Development and Applications
of Fringing Electric Field Dielectrometry Sensors
and Parameter Estimation Algorithms

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1 Abstract

Recent advances in the field of interdigital \( \omega - k \) (frequency-wavenumber) dielectrometry are described. The paper offers an overview of several applications of this technology developed during the last few years. Interdigital \( \omega - k \) dielectrometry offers the ability to non-destructively measure from one side dielectric permittivity, conductivity and related physical properties distributed spatially throughout the volume of dielectric materials. A separate mapping may be required to translate the distribution of the complex dielectric permittivity into the distribution of other properties, which include moisture concentration, impurity concentration, density, porosity, thickness of films, structural integrity, surface coatings, etc. As representative examples of applications of this technology, the results of the measurement of moisture diffusion into a 1.5 mm thick oil-free transformer pressboard are presented, followed by an illustrative case of spectroscopy-based landmine detection.

2 Introduction

Various aspects of interdigital \( \omega - k \) (frequency-wavenumber) dielectrometry have been advanced during the last fifteen years [1–6]. This methodology is protected by several patents [7–9] and is currently undergoing intensive commercialization. Interdigital dielectrometry has come a long way from a basic concept to a practical tool applied to a variety of industrial problems. Several generations of sensors have been developed [10–12]. In some cases, the transition from one generation to another was induced by the need to optimize the sensor design or parameter estimation algorithms. In other cases, new designs were prompted by specific applications, some of which are described in the following sections.

The ultimate goal of multi-wavelength dielectrometry is to measure physical properties of inhomogeneous materials. In most cases, a necessary intermediate step is to determine the complex dielectric permittivity profile of the material. Then, by using a separate mapping, the
permittivity is related to other physical properties, such as density, porosity, moisture content, structural integrity, presence of contaminants, surface coatings, and others. It is also possible to find geometric parameters of the material under test, most notably the thickness of the stratified medium layers. The technology is currently undergoing rapid developments aimed at the improvement of spatial resolution, precision, repeatability, and reliability of measurements.

Specific applications addressed in this paper include monitoring of moisture dynamics in transformer pressboard and detection of buried plastic and metallic landmines. The first application relating thermodynamic equilibrium between moisture in oil and pressboard insulation has been under development for more than ten years [4,6,13,14]. It is motivated by the need to analyze and forecast conditions of electrical insulation in power transformers. Moisture dynamics between oil and transformer pressboard as a function of temperature is very important in power transformer operation. For example, if the temperature were to drop too quickly before the moisture in the oil could diffuse into pressboard, oil moisture would exceed the saturation value at this temperature, resulting in free water in the oil. Such free water in the high voltage region of the transformer could result in catastrophic electric breakdown and transformer failure. Another transformer failure mode dependent on moisture dynamics is flow electrification, which often arises when a transformer that has been out of service is being recommissioned. A plausible scenario is that as the transformer heats up, moisture is driven out of the pressboard insulation into the oil. The moisture first comes from near the pressboard interface, leaving a very dry interface that is also highly insulating. Any accumulating surface charge has no leakage and thus the surface charge density can increase until spark tracking discharges occur. These sparks cause gas formation, which can rise into the high electric field region causing a high-energy discharge that causes transformer failure. If failure does not occur during the early times of the recommissioning process, the moisture deeper in the pressboard diffuses to the surface reaching equilibrium with the oil moisture. The moisture diffusion time can be a few weeks, but once there is no longer an interfacial dry zone, there is a leakage path for interfacial surface charge so that the surface charge density cannot rise to electric field strengths beyond the breakdown strength of oil and pressboard. Thus, once the transformer is in moisture equilibrium, this flow electrification hazard is minimized.

A more recent area of fringing field dielectrometry is detection of landmines. Current technology for demining is very slow and ineffective, and as a result, approximately 10,000 people die each year from landmine explosions and many more are wounded. Plastic landmines have little or no metal content so they are virtually undetectable to conventional metal detectors. But the demining of landmines can be successfully achieved using fringing electric field dielectrometry technology which is capable of finding both plastic and metal objects in the ground.

Admittance spectroscopy is commonly used to measure properties of dispersive materials. The algorithms that are used for the estimation of material properties are computationally expensive, because model-based material property estimation (as opposed to straightforward calibration) is required in order to extract the maximum amount of information about the material. Several alternative algorithms are currently being explored. Some of them involve off-line computation of solution spaces that are stored in computer memory, other algorithms take into account imperfections of interfacial contact through empirical functional dependence of the sensor response on contact conditions. In some cases, signals recorded by auxiliary sensors, such as a humidity sensor, provide additional information for solving the inverse
problem of material characterization. It is impossible to describe all the spectrum of algorithm approaches in detail in one paper. Instead, references are given throughout this paper to other publications that treat each specific issue comprehensively.

