Numerical analysis on effective electric field penetration depth for interdigital impedance sensor

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Abstract. Interdigital (finger-like) electrodes are widely used for electrical impedance and capacitance tomography of composite dielectric materials and complex insulating structures. Because of their advantages, they are now effectively introduced as capacitance sensors into a variety of industrial branches, agriculture, medical science, biological engineering, military branches, etc. In order to effectively apply the so-called interdigital impedance sensors in practice, of great importance is to optimize the sensor design parameters such as the electric field penetration depth, signal strength and so on. The general design principles of the interdigital capacitance sensor have been discussed for a long time by many researchers. However, there is no consensus on the definition of the effective electric field penetration depth of interdigital electrode. This paper discusses how to determine the effective electric field penetration depth of interdigital sensor on the basis of the refractive principle of electric field intensity and the FEM analyses of electric field distribution and capacitance for the sensor model.

1. Introduction

Dielectric permittivity and loss tangent are the important electrical properties of dielectrics and electrical insulating materials, which have been widely used as non-destructive diagnostic parameters in industrial applications, including the monitoring of curing degree for plastics and rubbers, the humidity measurement in oils, papers and gaseous media, the measurements of concentration for emulsions, suspensions and bio-cells, the measurements of thickness for dielectrics and the height level of liquids, the detection of freshness of foods and so on[1-13].

Traditional dielectrometry is based on measuring permittivity and loss tangent of dielectric samples placed in conventional parallel or cylindrical plate electrode cell, which is often not suitable to many practical cases, i.e. dielectric measurements for high-viscosity liquid, multi-layered and matrix composite materials, complex insulating structures, extra thin and thick liquids and solids, moving
bodies etc. It is just the interdigital impedance sensor, also often called fringing electric field (FEF) sensor that has been suggested for the sake of overcoming the above-mentioned disadvantages of the conventional one, which is comprised of two interdigital (finger-like or comb-like) metal electrodes fixed on the surface of inert insulating substrate (e.g. quartz or Teflon). The dielectric material sample to be measured is placed on this surface in intimate contact with the pair of come-like electrodes, one electrode being excited with the sinusoidal voltage of fixed amplitude and frequency and the other electrode having the ground potential, as a result of which the fringing electric field (FEF) formed by the interdigital electrodes penetrates into the sample (figure 1).

![Figure 1. Interdigital impedance sensor.](image)

Interdigital impedance sensors have the following advantages, compared with the conventional capacitance cells:

(i) The electrodes of the sensors are contacted only with one sides of the samples measured, making it possible to measure the impedance or capacitance of extra thin (i.e. nano- and micro-sized particles and films) and thick samples, complex insulating structures (i.e. power cable head insulation, etc.), the material samples difficult or inconvenient to be inserted into the conventional capacitance cells (i.e. bitmen, grease, heavy oil, etc.), the samples dimension-variable during electrode installation and measurements (i.e. powders, water converted into solid, liquid or gaseous state with the temperature changed, soft spongeous materials, etc.).

(ii) The electric field penetration depth of FEF sensor can be arbitrarily altered by changing the electrode geometry, allowing the measurements of the impedance or capacitance for individual layers of layered composite materials and the distribution of the defects inside the dielectric materials or structures considered (figure 2).

![Figure 2. Dependence of electric field penetration depth on the spacing between the interdigital electrodes.](image)

According to the previous studies, the longer the values of the spatial period of FEF sensors, the wider the width of interdigital electrodes, the greater the effective electric field penetration depth.
The general design principles of the interdigital impedance sensor have been discussed for a long time by many researchers since the early 1970s, and a variety of FEF sensors have been widely used in practical applications up to now [4-22], but some problems still require to be further investigated for the purpose of more effective applications of FEF sensors.

One of the most important problems is to optimize the geometries of the interdigital impedance sensors, including spatial period ($\lambda$) and width ($W$) of interdigital electrodes and so on, which play determinative roles in ensuring the effective electric field penetration depth of FEF sensors.

However, there is no consensus on the definition of the effective electric field penetration depth of the interdigital impedance sensor at present because the electric field between interdigital electrodes can be considered to show such an infinitely-spread distribution characteristic that it is nearly impossible to determinate the exact electric field penetration depth, and therefore the empirical relationship between the penetration depth and the spatial period of electrode system has been roughly accepted as

$$T = \frac{\lambda}{4} \sim \frac{\lambda}{3} \quad (1)$$

where $T$ is the effective electric field penetration depth; $\lambda$ is the spatial period.

According to previous papers, one way of evaluating the effective penetration depth of EFE sensor is based on measuring the position at which the difference between the current value (for the sample tightly in contact with the sensor surface) and asymptotic value (for the sample infinitely far from the sensor surface) of sensor terminal impedance equals to 3% of the difference between the maximum and minimum of the terminal impedance [4], however, to our knowledge, few researchers have discussed what the meaning of the critical value 3% of the normalized impedance (or capacitance) for a given FEF sensor is and whether or not this critical value is absolutely accepted, and few users have not ever paid attention to them.

