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The Soil Moisture Content Determination Using Interdigital Sensor

V. Markevicius[1], D. Navikas[1], A. Valinevicius[1], D. Andriukaitis[1], M. Cepenas[1]
[1]*Department of Electronics Engineering, Kaunas University of Technology, Studentu St. 50–418, LT-51368 Kaunas, Lithuania*
vytautas.markevicius@ktu.lt

***Abstract*—During geological soil examination humidity of the soil was decided to be measured using interdigital capacitance sensors. Using software „COMSOL v4.2“ the sensors were modelled and optimal sizes for use with AD 5933/34 chip were selected. Electrical impedance has proven to be the most suitable parameter for humidity measurement. Optimal probing frequency, geometry of the sensor and electrical impedance to humidity function were modelled.**

***Index Terms*—Soil moisture, capacitance, conductivity, impedance, soil measurements.**

I. INTRODUCTION

The moisture content in substance is very important parameter for different modes of technological processes, determines row material and production mass and quality, has influence on conditions of environment [1]. The amount of moisture in soil, in the context of construction of buildings, has influence on characteristics of foundation, its construction and price.

The moisture accumulation in the soil is very dependent on type of a soil, distance from the surface of the ground, climate and amount of organic substances in the soil. The amount of water in the soil can be determined visually (very inaccurate), using different indirect methods or direct method (drying of the soil) [2].

Interdigital electrode sensors are used to measure moisture in agricultural commodities and paper, as distance or biomedical sensors and as sensing elements in MEMS accelerometers [3]. The functioning of all these sensors is based on the measurement of the capacitance change. The sensor interaction with water or moist substance produces relatively considerable change of capacitance, because relative permittivity of water is very high (approximately 80). The interdigital sensor type was chosen for further investigations in order to determine its feasibility for measuring of the soil moisture content [4].

The soil consists of variety of substances (various metals, minerals, salts and etc.). The relative permittivity and conductivity of the soil additives are different, the density of soil is uneven and components are mixed chaotically.

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II. MODEL OF APPLICATION FOR MOISTURE CONTENT MEASUREMENT

On purpose to approve the possibility of soil moisture level determination using interdigital sensor, modelling was carried out.

The electrostatic system containing n electrodes can be described by these equations [5]:

$$\begin{cases} Q_1 = C_{11}U_1 + C_{12}(U_1 - U_2) + \ldots + C_{1n}(U_1 - U_n), \\ Q_2 = C_{21}(U_2 - U_1) + C_{22}U_2 \ldots + C_{2n}(U_2 - U_n), \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ Q_n = C_{n1}(U_n - U_1) + C_{n2}(U_n - U_2) + \ldots + C_{nn}U_n, \end{cases} \quad (1)$$

where Q_i – the charge of electrode i; U_i – the potential of electrode i; C_{ii} – capacitance of electrode i; $C_{i,k}$ — capacitance between electrodes i and k [6].

In order to calculate the capacitance, charge and potential of each electrode must be known. It is not always possible, therefore (1) the system of equations are more suitable for theoretical calculations. In the practical applications capacitance between two electrodes can be determined using alternating voltage among electrodes and current in electrode

$$i(t) = C \frac{d}{dt} u(t). \quad (2)$$

On the ideal capacitive element harmonic voltage and current phases differ by $\pi/2$. Expression of complex amplitude of current

$$\dot{I} = \dot{U}\, j\omega C, \quad (3)$$

where $\dot{U}$ – complex amplitude of voltage; ω – angular frequency.

According to [4] the charge Q and electrical capacitance C can be described as follows:

$$Q = \varepsilon_0 \iiint \varepsilon_r\,(x,y,z) dx \cdot dy \cdot d(\tfrac{1}{z}), \quad (4)$$

$$C = 2\frac{W}{\Delta V^2}, \quad (5)$$

where W – potential electric energy between electrodes; ΔV – the voltages difference between electrodes; Q – charge on electrodes.

$$W = \frac{1}{2}\varepsilon_0 \iiint \varepsilon_r(\bar{r})(\bar{E}(\bar{r}))^2 dV. \quad (6)$$

It is evident that in all these expressions capacitance is proportional to relative permittivity, which can be determined by measuring of capacitance [5]–[8].