3 Theoretical Background

3.1 Basic Concepts

A conceptual schematic of $\omega - k$ dielectrometry is presented in Figure 1. Periodic variation of electric potential along the surface in the $x$ direction produces an exponentially decaying pattern of electric fields penetrating into the medium in the $z$ direction. The variation of shade in the material under test indicates the possible variation of material properties and thus variations in the complex dielectric permittivity $\varepsilon^*$ with the distance $z$ from the surface.

Concepts of the forward and the inverse problems are widely used in the literature related to this technology. Here, the forward problem is defined as the task of determining the electric field distribution and the interelectrode admittance matrix when the geometry, material properties, and external excitations are given. Correspondingly, the inverse problem requires determining either material properties or associated geometry, or both, when the imposed excitations and experimental values of the sensor admittance matrix are available.

3.2 Continuum Model

The forward problem can be solved using several approaches. One of them is to use a continuum model [1]. From the electroquasistatic field point of view, the electric scalar potential of the field excited by the driven electrodes is a solution to Laplace’s equation. At any constant $z$ position, the electric field distribution far away from the sensor edges is periodic in the $x$ direction and assumed uniform in the $y$ direction. In this case, the scalar potential can
be written as an infinite series of sinusoidal Fourier modes of fundamental spatial wavelength \( \lambda \) that decays away in the \( z \) direction:

\[
\Phi = \sum_{n=0}^{\infty} \Phi_n e^{-k_n z} (A_n \sin k_n x + B_n \cos k_n x),
\]

where \( k_n = 2\pi n / \lambda \) is the wavenumber of each mode. The complex surface capacitance density \( \tilde{C}_n \) relates \( \varepsilon^* \tilde{E}_{zn} \) at a planar surface \( z = \text{constant} \) to the potential \( \tilde{\Phi}_n \) at that surface for the \( n \)-th Fourier mode in the following way:

\[
\tilde{C}_n = \frac{\varepsilon^* \tilde{E}_{zn}}{\tilde{\Phi}_n},
\]

where

\[
\varepsilon^* = \varepsilon - j\frac{\sigma}{\omega}
\]

is the complex permittivity with \( \varepsilon \) as material dielectric permittivity and \( \sigma \) as ohmic conductivity. Then, knowledge of \( \tilde{C}_n \) at the electrode surface lets us calculate the terminal current from the potential distribution at that surface. It is also possible to solve the forward problem with commercial finite-element software [17], with finite-differences techniques, or by using analytical approximations [18].

4 Three-Wavelength Sensor

A top view of the three-wavelength sensor is shown in Figure 2. It consists of three sets of copper electrodes deposited on the common hydrophobic Teflon substrate and connected to the dielectrometry interface circuit through the leads shown at the bottom of the drawing.

Figure 3 shows the equivalent circuit of the sensor superimposed onto the schematic view of a half-wavelength cell. Note that each wavelength has an opposite conducting guard plane at the bottom of the substrate. For each wavelength, a follower op-amp drives the guard plane at the substrate bottom at the voltage \( V_G = V_S \), thus eliminating any current between the sensing and guard electrodes. This measurement approach allows direct measurement of transadmittance between driving and sensing electrodes without the need to use the full-scale electromagnetic simulation to obtain the same information. Different measurement approaches, along with their advantages and drawbacks, are described in a recent publication [12] as well as in earlier work [19]. Usually, the driving voltage is a one volt peak sinusoid, however, to increase sensor sensitivity, higher voltages, up to several hundred volts, may be used in landmine detection applications.

The penetration depth of the fringing electric fields above the interdigital electrodes is proportional to the spacing between the centerlines of the sensing and the driven fingers. Figure 4 illustrates the idea of multiple penetration depths for a three-wavelength sensor. The variation of the material properties across the thickness of the material under test in the \( z \) direction can be found by simultaneously solving three complex integral equations (one for each wavelength) iteratively until measured and computed values of interelectrode capacitance \( C_{12} \) and conductance \( G_{12} \) match:

\[
Y_{12} = G_{12} + j\omega C_{12} = \frac{\varepsilon \omega \varepsilon^* \nabla \Phi \cdot \hat{d}}{v_D - v_S}
\]
where $S$ is the entire surface of the driven or sensing electrodes, $\hat{d}$ is the normal unit vector of that surface, and $v_D - v_S$ is the voltage difference between driven and sensing electrodes.