This paper aims to make the meaning of the critical value 3% of the normalized capacitance for a given interdigital impedance sensor clear, based on both the refractive principle of electric field intensity at the interface of two different dielectrics and the FEM analysis of electric field distribution and capacitance for FEF sensor.

2. Electric field behaviour at the interface between two different dielectrics

Let us consider the behaviours of the electrical potential and electric field intensity at the interface between two different dielectrics placed in a parallel plate capacitor (figure 3(a)).

If two kinds of dielectrics are placed between two electrodes as shown in figure 3(a), the electrical potential and electric field intensity are discontinuously varied along lines of PQR and KLMN between two electrodes, which are quite different from those in the single layer plate capacitor (right line PR and ST), as shown in figure 3(b) and (c).

In the case of the capacitor with double-layered dielectrics between two electrodes, the values of electric field intensity in the individual dielectric layers can be expressed respectively by

$$\begin{align*}
E_1 &= \frac{\varepsilon_2}{\varepsilon_2 d_1 + \varepsilon_1 d_2} U \\
E_2 &= \frac{\varepsilon_1}{\varepsilon_2 d_1 + \varepsilon_1 d_2} U
\end{align*} \quad (1)$$

where $E$, $d$, $\varepsilon$ and $U$ mean the electric field intensity inside a dielectric, the thickness of dielectric layer, dielectric permittivity and the voltage across two electrodes, respectively; the numbers “1” and “2” denote the dielectric layers “1” and “2”, respectively.

If the dielectric permittivity values of two individual dielectrics are the same ($\varepsilon_1 = \varepsilon_2$), the electric field intensity expressed by equation (1) is converted into
where $d$ is the distance between two electrodes.

This hints us at that considering the degree of the discontinuity of electric field intensity may help us with defining the effective field penetration depth of the interdigital impedance sensor.

$$E = \frac{U}{d} \quad (2)$$

**Figure 3.** The changes of the electrical potential and electric field intensity at the interface between two different dielectrics inserted into two parallel plates: (a) the double-layered capacitor model; (b) the potential distribution; (c) the distribution of electric field.

### 3. FEM analysis for interdigital impedance sensor model

#### 3.1 FEM analysis model

Since the electric field distribution of a FEF sensor is nonlinearly decreased along $z$-axis the direction vertical to the surface of the sensor, determining accurately the extent to which the electric field generated by one pair of FEF electrodes can spread out along the $z$-axis direction plays the key role in defining the E-field penetration depth of an interdigital impedance sensor.

For this, considering that a dielectric specimen ($\varepsilon_r = 2.5$) on the sensor surface was going up farther and farther away from it to infinity as shown in figure (4), the electric field distribution and capacitance were analyzed using the software package Maxwell by Ansoft Corp. If the dielectric
specimen is infinitely far away from the sensor, the sensor can be considered to be placed in air (ε₁ = 1).

![Image of FEM model](image)

**Figure 4.** FEM model for a FEF sensor with the dielectric specimens attached on the sensor surface (a), some distance away from the sensor surface(b) and infinitely far away from the sensor surface(c), respectively.

In the FEM model shown in figure (4), the electrode-to-electrode-separation, the electrode width, electrode thickness and the thickness of the insulating substrate (ε₃ = 2.3) were taken as g = 5 mm, w = 5 mm, d = 10 μm, and h = 2 mm, respectively.

The dielectric specimen on the sensor was considered as thick as the maximal value of the expected electric field penetration depth, and the very thin layer of air due to the thickness of metal electrode was also considered between the sensor surface and the dielectric specimen in FEM model (figure 4(a)). For the simplicity of analysis, the conductivity of the dielectric specimen considered was ignored, and the driving and the sensing electrodes were set to 5V and 0V, respectively.

3.2 Normalization of FEM analysis results

FEM analysis results were normalized in the range of 0 (minimum) to 100 (maximum) in order that it could be possible to compare an analysis result with another one.

Equation (2) and (3) show the normalized electric field intensity $E(\%)$ and capacitance $C(\%)$, respectively:

$$E(\%) = \frac{E - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}} \times 100 \, \% \tag{2}$$

$$C(\%) = \frac{C - C_{\text{min}}}{C_{\text{max}} - C_{\text{min}}} \times 100 \, \% \tag{3}$$

where $E$ and $C$ are arbitrary values of electric field intensity and capacitance between their maximum ($E_{\text{max}}$ and $C_{\text{max}}$) and the minimum ($E_{\text{min}}$ and $C_{\text{min}}$), respectively.

4. Results and discussion

Figure 5(a) and 5(b) represent FEM results for the change of the electric field intensity from the middle position between the driven and sensing electrodes along z axis when the dielectric specimen is attached to the electrode surfaces (figure 4(a)) and it is infinitely far away from the electrode surface (figure 4(c)), respectively, showing that the electric field intensity varies continuously with the distance $z$ increasing inside the specimen and air, which is ascribed to that the single dielectric layers can be thought to exist on the sensor surface in these cases.
Figure 5. The behaviours of E-field distribution along the z-axis direction for the dielectric specimens on the electrodes (a) and infinitely far away from the sensor surface (b).

