed from both sides. The teflon and aluminum layers serve this purpose, while at the same time allowing mass-transfer processes to occur at that surface through a multitude of holes.

ESTIMATION ALGORITHMS

These algorithms solve the *reverse* problem, i.e. calculating the dielectric properties of one or more unknown layers from the gain and phase of the response.

One-Dimensional Search

This approach has been used before for interpreting results from interdigitated sensor measurements [3] [2] [1]. It uses the Secant Method for root-finding. There can be an arbitrary number of known layers, in addition to one unknown layer. Data from only one wavelength is taken, since the problem has only one degree of freedom. A single complex number, ϵ^*, is calculated from a complex gain.

Applying this method to each of the three wavelengths of the 3-λ sensor with a homogeneous medium should produce the same results in all three cases. This provides a good test for the working condition of a multiple-wavelength sensor. Figure 4 shows the results from applying this algorithm to data taken with the 3-λ sensor in Shell Diala A transformer oil.

Conversely, if the results from a 3-λ sensor in good condition disagree, that will mean that the assumption of a homogeneous unknown layer is invalid, indicating an x-dependence (see Figure 1) of ϵ^* in the material. Such a case for a pressboard sample is shown in Figure 5, where the longest-wavelength sensor sees the lowest conductivity, suggesting that the region furthest from the sensor is least conducting. This result is confirmed by the multi-dimensional algorithm, as discussed in a later subsection.

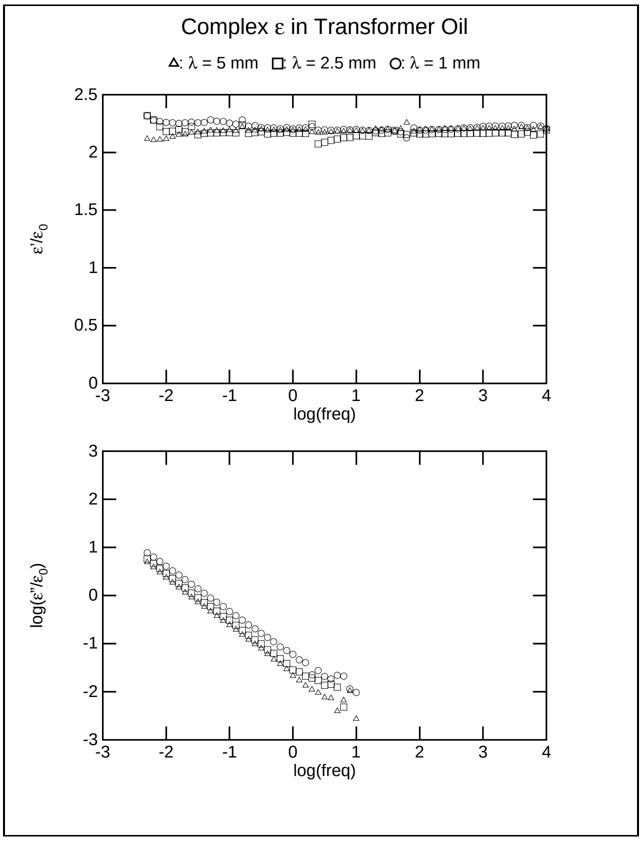

Figure 4: Dielectric spectrum of Shell Diala A transformer oil, taken with the 3-λ sensor.

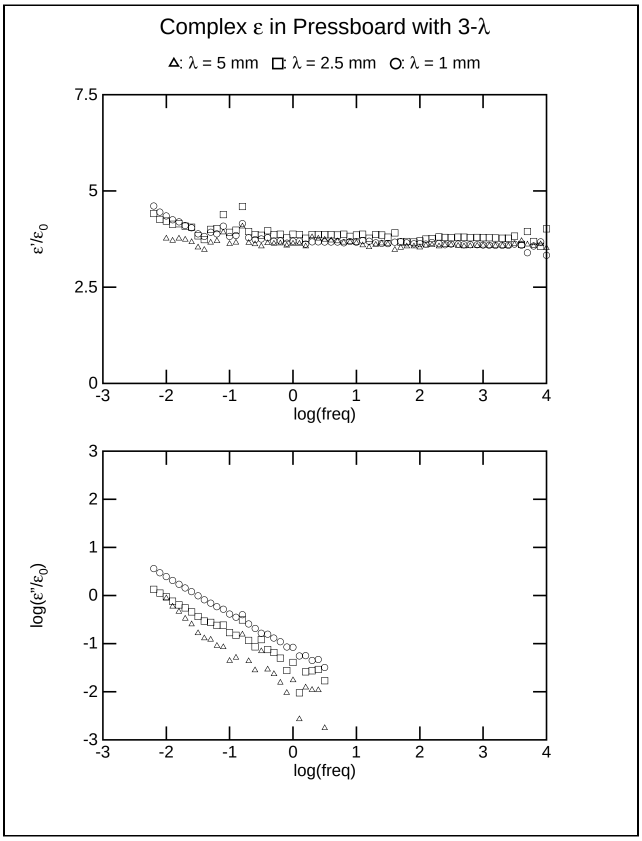

Figure 5: Dielectric spectrum of EHV-Weidmann HIVAL pressboard, taken with the 3-λ sensor.

Marching Approach

This is an approach that deals with inhomogeneous materials, which avoids the complications associated with multidimensional searches. It is only applicable when there is a single layer of material.

