

## Moisture Dynamic Measurements of Transformer Board Using A Three-Wavelength Dielectrometry Sensor

Y. Du, M. Zahn, A. V. Mamishev, and D. E. Schlicker  
Department of Electrical Engineering and Computer Science  
Laboratory for Electromagnetic and Electronic Systems  
Massachusetts Institute of Technology  
Cambridge, MA 02139, USA

**Abstract:** The spatial distribution of dielectric permittivity and conductivity of a medium affects the quasistatic distribution of the electric field. Multiple wavelength interdigital sensors using the imposed frequency-wavenumber ( $\omega$ - $k$ ) dielectrometry technique can measure complex permittivity distributions in dielectrics. Measurements of oil-free and oil-impregnated pressboard using a three-wavelength sensor with changes in ambient moisture concentration are presented. With a calibrated mapping relating conductivity and permittivity to moisture concentration in oil-impregnated pressboard, the spatial distribution of moisture can be measured.

### INTRODUCTION

The presence of moisture in transformer oil and oil-impregnated pressboard has a detrimental effect on insulation life by lowering electrical breakdown strength and thermal endurance [1]. When the transformer is in operation, the conventional way to estimate the moisture in the solid insulation is to measure the moisture content in the oil and to use moisture equilibrium curves to estimate the moisture level in the pressboard [2]. However, since it may take a long time for the system to reach equilibrium, using the curves under non-equilibrium conditions may result in errors. The three-wavelength sensor is designed to monitor the dielectric response of the insulation in real time and to calculate the moisture distribution in the pressboard by using a calibrated mapping relating dielectric permittivity and conductivity to moisture concentration [3].

Preliminary moisture dynamic experiments have been done with oil-free pressboard at room temperature [4,5]. We repeated the measurements at 70°C to increase the moisture diffusion speed. Measurements of oil-impregnated pressboard at 70°C, a more typical case for the transformer system, are also presented.

### THEORETICAL BACKGROUND

The structure of the three-wavelength interdigital sensor used in this investigation is shown in Figure 1. This electroquasistatic system has electric scalar potential obeying Laplace's equation. Neglecting variations in the x direction, the solution for each wavelength can be written as an infinite series of sinusoidal Fourier modes of fundamental spatial

wavelength  $\lambda$  in the y direction that decays away in the z direction [3]:

$$\Phi(y, z) = \sum_{n=1}^{\infty} \Phi_n \text{trig}(k_n y) \text{hyp}(k_n z), \quad (1)$$

where  $\text{trig}(k_n y)$  stands for any trigonometric function,  $\text{hyp}(k_n z)$  stands for any hyperbolic function, and  $k_n = 2\pi n/\lambda$  is the wavenumber of each mode. For heterogeneous media, spatial profiles of dielectric properties can be determined using multiple wavelength sensors, such as that in Figure 1 as each wavelength has a different penetration depth into the dielectric in contact with the sensor.

For each wavelength, one set of electrodes is driven with a variable frequency AC voltage and a high impedance measurement is made of the induced voltage on the alternate set of interdigitated electrodes. The magnitude  $G$  and phase  $\phi$  of this floating voltage depend on the permittivity  $\epsilon$  and electrical conductivity  $\sigma$  of the medium adjacent to the sensor. With three different penetration depths it is possible to calculate spatial profiles of permittivity and conductivity from the gain and phase of the floating voltage as a function of frequency for each sensor wavelength [5,6].

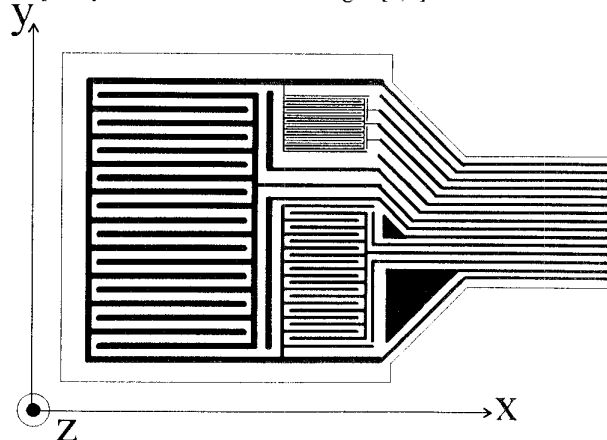


Figure 1. The three-wavelength interdigital sensor with wavelengths of 5, 2.5, and 1 mm.

