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# DIELECTROMETRY MEASUREMENTS OF MOISTURE DYNAMICS IN OIL-IMPREGNATED PRESSBOARD

Y. Sheiretov and M. Zahn

Massachusetts Institute of Technology
Department of Electrical Engineering and Computer Science
Laboratory for Electromagnetic and Electronic Systems
Cambridge, MA 02139

## 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. The complex permittivity of pressboard is measured in two different ways. The first method places the sample between two parallel metal plates, in effect creating a lossy lumped capacitor, whose complex impedance can easily be measured. The complex permittivity thus calculated is effectively averaged across the sample's bulk. The other method 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 can obtain 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 determines the dissipated power and the rate of static charge relaxation and is thus 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 from the pressboard that diffuses into 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 as a function of frequency. The real component of the complex permittivity gives the dielectric constant while the imaginary component 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 will be possible to measure the moisture content in a sample by taking a frequency scan and comparing the results to the known calibration mapping.

In this paper we present a *universal spectrum*, which represents a mapping of the dielectric spectrum of EHV-Weidmann HIVAL pressboard, impregnated with Shell Diala A transformer oil, versus temperature and moisture content. We also discuss experiments with interdigitated sensors of multiple wavelengths.

## INSTRUMENTATION

Measurements were taken with the parallel-plate sensor, which is essentially a lossy capacitor, with the two parallel plates in physical contact with the test sample. Its structure is shown in Figure 1 and its equivalent circuit representation is that of a resistor and capacitor in parallel. A driving AC potential with a magnitude of 1V is applied to one of the plates and the frequency is varied from 0.005 to 10,000 Hz. The other plate is loaded with a known parallel resistor and capacitor impedance to ground, which is in series with the test sample. The magnitude and the phase of the potential $\hat{V}_{OUT}$ at the second plate are measured with respect to the driven potential $\hat{V}_{IN}$ and this information is used to determine the resistive and the capacitive components of the impedance of the test cell.

Let $Z_T = R_T + 1/j\omega C_T$ be the unknown test impedance and $Z_L = R_L + 1/j\omega C_L$ be the known load impedance. Then the measured potential across the load impedance

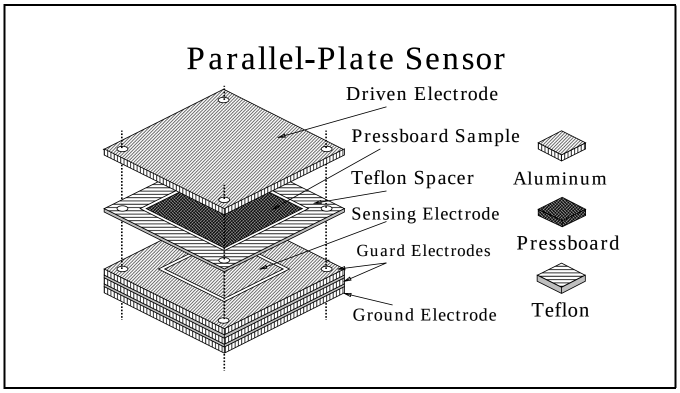

Figure 1: Structure of the parallel-plate sensor

can be expressed as a voltage divider relation:

$$\hat{V}_{OUT} = \frac{Z_L}{Z_T + Z_L}\hat{V}_{IN}$$

and from this we obtain expressions for $R_T$ and $C_T$ as functions of the magnitude $M$ and the phase angle $\varphi$ of the response:

$$\begin{aligned}\frac{1}{R_T} &= \frac{(M\cos\varphi - M^2)(1/R_L) - M\sin\varphi\,(C_L\omega)}{1 + M^2 - 2M\cos\varphi}\\ C_T &= \frac{M\sin\varphi\,(1/R_L\omega) + (M\cos\varphi - M^2)C_L}{1 + M^2 - 2M\cos\varphi}\end{aligned}$$

The complex permittivity data of the pressboard normalized with respect to $\epsilon_0$ can then be expressed in terms of the measured impedances:

$$\frac{\epsilon^*}{\epsilon_0} = \frac{\epsilon'}{\epsilon_0} - j\frac{\epsilon''}{\epsilon_0} = \frac{\epsilon}{\epsilon_0} - j\frac{\sigma}{\omega\epsilon_0} = \frac{C_T}{C_{AIR}} - j\frac{1}{R_T C_{AIR}\omega}$$

where $C_{AIR}$ is the capacitance of the sensor in air, $\epsilon$ is the permittivity, and $\sigma$ is the conductivity.