The relative permittivity of the soil can be different depending on direction, therefore the direction displays highest dependence of relative permittivity on the moisture content should be segregated. As it can be seen from (6) the maximum energy dependability on relative permittivity is reached when electrical field direction will be the same as direction of investigative relative permittivity component.

The modelling result shows that electric field near the electrode is perpendicular to the surface. Receding from the surface electric field direction depends on adjacent electrodes and relative permittivity of substance.

When the behaviour of capacitive structures in frequency domain is modelled electrical impedance depends on conduction losses in the structure

$$-\nabla \cdot ((\sigma + j\omega\varepsilon_0\varepsilon_r)\nabla V) = 0, \quad (7)$$

where σ – electrical conduction; ω – frequency.

If the conductivity is not high the tangent of losses angle can be equated to conductivity:

$$\varepsilon_r = \varepsilon' + j\varepsilon'', \quad (8)$$

$$\delta \approx tg\delta = \varepsilon'' / \varepsilon'. \quad (9)$$

The real part ε' is influenced by the mobility and the quantity of the electric dipoles. The imaginary part ε'' describes conductive and dipole losses [8]–[10].

The main task is to find the optimal topology of electrodes which allows achieving highest sensitivity to change of electrical impedance depending on moisture content in a soil.

In order to determine optimal topology of interdigital electrodes the electric field of capacitive element distribution was modelled. Finite element method software „COMSOL v4.2“ was used for modelling.

After the 3D model geometry description (Fig. 1) boundary conditions were set: the copper was set as interdigital capacitive element; the potential of 3 V was set for one electrode and 0 V potential – for another.

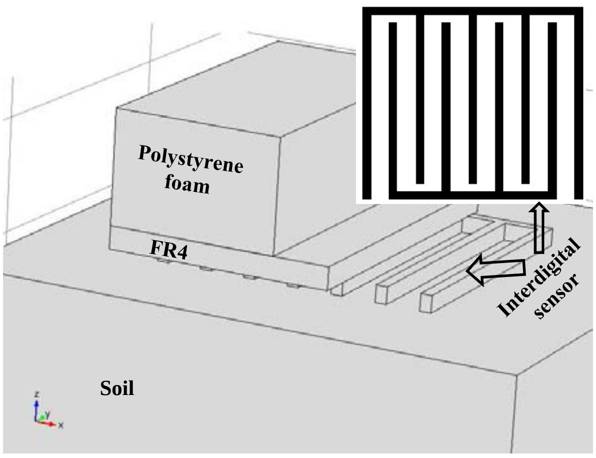

Fig. 1. COMSOL model of measurement application.

Thin (2.3 mm) FR4 plate was placed on the electrodes and on top of that a plate of polystyrene foam was placed. On the other side of electrode very thin (less than 30 µm) film of polyethylene and dielectric electrically equivalent to soil was placed. The whole construction was bounded by air cube.

A three dimensional finite element analysis simulation was conducted to determine optimal count, length and pitch of electrodes. Despite the fact that design of the model is more complicated, 3D modelling was chosen because the further analysis of modelling results is more convenient. The modelling algorithm is presented in Fig. 2.