If the dielectric adjacent to the sensor is pressboard, as moisture diffuses into the pressboard, the outer layer of the

pressboard gets wet first, changing the permittivity and conductivity near the interface. Thus the largest wavelength with the largest penetration depth senses the change first. As the moisture diffuses further into the pressboard, the middle wavelength and then the small wavelength detect the change in dielectric properties.

## EXPERIMENTAL SYSTEM

The test chamber for moisture dynamic measurements is shown in Figure 2. The temperature, vacuum, and relative humidity of the chamber are well monitored and controlled. The circulating system gets the liquid or gas in or out of the chamber as well as uniformly mixes the moisture distribution in the liquid.

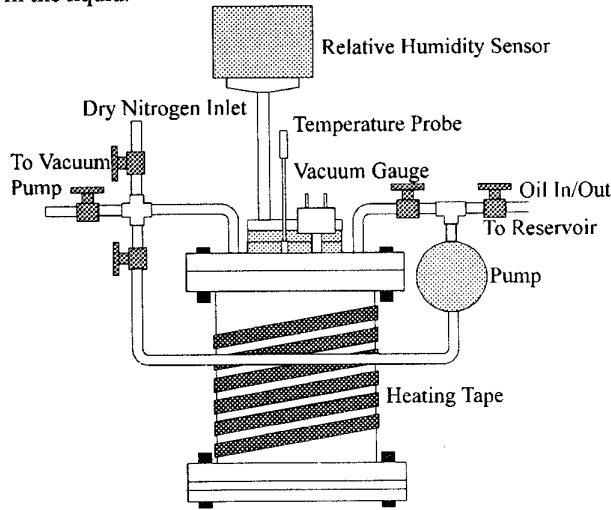


Figure 2. Experimental setup for moisture dynamic measurements.

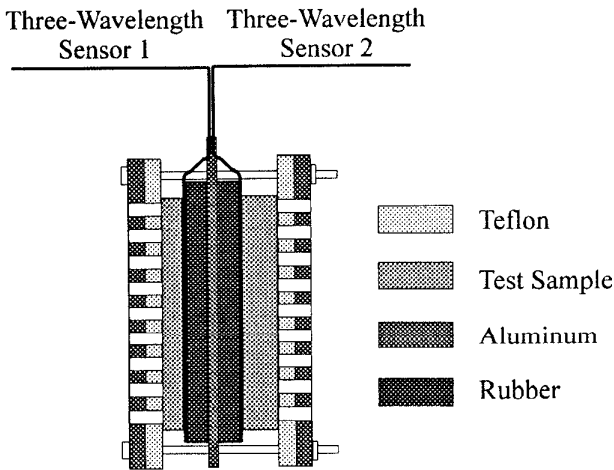


Figure 3. Test structure simultaneously using a pair of three-wavelength sensors in laboratory bench-top measurements.

The three-wavelength sensor testing structure in Figure 3 is inside the chamber and includes two back to back sensors to allow simultaneous measurement of two samples. The porous Teflon and aluminum plates squeeze the whole structure, and at the same time allow maximum mass-transfer between the test samples and the surrounding environment. The leads of the sensors come out of the chamber through a Lexan feedthrough.