5 Benchmark Simulation and Measurements

Finite-element software *(Maxwell* by Ansoft Corp.) has been used to model the interdigital electrode structure. For any given setup, the distribution of the electric fields and the admittance matrix can easily be found. Figure 5 shows the results of the field simulation for a 5.0 mm wavelength Teflon substrate sensor at the frequency of 0.005 Hz. The material properties in the region above the sensor correspond to those of corn oil, a dielectric liquid frequently used in our diagnostic measurements. The admittance between the driven and sensing electrodes depends primarily on the properties of the upper region, however, some field lines go through the substrate material. It is desirable for most applications that the substrate material properties remain constant when physical processes of interest affect the dielectric properties of the upper layer.

Figure 6 shows the experimental results and the computer simulation of the transcapacitance and transconductance as the driving voltage frequency is swept from 10 kHz to 0.005 Hz. This plot contains several features frequently encountered in dielectrometry measurements, described below. A reasonable agreement between the measurements and the theory is achieved at all frequencies except at the lowest frequencies (below 0.03 Hz). The rise of capacitance $C_{12}$ at low frequencies is due to electrochemical double layer formation at the metal-dielectric interface. It is possible to account for the double layer effects, and even evaluate its prop-
properties [5]. The simulations in Figure 6 did not account for the double layer but above 0.03 Hz show the ideal theoretical response of a non-dispersive liquid dielectric. The data for the transconductance at the frequencies above 5 Hz are not shown here because the capacitive currents at these frequencies dominate the conduction currents and the accurate measurement of the real part of the transadmittance becomes very difficult. The negative capacitance values for the 5 mm wavelength are due to the lumped-element π-circuit representation of the inter-electrode space as shown in Figure 3 which does not match the actual topology of the sensor. The actual circuit topology includes admittance elements from the sensor/dielectric interface between driven and sensing electrodes to the guard electrode. A more detailed explanation of this phenomenon is available in [12].

The values of the relative dielectric permittivity \( \varepsilon_r = 3.15 \) for this new corn oil sample and conductivity \( \sigma = 60 \) pS/m, 53 pS/m, and 14.2 pS/m for 1.0 mm, 2.5 mm, and 5 mm wavelengths, respectively, used in the simulation were measured separately with a guarded parallel plate capacitor. The values of the conductivity differ because the measurement with each wavelength were taken at different moments of time and at different ambient temperatures.
Figure 5: The arrows indicate the direction and magnitude of the electric field at an excitation frequency of 0.005 Hz. The relative dielectric permittivity of the material under test (corn oil) is $\varepsilon_r = 3.015$ and the conductivity is $\sigma = 3.2 \times 10^{-11}$ S/m as measured by a guarded parallel plate capacitor.

between 15°C and 25°C.

Table 1 lists the results of measurements made on a variety of fluid and solid homogeneous dielectrics. For a homogeneous material, all three wavelengths should indicate approximately equal values of $\varepsilon_r$, and each of them should be close to the value found with the parallel plate capacitor measurements. For solid materials, parallel-plate measurements were done with guard ring electrodes deposited on the surface of specimens in accordance with ASTM standard D150-81 [20], and for liquid materials, they were done by immersing the guarded parallel plate capacitor into the liquid. The air measurement is guaranteed to be perfect by the nature of the calibration procedure.

The contact conditions between the sensor and the solid dielectrics strongly affect sensor response and may lead to incorrect estimates of material properties. The algorithm that empirically takes into account contact parameters under a specified pressure on the sensor head that was used for estimates listed in Table 1 is described in [21]. It involves the use of empirical correction coefficients that work for an acceptably wide range of the dielectric permittivity values. Newer sensors that are currently under development are designed to reduce the effects of the surface contact.

6 Moisture Dynamics

Monitoring of moisture concentration in transformer pressboard is one of the promising areas of application of interdigital dielectrometry. The process of diffusion of water molecules
into oil-free transformer pressboard was simulated and staged experimentally in a controlled environment chamber. Figure 7 shows the cross-section of the 1.5 mm thick pressboard modeled as a three-layer medium with the thickness of the layers of 300 μm, 450 μm, and 750 μm. The distance from the sensor to the postulated layer boundaries are chosen to be 30% of each of the spatial wavelengths of the sensor.

The surface of transformer pressboard is very irregular on the scale of penetration depths of our three-wavelength sensor. The distance between high and low points can be as high as 0.1 mm. For this reason, the assumption that the dielectric region is homogeneous during steady state leads to failure of straightforward model-based parameter estimation. The algorithm employed in this case relies on calibration procedures which guarantee reasonable estimates of smooth spatial profiles of material properties under most conditions. The details of this approach are given in [22].