Figure 6. The dependences of the electric field intensity on the distance away from the sensor surface.
However, when the dielectric specimen is a distance away from the sensor surface, an apparent jump-like change of electric field intensity is found at the air-dielectric interface, getting smaller and smaller as the dielectric specimen goes up farther and farther away from the sensor surface (figure 6), which may be ascribed both to the weakness of the electric field and to the conversion of the double-layered dielectric structure into the single one with the specimen-to-sensor distance increased.

It can be clearly seen from the results of FEM analyses in figure 6 and their normalization (figure 7(a)) that the jump-like change of the electric field intensity can hardly be observed when the dielectric specimen goes up more than 6 mm away from the surface of the sensor model considered in this study, but the refractive property of field intensity still exists at those positions, too, which means that the dielectric-to-air interface is still in the electric field formed by the FEF electrodes although its intensity is very weak.

To measure the electric field distribution in the dielectric layers of a capacitor is less realistic than to measure the capacitance, but the latter is not available to distinguish the interface between two dielectrics (figure 7(b)).

Expecting that too weak electric field may give little influence on the impedance values measured, the distance from the sensor surface to the position at which the jump-like change of electric field intensity may be nearly neglected can be accepted as the effective electric field penetration depth for an interdigital impedance sensor.

**Figure 7.** The normalized plots of electric field intensity (a) and capacitance (b) with the distance away from the FEF sensor surface.

**Figure 8.** The normalized plots of electric field intensity (a) and capacitance (b) with the distance away from the FEF sensor surface.
As can be seen in figure 8, the normalized electric field intensity jumps from about 3% down to about 2% at the position of \( z = 6 \) mm, that is, the jump-like change of normalized field intensity is only 1%, which corresponds to 3% of the normalized capacitance for the FEF sensor considered in this study (figure 8(b)).

Let us consider in detail the meaning of the change of the normalized electric field intensity by 1%, based on the double-layered parallel plate capacitor model shown in figure 3(a).

The jump-like change of electric field intensity \( \Delta E \) observed at the dielectric-to-air interface can be written as

\[
\Delta E = E_2 - E_1 = \frac{(\varepsilon_2 - \varepsilon_1)}{\varepsilon_1 d_2 + \varepsilon_2 d_1} U
\]

where \( E_1 \) and \( E_2 \) are the electric field intensities for the air and dielectric layers, respectively; \( \varepsilon_1 \) and \( \varepsilon_2 \) are the dielectric permittivity of air and the dielectric considered, respectively; \( d_1 \) and \( d_2 \) are the thickness of air and dielectric layers, respectively.

Assuming that \( \varepsilon_1 = 1 \), \( d_1 = 6 \) mm, \( d_2 = 7 \) mm and \( U = 5 \) V in figure 3, then the dielectric permittivity of the dielectric layer in the double-layered parallel plate capacitor model, required for the jump-like change of the normalized electric field intensity by \( \Delta E = 0.01 \) (or 1%) at the dielectric-to-air interface can be calculated from equation (4) to be \( \varepsilon_2 = 1.026 \), which is so close to the value of permittivity of air that it may be nearly identified with the permittivity of air \( (\varepsilon_1 = 1) \) from the viewpoint of practically-available measurement accuracy.

It can be clearly understood that at the position where the jump-like change of the normalized electric field intensity due to the difference in permittivity values at the dielectric-to-air interface is about 1%, the existence of the dielectric-to-air interface may be just as well neglected, which means that the electric field intensity at this position is too weak to distinguish the dielectric specimen from the air layer.

The results of FEM numerical analysis in this study suggest that the jump-like change of the normalized electric field intensity by about 1% is the premise for the previous definition of the effective electric field penetration depth which has been adopted without any doubt, and that for the sake of determination of more accurate penetration depth, less than 1% of the normalized electric field intensity or less than 3% of the normalized capacitance may be selected.

5. Conclusion

Numerical analysis on the effective electric field penetration depth has been performed for the interdigital impedance sensor, based both on the refractive characteristics of electric field at the interface between two different dielectrics and on the FEM analysis of electric field distribution and capacitance, through which it has been more clearly understood how to define the effective electric field penetration depth for FEF sensors, and what is the physical meaning of 3% of the sensor terminal capacitance which has been accepted as the critical value for defining the effective field penetration depth in the previous papers.

As discussed in this paper, as the dielectric specimen goes up farther and farther away from the sensor surface, the electric field distribution shows an apparent jump-like change at each position due to the existence of the dielectric-air interface, whereas the capacitance change is found to be monotonically continuous, which hints us at that the FEM analysis of electric field distribution makes it more convenient to grasp the extent to which the electric field generated in the FEF sensor spreads out.

According to the FEM analysis results, the jump-like change of the normalized electric field intensity by about 1% is the premise for accepting 3% of the normalized capacitance as the criteria for defining the effect electric field penetration depth for a FEF sensor, which may be reasonable from the viewpoint of the practical measurement accuracy.
However, for the sake of determination of more accurate penetration depth, less than 1% of the normalized electric field intensity or less than 3% of the normalized capacitance may be selected.

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