## EXPERIMENTS AND DISCUSSIONS

### Oil-Free Pressboard

EHV-Weidmann Hi-Val pressboard of thickness  $d_{pb}=2$  mm is used in one measurement. The pressboard was first dried with vacuum for about 24 hours at  $70^{\circ}\text{C}$ . After the drying process, wet air produced by bubbling air through a wetting flask was introduced into the chamber and moisture started to diffuse into the pressboard. Figure 4 shows the different response of the three wavelengths. As predicted by theory, when the moisture diffuses into the depth  $d$  which is within the penetration depth  $d_{pen}$  of the sensor, the sensing signal will begin to change. For each wavelength, the corresponding distance is  $d=d_{pb}-d_{pen}$  where  $d_{pen}\sim\lambda/5$ . The diffusion coefficient can be calculated from measurement of the moisture diffusion time  $\tau$  and  $d$  by

$$D = d^2 / \tau , \quad (2)$$

For each of the wavelength and measured  $\tau$  values given in Figure 4, the calculated  $D$  is  $\sim 1.1 \times 10^{-9} \text{ m}^2/\text{s}$  from (2). A similar measurement at room temperature gave a diffusion coefficient  $D \sim 2.7 \times 10^{-11} \text{ m}^2/\text{s}$  [5]. Moisture diffusion processes are about 50 times faster at  $70^{\circ}\text{C}$  than at room temperature.

Earlier empirical work has fitted a diffusion coefficient as a function of temperature  $T$  in  $^{\circ}\text{K}$  and moisture concentration  $C$  in % by weight as [7]

$$D = D_0 \exp[0.5C + E_a \times (1/T_0 - 1/T)] \quad (3)$$

where  $T_0=298^{\circ}\text{K}$ , and for oil-free and oil-impregnated paper

$$\begin{aligned} E_a &= 8140^{\circ}\text{K}, D_0 = 2.62 \times 10^{-11} \text{ m}^2/\text{s}, && \text{oil-free} \\ E_a &= 8074^{\circ}\text{K}, D_0 = 1.34 \times 10^{-13} \text{ m}^2/\text{s}, && \text{oil-impregnated} \end{aligned} \quad (4)$$

Assuming that the dried pressboard has the typical moisture concentration of  $C=0.5$ , the computed values of  $D$  for oil-free paper from (3) are  $D(70^{\circ}\text{C})=1.2 \times 10^{-9} \text{ m}^2/\text{s}$  and  $D(20^{\circ}\text{C})=2.1 \times 10^{-11} \text{ m}^2/\text{s}$ , in good agreement to measured values using the three-wavelength sensor.

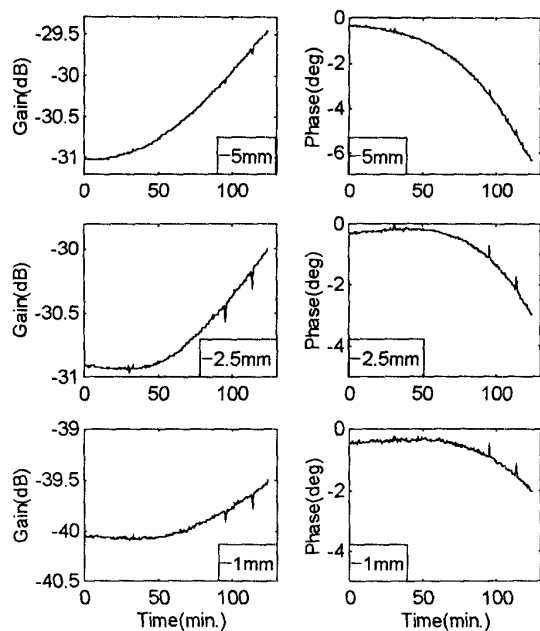


Figure 4. Gain and phase measurements of the moisture diffusion process of 2 mm thick EHV-Weidmann Hi-Val oil-free pressboard at 70°C and  $f=1$  Hz showing approximate moisture diffusion times of 50, 35, and 15 minutes for respective wavelengths of 1, 2.5, and 5 mm.

## Oil-Impregnated Pressboard

### Frequency Domain Measurement:

A full frequency scan (0.005 to 10,000 Hz) was measured in 2 mm thick EHV-Weidmann oil-impregnated pressboard in equilibrium under ambient air at 70°C. Using the parameter estimation program for homogeneous materials that relates measured gain and phase to complex permittivity  $\epsilon = \epsilon' - j\epsilon''$  [5], we obtain the dielectric spectra in Figure 5. The three wavelengths approximately give the same value indicating that the moisture distribution is essentially uniform throughout the pressboard. The relative permittivity at high frequency is about 3.8 which is consistent with manufacturer's specifications. The difference of  $\epsilon'$  at low frequency may be due to the electrical double layer. By linear regression, the slope of the  $\epsilon''$  curve is -0.7, verifying earlier reported measurements that pressboard is dispersive, i.e., the conductivity changes with frequency. A constant conductivity would have a slope of  $\log \epsilon''$  versus  $\log f$  of -1 [3].