## Universal Spectrum

The dielectric spectrum of pressboard is a function of the temperature and of its moisture content. This property can be used to measure the amount of water present in a sample by performing a dielectrometry measurement and then comparing it to an established mapping. The object of this set of experiments is to present a methodology for obtaining such a mapping and to examine the nature of the suggested functional dependence.

In an *ohmic* material $\epsilon$ and $\sigma$ are independent of the frequency or amplitude of the applied electric field and a plot of $\log(\epsilon''/\epsilon_0)$ versus $\omega$ has a slope of $-1$. In a *dispersive* material, when $\epsilon''$ is plotted against frequency on a log-log scale, it can be characterized by one or more *loss peaks*. The magnitude of the slope at which these peaks are approached on either side is between 0 and 1 for most materials [1, pp. 163–200]. For every loss peak in the $\epsilon''$ spectrum, there is an associated elevation in the $\epsilon'$ spectrum [1, pp. 47–52].

Often the shape of the loss peaks is independent of moisture and temperature. They only shift position. It should therefore be possible to create a single universal spectrum, to which all other spectra map, after having been shifted (horizontally with frequency and/or vertically) by an amount which is a function of the temperature and moisture content. The goal of this set of experiments is to find that function and a corresponding universal spectrum.

## Experimental procedures

Seven samples of 40 mil thick EHV-Weidmann HIVAL pressboard, were dried under vacuum for different lengths of time in order to give them different moisture contents. Each sample was then impregnated with Shell Diala A transformer oil and tested at temperatures between 30°C and 70°C. A ‘test’ in this sense was a set of complex impedance measurements at frequencies ranging from 0.005 to 10,000 Hz, spaced evenly on a logarithmic scale. Four hours were allowed after a temperature change to let thermal transients die away.

The moisture content of the pressboard samples was measured twice, immediately before and after the frequency scans were made. A Mitsubishi VA-05 Vaporizer was used, with the Mitsubishi CA-05 Moisture Meter.

Table 1: Relative logarithmic frequency shifts for data at different temperatures and moisture contents. Reference curves are at 50°C and 2.4% moisture (shown in bold).

| | 30°C | 40°C | 50°C | 60°C | 70°C |
|---|---|---|---|---|---|
| 0.42% | -1.6 | -1.3 | -1.0 | -0.7 | -0.4 |
| 0.83% | -1.8 | -1.3 | -1.0 | -0.7 | -0.3 |
| 1.1% | -1.2 | -0.9 | -0.6 | -0.3 | 0.1 |
| 1.8% | -1.3 | -1.0 | -0.6 | -0.3 | 0.2 |
| 1.8% | -1.1 | -0.7 | -0.4 | -0.2 | 0.1 |
| 2.2% | -1.4 | -0.9 | -0.5 | -0.2 | 0.2 |
| 2.4% | -0.7 | -0.4 | **0.0** | 0.4 | 0.5 |

Table 2: Average frequency shift due to temperature

| 30°C | 40°C | 50°C | 60°C | 70°C |
|---|---|---|---|---|
| -0.73 | -0.33 | **0.0** | 0.31 | 0.65 |

Table 3: Average frequency shift due to moisture

| 0.42% | 0.83% | 1.1% | 1.8% | 1.8% | 2.2% | 2.4% |
|---|---|---|---|---|---|---|
| -0.96 | -0.98 | -0.54 | -0.56 | -0.42 | -0.48 | **0.0** |

