Development of Low Cost Soil Sensor Based on Impedance Spectroscopy for In-Situ Measurement

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Abstract. This paper presents a low cost sensor for soil moisture measurement based on impedance spectroscopy. A probe has been designed which uses a simplified impedance measuring system to determine soil water content. Methods of soil moisture measurement need extensive calibration processes because of the strong dependence on soil properties. Using impedance spectroscopy, more information can be delivered from real and imaginary part of the complex permittivity for several frequencies at the same moisture value. Agriculture area in East Sumatra is especially selected for this investigation because measurements of soil moisture in peat swamp area were generally reported as difficult.

Keywords: Soil Moisture Measurement, Dielectric Measurement, Impedance Spectroscopy

1. INTRODUCTION

Soil plays a key role in crop production as a physical support and a reservoir of water and nutrients. Site-specific crop management decisions for optimized input rates of water, fertilizer, pesticides, and seeds are largely based on physical, chemical, and biological properties of soils. Traditional soil surveys and accompanying soil databases are too general for use in site-specific farming systems, and the current method of intensive grid sampling requires a sizeable investment of money and time [Charlesworth, 2000]. Therefore, inexpensive sensors those are capable of measuring multiple soil properties in real-time are needed.

Several methods are available for in-situ soil water content measurement. The most developed and therefore most reliable of the electromagnetic methods is Time Domain Reflectometry (TDR) which operates by launching a fast rise voltage step along the transmission line or probe in the soil the pulse travels to the end of the probe and back where it is detected and analysed. The velocity of propagation of the pulse is related to the dielectric constant (Topp 2003). The TDR technique determines the dielectric constant of a medium from measurements of the propagation speed of an electromagnetic wave obtained from a pulse generator. Topp (1980) developed the empirical relationship between the dielectric constant of soil and soil moisture and since then the application of TDR has been widely accepted. Conductivity sensors and tensiometers measure soil water potential, which refers to energy required in order to extract water from porous soil material. Conductivity sensors are e.g. gypsum blocks like the Watermark sensor. The sensor signal is highly dependent on soil salinity and gypsum blocks dissolve it self with time. Tensiometers measure the pressure difference describing the water loss from a porous water reservoir. They need high maintenance expenditure because the water reservoir should be permanently filled and even short-range reservoir total evacuation leads to pore blockings changing the measurements behavior.

Capacitive sensors are easy to use but their measurements are dependent on soil salinity and on soil properties. This means that calibration processes are required in order to maintain an acceptable accuracy. This should be also regularly done because of changes in soil properties by rain, fertilization and agricultural work. Capacitive sensors have also special difficulties to measure sandy soils because of the difficult contacting of soil probes and the dependence upon dissolved electrolytes and so-called soil density.

In this paper, we will develop a soil moisture sensor for investigating of soil wetness in the peat swamp area in East Sumatera that contains of organic component, the rest clay and silt based on impedance measurement. It is therefore a very interesting special case for the investigation of impedance spectroscopy for soil moisture measurement in general.

2. BASIC PRINCIPLE OF IMPEDANCE SPECTROSCOPY FOR SOIL WATER CONTENT MEASUREMENT

Soil permittivity is a good indicator of several important soil properties closely related to crop productivity. For characterizing material properties, material interfaces, geometrical structures and diffusion processes, the impedance spectroscopy method is commonly a used [2, 3]. Typical applications are electro-chemistry, material science, biology and medicine.

The main advantage of impedance spectroscopy is the possibility to get information about the real and imaginary part of sample's impedance at different frequencies. This can be considered as a "multi input sensor" in which the dependence on the frequency is modeled in order to separate effects with different frequency dependences.