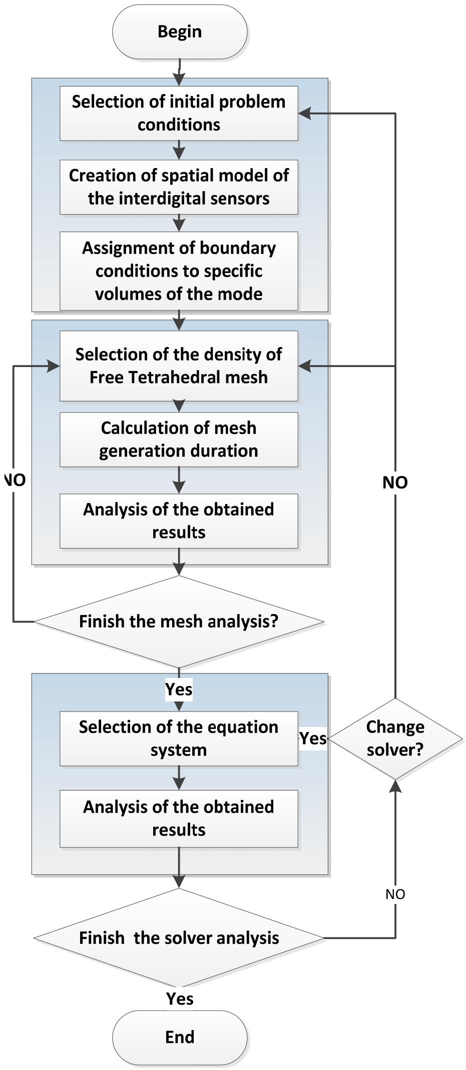

Fig. 2. The algorithm of the modelling.

The electrical impedance and capacitance dependencies of the system, with the main source of capacitance being soil, on frequency were calculated.

III. RESULTS OF MODELLING

The electric field distribution is presented in Fig. 3. It can be seen that electric field penetrates the soil deep enough to determine the average moisture value of the sample.

The electrical impedance of the system of electrodes is the function of various parameters

$$Z = f_z(M, T, D, \omega), \quad (10)$$

where M – concentration of moisture, T – temperature, D – density, ω – frequency of signal.

Real application to the measure the moisture content is faced with inverse main problem – by measuring electrical impedance and capacitance to evaluate moisture content in the soil. In ideal conditions, it can be assumed that the electrical impedance of the system is directly dependent on the moisture content in the substance. However, this assumption is valid if there are no other factors and the requirements for measurement precision are low.

By choosing suitable topology of the electrodes maximum electrical impedance change, when comparing dry and wet soil samples, can be achieved

$$K = \frac{Z_S - Z_D}{Z_S}, \tag{11}$$

where Z_S – the electrical impedance of dry soil, Z_D – the electrical impedance of wet soil.

The task is to find optimal topology of electrodes which ensures maximal value of coefficient K.

Primary, the electrical potential distribution in the soil was calculated (Fig. 3).

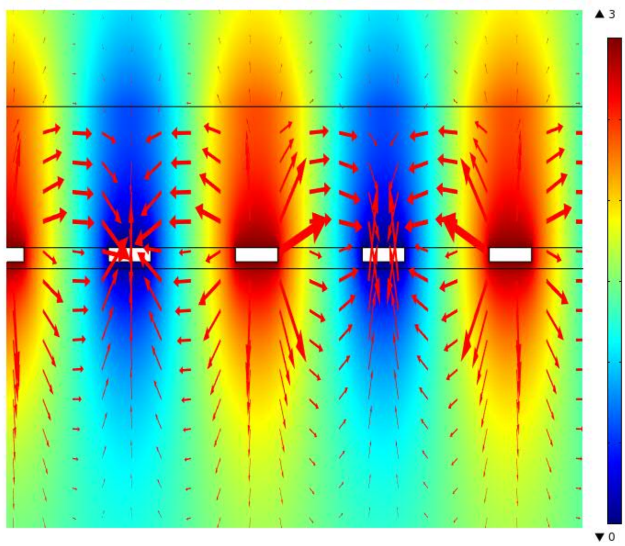

Fig. 3. Electrical potential distribution.

The electrical impedance dependence on permittivity and conductivity was modelled not taking temperature and density of soil into account. The width of modelled electrodes was 1–2 mm, thickness – 0.05 mm, the gap varied from 0.5 mm to 5 mm.

The relative change of electrodes impedance dependence on the relative permittivity of soil and conductivity were modelled (Fig. 4 and Fig. 5). The following parameters were set: the width and the gap of electrodes – 1 mm, the thickness of electrodes – 0.05 mm. In the first case the conductivity of the substance was set to $7{,}5 \cdot 10^{-5}$ *(S/m)* and permittivity varied from 4 to 10. In the second case the relative permittivity was set to 7 and conductivity varied from $1.0 \cdot 10^{-5}$ to $1.0 \cdot 10^{-4}$.