Initially, the pressboard was vacuum-dried. The moisture diffusion process started with a step change in the ambient air humidity from 0% to about 12% with temperature being held at 70° C. Air-pressboard equilibrium relationships [23] were used to provide boundary conditions at the air-pressboard interface and relative moisture level information needed for the parameter estimation algorithms. According to these relationships, a 12% humidity level in air at 70° C corresponds to 1.8% equilibrium moisture concentration in the transformer pressboard. Thus, the left side boundary condition at x=0 for this experiment is that the moisture level is equal to 1.8% for the duration of the experiment.

Figure 8 shows calculated moisture profiles from dielectrometry measurements for 14
distinct moments of time. The moisture spatial profiles were calculated from the measurement data using multi-variable parameter estimation algorithms for the three-wavelength sensor combined with the moisture measurement data of the ambient environment together with moisture equilibrium curves. A fitted moisture diffusion coefficient is $D \approx 2.3 \times 10^{-11} \text{ m}^2/\text{s}$.

<table>
<thead>
<tr>
<th>Material</th>
<th>1 mm</th>
<th>2.5 mm</th>
<th>5 mm</th>
<th>Average</th>
<th>Parallel plate</th>
<th>Error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0</td>
</tr>
<tr>
<td>Teflon</td>
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<td>2.02</td>
<td>1.99</td>
<td>2.06</td>
<td>3.51</td>
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<tr>
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<td>2.29</td>
<td>2.27</td>
<td>2.26</td>
<td>2.20</td>
<td>2.72</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>2.24</td>
<td>2.26</td>
<td>2.29</td>
<td>2.26</td>
<td>2.23</td>
<td>1.34</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>2.35</td>
<td>2.35</td>
<td>2.29</td>
<td>2.33</td>
<td>2.35</td>
<td>0.86</td>
</tr>
<tr>
<td>HD Polyethylene</td>
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<td>2.44</td>
<td>2.38</td>
<td>2.40</td>
<td>2.36</td>
<td>1.69</td>
</tr>
<tr>
<td>Lexan</td>
<td>3.11</td>
<td>3.04</td>
<td>3.11</td>
<td>3.09</td>
<td>3.01</td>
<td>2.66</td>
</tr>
<tr>
<td>Corn Oil</td>
<td>3.09</td>
<td>3.19</td>
<td>3.10</td>
<td>3.13</td>
<td>3.10</td>
<td>0.96</td>
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<td>PVC</td>
<td>3.30</td>
<td>3.23</td>
<td>3.45</td>
<td>3.32</td>
<td>3.35</td>
<td>0.90</td>
</tr>
<tr>
<td>Delrin (white)</td>
<td>3.36</td>
<td>3.49</td>
<td>3.77</td>
<td>3.54</td>
<td>3.63</td>
<td>2.54</td>
</tr>
</tbody>
</table>

Table 1: Measurement of relative dielectric permittivity of non-conductive materials in 100 Hz -10 kHz range.

Figure 7: A schematic representation of the experimental arrangement for moisture diffusion into oil-free pressboard. The pressboard is modeled as a three-layer medium with distinct properties for each layer related to the quantity of moisture in each layer.
Figure 8: Calculated spatial profiles of moisture concentration at two-hour intervals across the thickness of pressboard from dielectrometry measurements.

Figure 9: Theoretical spatial profiles of moisture concentration across the thickness of pressboard, using a fitted diffusion coefficient of $D = 2.3 \times 10^{-11}$ m$^2$/s$^2$. Numbers next to the curves correspond to the time in hours after the moisture was stepped on to 1.8% at $x = 0$.

Table 2: A comparison of our measured diffusion coefficient (m$^2$/s) and literature reported values at 60°C in oil-free pressboard.

<table>
<thead>
<tr>
<th>Source</th>
<th>MIT</th>
<th>Foss [25]</th>
<th>Quarshte [26]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Pressboard</td>
<td>Kraft paper</td>
<td>Manilla paper</td>
</tr>
<tr>
<td>$C = 2.1%$</td>
<td>$2.5 \times 10^{-11}$</td>
<td>$1.3 \times 10^{-9}$</td>
<td>$1.3 \times 10^{-11}$</td>
</tr>
<tr>
<td>$C = 3.0%$</td>
<td>$3.8 \times 10^{-11}$</td>
<td>$2.1 \times 10^{-9}$</td>
<td>$4.8 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

Figure 9 shows theoretical moisture profiles generated using the estimated value of diffusion coefficient that are in reasonable agreement with the measured profiles in Figure 8. A standard finite difference technique was used to solve the one-dimensional diffusion equation.