Using impedance spectroscopy, we dispose of both capacitive and conductance measurement of soil at different frequencies [Flaschke, 2001]. Both real (G) and imaginary part (B) of the admittance are dependent on moisture and material properties of soil in different manners.

$$\underline{Y} = G + jB \quad (1)$$

The complex permittivity can be derived from the measured admittance as follows:

$$\underline{\varepsilon_r} = \varepsilon_r^{'} - \varepsilon_r^{''} = \frac{B}{\omega \cdot C_0} - j \cdot \frac{G}{\omega \cdot C_0} \quad (2)$$

The big discrepancy between the permittivity of water (ε_w ~81) and the permittivity of dry soil (ε_s ~ 2-4) allows the measurement of water content. Impedance of dry soils does not change appreciably with frequency. Observed frequency dependences are due to dispersions of different water forms present, such as bound water, free water and water in the particle pores. In [Sternberg et al, 2001] was shown, that the value of ε_r is more dependent on the soil composition (percentage of sand, clay and silt) than on the dry bulk density. In figure 1 different effect influencing the imaginary part of the permittivity are shown in semi logarithmic curve.

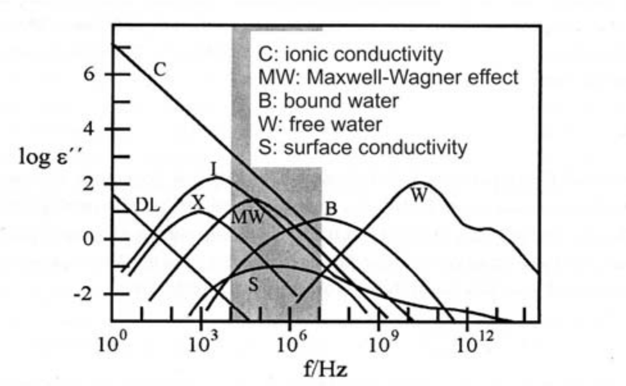

Figure 1. Dielectric dispersion in wet soil [Hasted, 1973]

The total losses can be described as a sum of the weighed imaginary parts of the permittivity corresponding to each effect [Hilhorst, 1998]:

$$\varepsilon''(\omega) = \sum g_i \cdot \varepsilon_d''(\omega) \quad (3)$$

Several effects are taking place in the frequency range under 10 MHz such as ionic conductivity, surface water effect, bound water effect and the Maxwell-Wagner effect. These effects have different dispersions and can be therefore separated if sufficient frequencies are used and they are not overlapped over the whole frequency range considered.

3. Material and Methods

3.1. Soil Sample Preparation

A local andisol soil with a pH of 7.5 was used. Soil samples with different water contents were prepared in covered containers. Before adding water, soil samples were oven-dried at 105°C for 24 h and then ground to through a 2-mm sieve, see Figure 2. Known weights of water were added to the soil samples to achieve desired water contents. Measurements were initiated at least 24 h after the water was added to allow the sample to reach equilibrium. The actual water contents were reexamined and recorded after each test by weighing. The intended gravimetric water contents were 10, 20, 30, 40 dan 50%. Actual gravimetric water contents slightly deviated (±1% max.) from these values. Volumetric water contents were calculated from the measured values of gravimetric water contents using a bulk density of 1.25 g cm^{-3}, which was maintained for all soil samples used in the experiment.

Figure 2. Different soil samples, after preparation using oven dried

3.2. Sensor Design and Measurement Setup

The prototype sensor was designed based on the double-electrode structure (Fig. 3). The double electrodes were made of cylinders rod of brass alloy with diameter 4-10mm. They were assembled on a Teflon holder with 12mm thick. The space between adjacent electrodes was 25 mm. The sensor electrode design was intended for in situ measurement, where the sensor penetrates deep inside the soil. Penetration depth and electrode size were considered depend on the soil measurement purpose and field characteristic.