### Time Domain Measurement:

One piece of 1.0 mm thick EHV-Weidmann Hi-Val pressboard and one piece of 1.6 mm thick transformer BD-M pressboard are assembled with two sensors into the sandwich

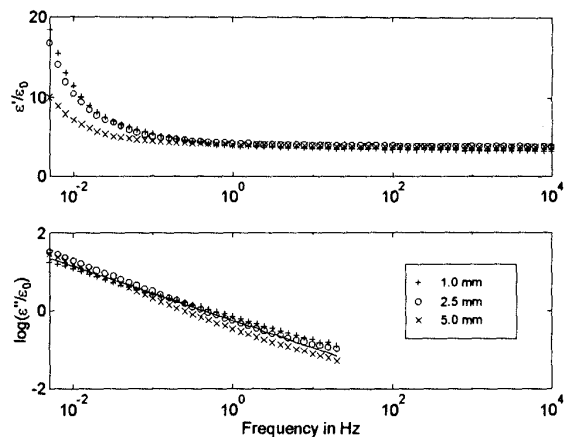


Figure 5. Dielectric spectra for 2 mm thick oil-impregnated EHV-Weidmann Hi-Val pressboard at ambient air in equilibrium at 70°C.

structure of Figure 3. To simulate the commercial impregnation procedure for transformers, the oil-free pressboard was first dried under vacuum at 70°C for about 24 hours, then impregnated with oil dried under vacuum and then the oil-impregnated pressboard was kept under vacuum for another 24 hours. The dry oil was then removed and wet oil was introduced with 290 PPM moisture concentration corresponding to 83% relative saturation at 70°C, shown at  $t=0$  in Figure 6. The total volume of the wet oil is about 2400 milliliters. After the system reaches equilibrium after  $t > 200$  hours, the relative humidity is 42%, which corresponds to 150 PPM moisture in oil. By mass balance, the total moisture transported to the pressboard is about 140 PPM and is equivalent to a mass of 0.3 g in 2400 milliliter oil. Since the total weight of the dry pressboard of both samples is about 10g, there is approximately a 3% increase of moisture in the pressboard.

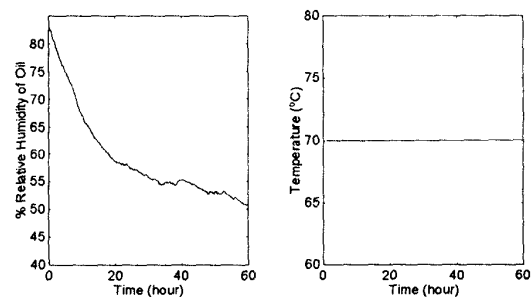


Figure 6. As moisture diffuses into the oil-impregnated pressboard at a constant temperature of 70°C, the relative humidity of the oil decreases.

Figure 7 for oil-impregnated pressboard shows a similar sensor response to that of oil-free pressboard as in Figure 4 except that for oil-impregnated pressboard the diffusion process takes much longer. Due to a small sensing area and low level sensing signal, the smallest wavelength (1 mm) is most sensitive to thermal, mechanical, and electrical noise, and the first 27 hour data of the smallest wavelength are noisy. Using the parameter values in (4) for oil-impregnated pressboard, (3) gives the diffusion coefficient at 70°C to be  $6.0 \times 10^{-12} \text{ m}^2/\text{s}$  [7]. We then predict the time  $\tau$  it takes for the sensing signal of each wavelength to begin to change using (2) as listed in Table 1. The experimental data of Figure 7 match well with the theoretical computation.