Using a similar approach, a diffusion coefficient is estimated in [24] as a function of moisture concentration and temperature. The diffusion coefficient for oil-free pressboard calculated here is much smaller than that reported in [25]. This could be due to two reasons. First, the materials are different. Data in [25] is for A50P281A Kraft paper made from 100% sulphate fiber with thickness of 0.01 inch (0.254 mm). The reported value in [26] is close to our results given in Table 2. In the latter case, 50 layers of Manilla paper each 0.045 mm thick were used.

Second, our sample is tightly compressed. An increase in pressboard density has been shown to slow down the diffusion process [26]. For the EHV Weidmann T-IV pressboard that was tested in [26], the diffusion coefficient of unclamped pressboard is about 1.3 times that of clamped pressboard. A comparison of our measured diffusion coefficient (m$^2$/s) and literature reported values at 60°C is given in Table 2.
Figure 10: A two-dimensional cross-section of the half-wavelength cell of the interdigital landmine detector with equipotential lines for the \((\varepsilon_r=2.7)\) landmine in sand \((\varepsilon_r=6)\). The wavelength is 80 cm and the distance from the sensor electrodes to the sand is 2 cm.

7 Detection of Landmines

Another recent application of interdigital dielectrometry is the detection and discrimination of buried landmines. In general, dielectrometry is capable of detecting and discriminating both plastic and metal objects in the ground, whereby the presence of low dielectric constant plastic landmines in a high dielectric constant sand will decrease the measured capacitance while a metal landmine would increase the capacitance for most configurations. Further improvements in measurement selectivity will be gained from low frequency measurement of terminal conductance as well as capacitance and their variation with frequency.

A larger (in size) version of the sensor with a smaller number of electrode fingers can be used for the detection of buried landmines. Figure 10 shows a cross-section of a half-wavelength of such a sensor. The sensor is placed 2 cm above the ground level, and the landmine is assumed to be just under the surface. The landmine relative dielectric constant is taken to be \(\varepsilon_r = 2.7\), which is that of acrylonitrile-butadiene-styrene (ABS), a typical material used in plastic landmines. The relative dielectric permittivity of soil is \(\varepsilon_r = 6\) and the conductivity is \(\sigma = 10^{-8} \text{ S/m}\).

A potential weak spot in the amplitude-based detection considered in the previous section is the fact that the amplitude of the response will change with irregularities of the surface, presence of other objects in the studied area, and the vertical movement of the sensor. In other words, although detection of the landmine is very straightforward, its discrimination from other sources of the signal perturbation is a more challenging task. More sophisticated algorithms should be used to reduce the false alarm rate. Most of the materials under consid-
<table>
<thead>
<tr>
<th>Material</th>
<th>Relative permittivity</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>6</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Landmine</td>
<td>2.7</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Electrodes</td>
<td>-</td>
<td>$5.8 \times 10^7$</td>
</tr>
<tr>
<td>Ambient (air)</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Dielectric properties of materials assumed in the simulation.

Figure 11: Simulated capacitance per meter length with and without landmine for three spatial wavelengths of interdigital electrodes.

eration (soil, landmine, small pieces of metal) are far from being perfectly insulating. Their conductivity varies over many orders of magnitude. For every landmine, the combination of capacitive and conductive currents produces a characteristic frequency response signature which we will illustrate with the following simulation. Consider the landmine detector driven with a frequency sweep from 0.005 Hz to 10 kHz. The assumed dielectric properties of the materials are described in Table 3.

Suppose that the landmine is centered as in Figure 10, and the signal frequency is swept from 0.005 Hz to 10 kHz. A more narrow sweep will suffice once properties of the specific landmines are determined. Figure 11 and Figure 12 clearly show the signature left by the landmine. The peaks in the frequency derivative plots can be predicted once the complex dielectric permittivities of the composing materials are known.

8 Summary

Multi-wavelength interdigital dielectrometry holds a significant potential for a variety of industrial applications. Recent work in this area includes characterization of liquid and solid
Figure 12: Simulated capacitance derivative with respect to the logarithm of frequency accentuates the characteristic signature of the landmine.

dielectrics, monitoring of moisture dynamics in transformer pressboard, and detection of buried plastic and metallic landmines. A good match between the theory and the experimental results is achieved in benchmark studies of homogeneous solid and liquid dielectrics. Calibration-based algorithms that use transcapacitance to moisture mapping allow estimation of spatial moisture profiles in transformer pressboard even when the contact between the sensor and the pressboard surface is far from ideal. Future research and commercialization of this technology will heavily rely on model-based algorithms as opposed to simpler calibration-based techniques.

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