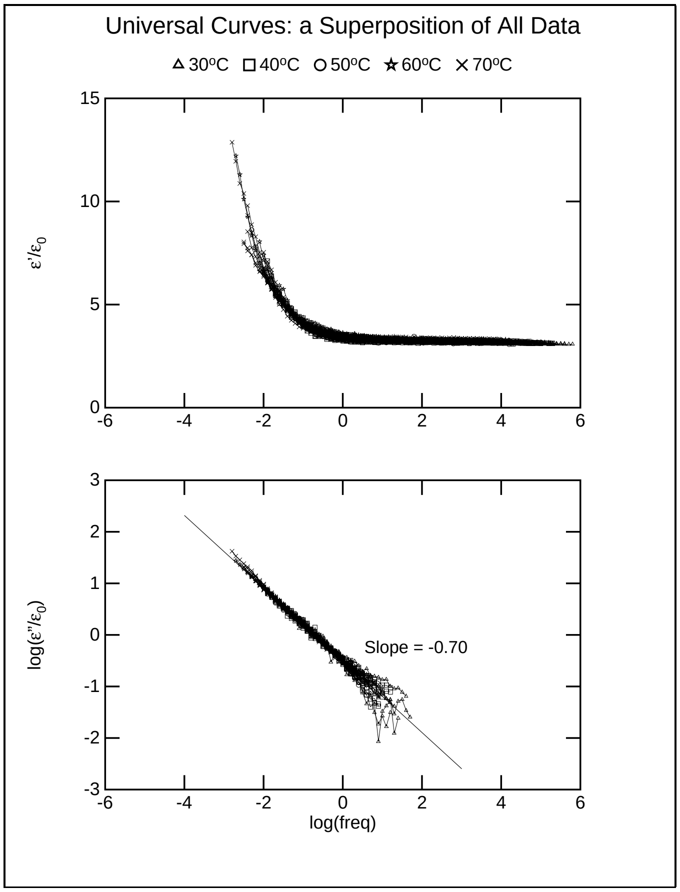

Figure 2: Universal dielectric spectrum of pressboard

After oil-impregnation, we allowed the samples to rest for a few days, to let the moisture redistribute itself across the thickness of the pressboard. This was necessary because during the impregnation process the surfaces of the sample were exposed to relatively wetter oil and might acquire a different moisture content than the bulk. The transient associated with this conditioning process has a time constant of about 30 hours [2].

## Results

No loss peaks are visible in the experimentally measured spectra of the pressboard samples; $\epsilon''$ data falls on straight lines of negative slope[1]. This indicates that the material is so insulating, that the loss peak occurs at frequencies below 0.005 Hz, which is the lower limit of our equipment. As a result there is an extra degree of freedom in the mapping of the loss curves to one another. We have made the choice that frequency spectra be shifted only horizontally (i.e. in frequency), which is motivated by other similar experiments [3] [4]. A least-squares fitting technique [2] was then used to find by how much every frequency spectrum has to be shifted in order to match a reference curve. Figure 2 shows a superposition of 35 spectra, which have been shifted by the amounts shown in Table 1. Although only one loss peak is implied in these spectra[2], at high moisture contents (greater than 3%) a second loss peak becomes visible, suggesting that water at higher concentrations exists in a different band state [5].

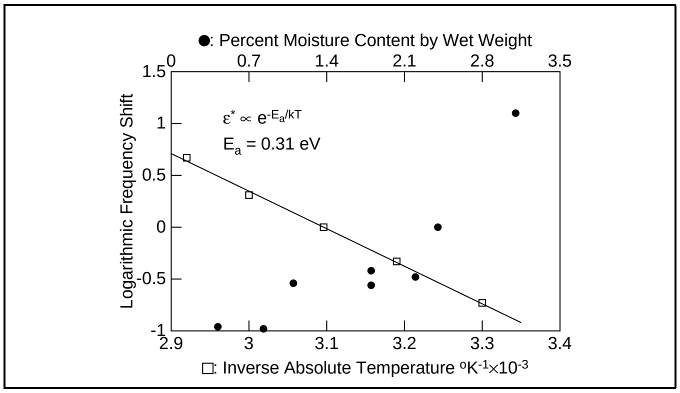

Figure 3: Frequency shift as a function of temperature (an Arrhenius plot, bottom axis), and moisture (top axis) for oil-impregnated pressboard:

The next step is to relate the frequency shifts shown in Table 1 to the samples' temperatures and moisture contents. Some processing of the data shows that the effects of temperature and moisture can be considered *independent* of each other, yielding shifts which add [2]. Symbolically, this idea may be represented as:

$$\log((\epsilon' - \epsilon_\infty)/\epsilon_0) = \mathcal{F}'\left[\log\omega - (f_T(T) + f_M(m))\right]$$

$$\log(\epsilon''/\epsilon_0) = \mathcal{F}''\left[\log\omega - (f_T(T) + f_M(m))\right]$$

where $f_T(T)$ depends only on absolute temperature and $F_M(m)$ depends only on moisture. These formulations also indicate that the real and imaginary components of $\epsilon^*$ shift by the same amount, as required by the Kramers-Krönig Relations [1, sec. 2.8].