**Table 1. Theoretical computation of the response delay time for the three-wavelength sensor in 1 mm thick oil-impregnated EHV-Weidmann Hi-Val pressboard.**

Wavelength	Penetration Depth	Predicted Response Delay
5.0 mm	≈1.0 mm	≈ 0 hours
2.5 mm	≈0.5 mm	≈10 hours
1.0 mm	≈0.2 mm	≈30 hours

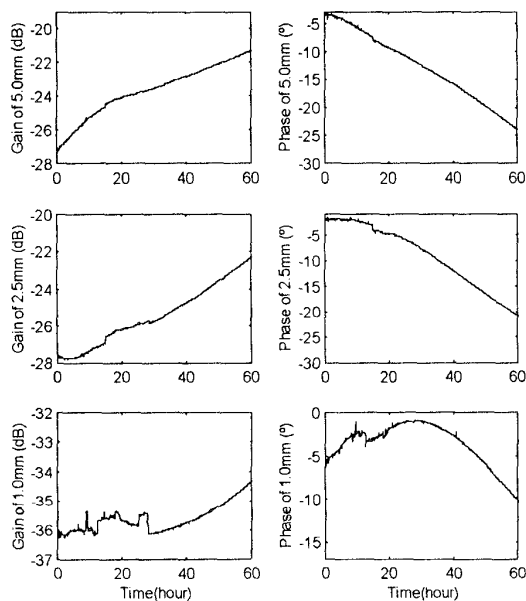


Figure 7. Gain and phase measurements of the moisture diffusion process of 1 mm thick EHV-Weidmann Hi-Val oil-impregnated pressboard at 70°C and  $f = 1 \text{ Hz}$  for each of the wavelengths of the three-wavelength sensor.

## CONCLUSIONS

The three-wavelength sensor is capable of temporal and spatial dielectrometry measurements of insulating materials. By a calibrated mapping relating dielectric properties to moisture concentration, the distribution of moisture in transformer insulation can be obtained from dielectrometry measurements. Such measurements also determine the moisture diffusion coefficient as a function of temperature and moisture concentration. The diffusion coefficients estimated from presented measurements agree well with literature values.

## ACKNOWLEDGMENTS

The authors acknowledge financial support from the Electric Power Research Institute, Palo Alto, CA, under WO 3334-1, managed by Mr. S. Lindgren, the National Science Foundation under Grant No. ECS-9523128, and a Demonstration of Energy-Efficiency Developments (DEED) Scholarship from American Public Power Association, Washington, D.C. We would like to thank Prof. B. C. Lesieutre and Dr. P.A. von Guggenberg for valuable discussions.

## REFERENCES

- Oommen, T.V. "Moisture Equilibrium Charts for Transformer Insulation Drying Practice", IEEE Trans Power Appar. Syst., Vol.103(10), 1984, pp.3063-3067.
- Oommen, T.V. "Moisture Equilibrium in Paper-Oil Insulation Systems", Proceedings of the 16th Electrical/Electronics Insulation Conference, 1983, pp.162-166.
- Sheiretov, Y.K and M. Zahn. "Dielectrometry Measurements of Moisture Dynamics in Oil-Impregnated Pressboard," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 2, June 1995, pp. 329-351.
- von Guggenberg, P.A and J.R. Melcher. "A Three-Wavelength Flexible Sensor for Monitoring the Moisture Content of Transformer Pressboard", Proceedings of The 3rd International Conference on Properties and Applications of Dielectric Materials, 1991. IEEE Publication 91-CH-2937-1, pp.1258-1265.
- von Guggenberg, P.A. "Application of Interdigital Dielectrometry to Moisture and Double Layer Measurements in Transformer Insulation", Ph. D. thesis, EECS Department, M.I.T., 1993.
- Mamishev, A.V., Y. Du and M. Zahn. "Measurement of Dielectric Property Distributions Using Interdigital Dielectrometry Sensors", 1995 Annual Report of Conference on Electric Insulation and Dielectric Phenomena. IEEE Publication 95CH35842, pp.309-312.
- Foss, S.D. "Power Transformer Drying Model," Report prepared for General Electric Company, Large Transformer Operation, Pittsfield, MA, and Consolidated Edison Corporation, New York, NY, by Dynamic Systems, Pittsfield, MA, 1987.