An assumption is made that every sensor has a depth of penetration into the material equal to $\alpha\lambda$, where λ is the spatial wavelength of the sensor and α is a parameter which represents the discreteness of the assumed regions. We are allowed some freedom in choosing α in order to aid convergence. This parameter usually takes up values between 0.1 and 0.5, nominally 0.25[1] [3]. We can approximate the inhomogeneity of the medium by several homogeneous sublayers, with the sublayer boundaries at $x = \alpha\lambda_n$. We have not used the marching approach with the 3-λ sensor, because the greater flexibility of the multidimensional search, described in the next subsection, is better fitted to our problem.

Multidimensional Search

This approach allows the estimation of the dielectric properties of more than one unknown layer by combining measurements from several sensors of different spatial wavelengths. One degree of freedom is associated with every spatial wavelength. Therefore the number of unknown layers must equal the number of sensors. With our three-wavelength sensor we may estimate the properties of three unknown layers simultaneously.

This method has the advantage that an arbitrary number of known layers may be included in the layer structure. In addition, if we were to use this method to calculate profiles in an inhomogeneous material by approximating it with a stair-step function, we would be free to choose the widths of every sublayer, unlike the marching approach, where the widths were determined by the wavelengths of the sensors. At least one unknown layer must fall within the reach of every sensor and every unknown layer must fall within the reach of at least one sensor, as required for convergence [5].

Case studies of this method indicate that convergence is always reached if every unknown layer is well within the scope of at least one sensor [5]. However, in those cases the method was applied to error-free computer-generated gain-phase data, which meant that there always was a solution. Instrumentation errors inherent in every measurement may cause the problem to have no solution. This obstacle can be overcome by allowing for a larger tolerance in the convergence test.

When this method was applied to data obtained from measurements with the setup shown in Figure 3 on oil-impregnated pressboard at 0.01 Hz, the results shown in Table 1 were obtained. These results are consistent with moisture diffusing out through the exposed surface of the pressboard into air with a lower relative humidity. The pressboard sample's dielectric profile was approximated by a stair-step function, namely layer numbers 2, 3, and 4. (Layer numbers 0 and 1 are the aluminum and teflon respectively and layer number 5 is the parylene coating, which falls between the sensor and the

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Layer #	Width	Permittivity	Conductivity
2	0.80 mm	2.63×10^{-11}	0.0
3	0.25 mm	4.74×10^{-11}	6.48×10^{-14}
4	0.05 mm	2.35×10^{-11}	3.23×10^{-12}

Table 1: Results from the multidimensional search method applied to an inhomogeneous sample of oil-impregnated pressboard at 0.01 Hz

pressboard. See Figure 3.) Layer number 4, which is closest to the sensor, displays the highest conductivity, as suggested by the plots in Figure 5. There is a slight inconsistency in these results, because on the right side of the loss peak higher values of $\epsilon'' = \sigma/\omega$ must correspond to higher values of ϵ', as required by the Kramers-Krönig Relations [7, Sec 2.8]. This can be accounted for by an extra oil layer formed between the pressboard and the Parylene, due to the rough surface of the pressboard [5]. The values of the conductivity listed in Table 1 correspond to a moisture content of 2.6% for layer number 4, and near 0% (too low to estimate) for layers 2 and 3 [4].

Multidimensional Search with an Assumed Profile Function

This method is very similar to the one described in the previous subsection. It allows for one unknown inhomogeneous layer, whose dielectric properties can be represented by a smooth function of x. The unknowns are several parameters of this function. The motivation behind this method is that some knowledge about the physics of the inhomogeneous layer may be incorporated into the estimation algorithm to gain a better approximation to the spatial profile than a stair-step distribution can provide.

Based on arguments related to water diffusion in pressboard [5] and the dependence of the dielectric properties of pressboard on moisture [4], we arrive at the final functional form describing the complex dielectric profile of the unknown inhomogeneous pressboard layer at a time t:

$$\epsilon^* = \epsilon_\infty + \epsilon_0 \left[\frac{1}{\omega} \left(A + B \sum_{n=1,\mathrm{odd}}^{\infty} \frac{4}{\pi n} e^{-Dtk_n^2} \sin k_n \xi \right) \right]^{-\gamma}$$

where $\epsilon_\infty = \epsilon'(\omega \to \infty)$, $k_n = \pi n / 2d$, and $\xi = x_1 - x$ (see Figure 3).

Since $\gamma \approx -0.7$ (the logarithmic slope) and $\epsilon_\infty \approx 2.9 \times 10^{-11}$ are known parameters of pressboard [4], ϵ and σ are fully determined by the three unknown parameters A, B, and Dt. This corresponds to three degrees of freedom, i.e. measurements with three wavelengths are enough to fully determine the spatial profile. For simplicity in this derivation we have assumed that the diffusion coefficient D is constant throughout the entire sample. Although values for D can be measured, we may not know the value of t, so the product Dt is treated as an unknown parameter. For the purposes of the numerical algorithm, the inhomogeneous layer is approximated by a number of homogeneous sublayers, but unlike the multidimensional search, for the method described in this subsection the number of such sublayers is not limited by the number of degrees of freedom, and the smooth profile function can be approximated as closely as we wish. We are currently working on applying this method to results from experiments.

Conclusions

Flexible sensors with different spatial wavelengths may be used to extract information about the spatial profile of the dielectric properties of a material by combining the results of several sensors of different spatial wavelengths.

Three different methods of processing the data from such measurements exist: the marching approach, the multidimensional search, and the multidimensional search with a given profile function. The first method is simpler and more reliable, but it is not applicable to more complex structures. The first two methods approximate the profile with a stair-step distribution. The third method attempts to include in the estimation algorithm some knowledge of the physics of moisture diffusion, by using a smooth function to represent the variation of the dielectric properties of the pressboard across its thickness.

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