According to the modelling results, the impedance of the system of electrodes depends mostly on the conductivity of soil. It has direct dependence on moisture content and it could be used for estimation of moisture content.

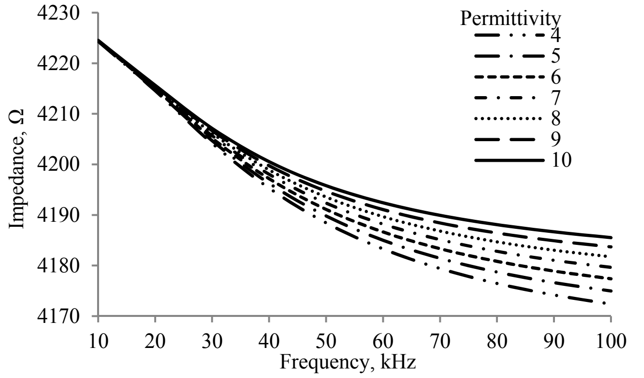

Fig. 4. The impedance dependence on relative permittivity and frequency when σ=7,5·10^-5(S/m).

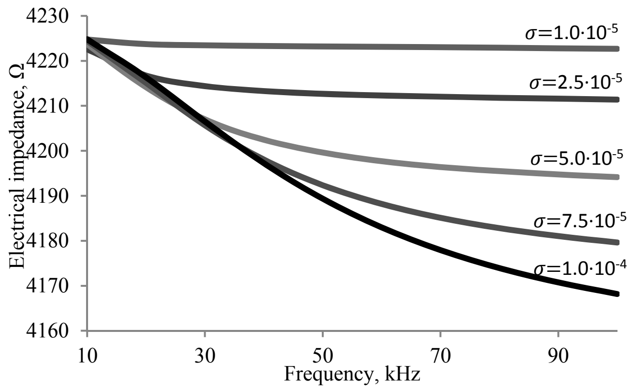

Fig. 5. The impedance dependence on conductivity and frequency (ε=7).

The real functional dependence of sensor impedance on moisture content can be nonlinear. It can depend on temperature, type of soil, density and other parameters.

As can be seen from Fig. 4, the change of impedance is higher when relative permittivity of substance is lower.

The dependence of impedance on the gap between electrodes was investigated. In order to make results more informative instead of the gap between electrodes the ratio *a/b* were used (*a* – the width of electrodes, *b* – the gap between electrodes). The Fig. 6 shows the dependence between the coefficient K and ratio *a/b*, when thickness of electrodes is 0.05 mm.

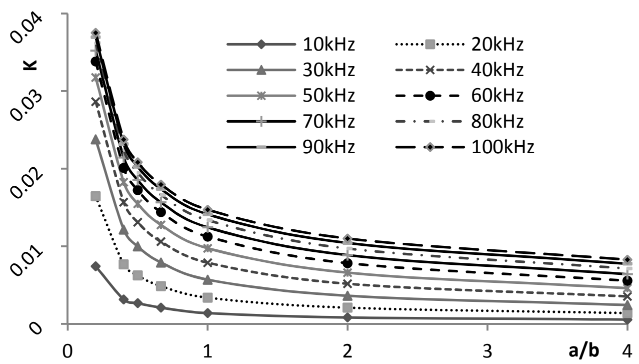

Fig. 6. The impedance dependence on the ratio a/b and frequency.

The investigation of the dependence between impedance and dielectric thickness was carried out in two cases: the first was performed when material with $\varepsilon_r = 2.5$ was used between substance and electrodes, and the second was performed when the thickness of the material varied from 0.01 mm to 0.3 mm and

The variation of the impedance (Fig. 7) is higher when thin layer of dielectric between the electrodes and the substance is inserted. It occurs because the lines of the electric field close in dielectric and only few penetrate to the substance investigated. The modelling results clearly show that the dielectric has to be as thin as possible.

The Fig. 8 shows the dependence of impedance on thickness of the electrodes. The modelling conditions were: the width of electrodes – 2 mm and the gap between electrodes – 4 mm.