Tables 2 and 3 list the amount of logarithmic frequency shift as a function of temperature and moisture respectively. These results are also plotted on Figure 3. More data are necessary if $f_M(m)$ is to be defined better. An Arrhenius functional dependence is assumed for $f_T(T)$ in Figure 3, i.e. $\epsilon^* \propto e^{-E_a/kT}$. The slope in the figure corresponds to an activation energy of $E_a = 0.31$ eV.

## INTERDIGITAL FLEXIBLE SENSORS

In this section we shall briefly discuss a different kind of dielectrometry measurement using interdigital flexible sensors. They probe the material only on one surface via a

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[1] The slope of the $\epsilon''$ curves is not equal to $-1$, illustrating the dispersive nature of pressboard.

[2] The $\epsilon''$ slope is constant, indicating a single dominant peak.

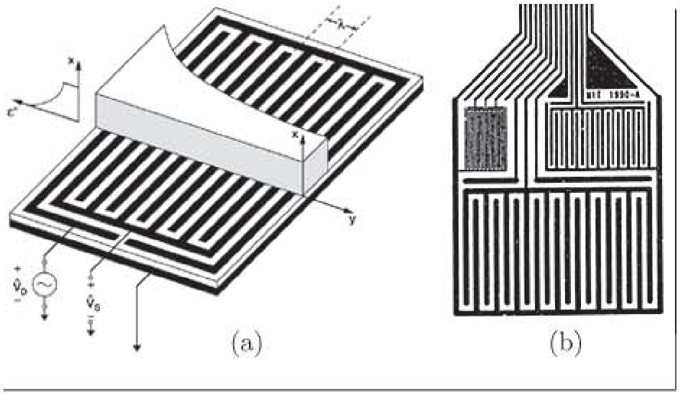

Figure 4: (a) Structure of the flexible interdigitated sensor. (b) Three-wavelength sensor. [6]

set of interdigitated electrodes, as shown on Figure 4a. The electrodes are deposited on a flexible polyimide substrate. The entire structure is then coated with 5 $\mu$m of parylene which protects the surface from contamination [6, sec. 6.2.2]. The depth of penetration of the applied electric field is directly proportional to the fundamental spatial wavelength of the sensor.

For the case of the parallel-plate sensor the complex permittivity of the material $\epsilon^*$ can be expressed in closed form as a function of the magnitude and phase of the measured potential, and the geometry of the structure (represented by $C_{AIR}$). With an interdigital sensor the situation is vastly more complex for the following reasons: the potential distribution is now two-dimensional; the driving potential is represented by an infinite number of Fourier modes, each of which sees a *different* capacitance density[3] at the plane of the electrodes [7, sec. 2.3]. 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. This is accomplished numerically by finding the potential at a given number of fixed locations (collocation points) between the electrodes and approximating the true distribution by linear interpolation. When the medium above the electrodes is not homogeneous, we assume it can be represented by a set of uniform layers stacked vertically. The algorithm used to find the impedance in this case is outlined in [7, sec. 2.4].

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 materials. A variety of numerical root-finding one- or multi-dimensional algorithms can be used for this kind of data processing [7] [2] [8].

The three-wavelength sensor, shown in Figure 4b, 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, 1.0 mm. The sensor is more fully described in [6, sec. 6.3.1].

## CONCLUSIONS

The universal spectrum obtained from experiments with the parallel-plate sensor on oil-impregnated pressboard may be used to measure the moisture content of a sample by measuring its complex permittivity at a given temperature. The dielectric spectrum shifts in frequency both as a function of temperature and moisture, the two effects being independent of each other.

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 all sensors.

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[3] The capacitance density is used to relate the voltage to the current at the terminals and thus the complex impedance of the sensor.

(a) (b)

Figure 4: (a) Structure of the flexible interdigitated sensor. (b) Three-wavelength sensor. [6]

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