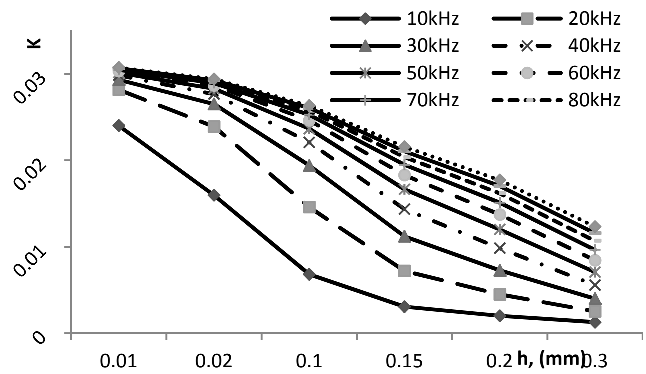

Fig. 7. The impedance dependence on the thickness of the dielectric layer and frequency.

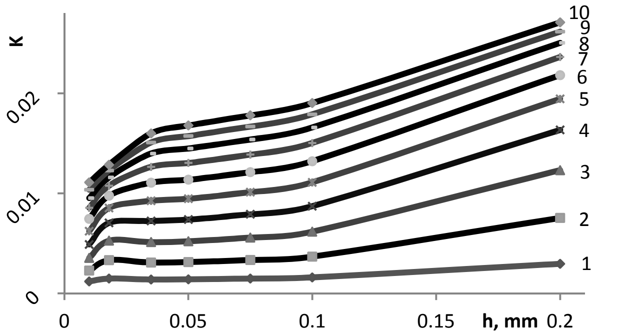

Fig. 8. The impedance dependence on the thickness of electrodes and frequency.(1-10kHz, 2-20kHz, 3-30kHz, 4-40kHz, 5-50kHz, 6-60kHz, 7-70kHz, 8-80kHz, 9-90kHz, 10-100kHz).

As can be seen from Fig. 8, the thickness of the electrodes should be minimal, because it assures higher ratio K.

In order to determine minimal thickness of the sample theoretical impedance dependence on thickness of soil sample was investigated (Fig. 9). The investigation was carried out in two cases: the first was performed when the width of electrodes a=2 mm and the gap between them b=0.5 mm (*2/0.5=4*), and the second was performed when the width of electrodes a=2 mm and the gap between them b=10 mm (*2/10=0.2*).

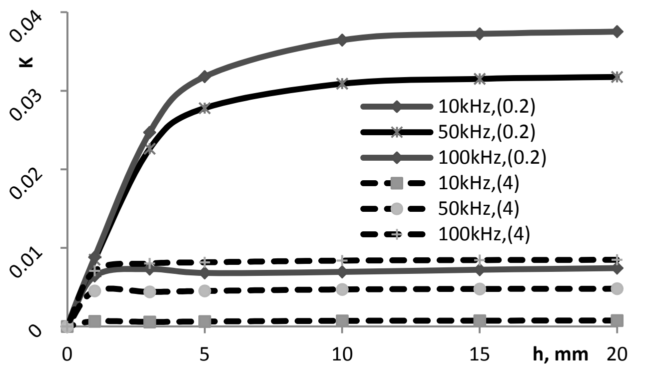

Fig. 9. The impedance dependence on the thickness of sample of soil and frequency.

It was established that the thickness of sample should be at least 10–15 mm, otherwise the most of electric field lines bypass the sample.

The impedance of the sensor depends on the thickness of sample nonlinearly up to a certain limit and after that the thickness does not affect this parameter.

In order to achieve optimal size of the electrode system it is important to determine the optimal gap between electrodes and the width of the electrodes should be acceptable comparing to the thickness of the substance sample.

IV. CONCLUSIONS

The modelling in the frequency range from 10 kHz to 100 kHz using COMSOL Multiphysics proved that influence of relative permittivity and conductivity of soil on impedance of interdigital sensor can be determined

In order to achieve higher sensitivity, the electrodes have to be as thick and narrow as possible and the thickness of dielectric between sample and the electrodes should be minimal.

The bigger gap between electrodes ensures ~~the~~ higher measurement accuracy.

The influence of the type and salinity of the soil on impedance of sensor should be determined experimentally.

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