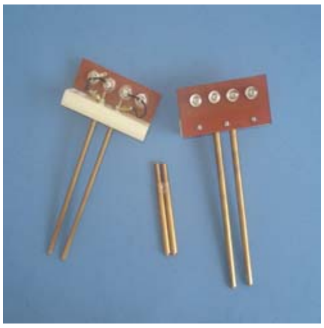

Figure 3. Soil sensor electrode

Measurement and sensor characterization is done at FST University Kebangsaan Malaysia (UKM) Bangi, Kuala Lumpur using Impedance Gain-Phase Analyzer type 1260 from Solartron Analytical. Sweep Frequency was set from 0,1 Hz - 10MHz with a 10mV AC voltage. At first, the soil sample is prepared by dividing the soil into 6 different levels moisture 10, 20, 30, 40, 45, 50% respectively. Impedance spectroscopy usage is intended to scan the frequency of the sensor at defined soil moisture. The results of the measurements give impedance curve in complex space and bode plot of the sample respectively. To analyze the real part G and the imaginary B of the soil sample, we used ZView2 software.

4. RESULTS AND DISCUSSION

Figure 4 shows the result of measurement at different defined soil moisture. As can be seen in Figure 4, semi circle of real and imaginary part of the complex permittivity are dependent on soil moisture. Both real an imaginary part of the complex permittivity decrease with frequency and increase with soil moisture, Figure 5.

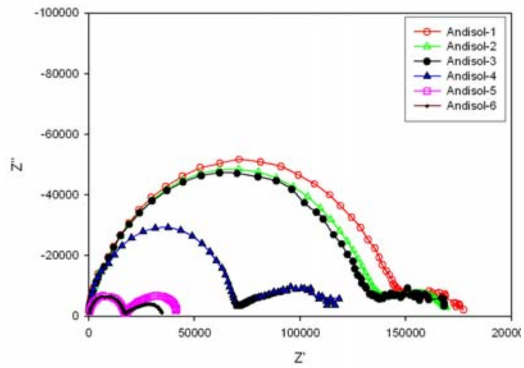

Figure 4. Semi circle impedance of soil moisture measurement

The imaginary part Z" describes more the material losses [Kanoun, 2004] and the real part Z' describes more the dependence on the soil moisture and changes therefore more its value.

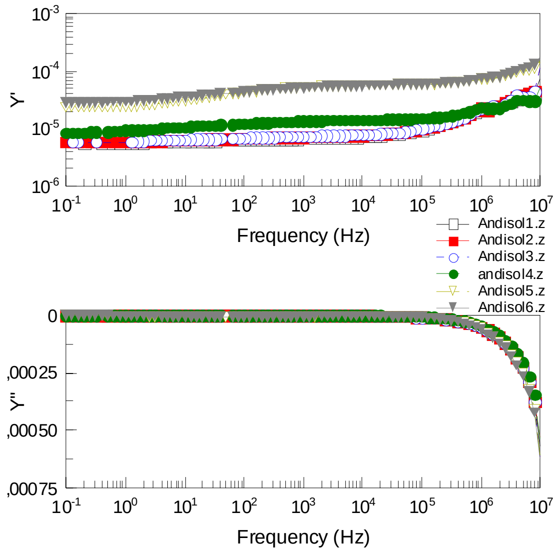

Figure 5. Real and imaginary part of the permittivity of soil

At low frequencies range less than 1 MHz, the ionic effect in the characteristic is dominated by a marked decrease of the imaginary part of the permittivity. In both Figure 4 and Figure 5 we can observe some significant difference between the characteristic at soil moisture. This seems to be a special effect and was reported in [Perkins, 1987].

In impedance spectroscopy, the experimental aspect and signal processing methods are both very important prerequisite for the extraction the information with acceptable accuracy. Using equivalent circuit models requires modeling of the impedance spectrum in conformity to physical, chemical and biological process, taking place in the impedance under investigation. Extraction parameters are a matter of concern and can be supported by different methods of optimization. Figure 6 and 7 shown the real part G and imaginary part B at certain frequency depend on the soil moisture and increase due to wet level.

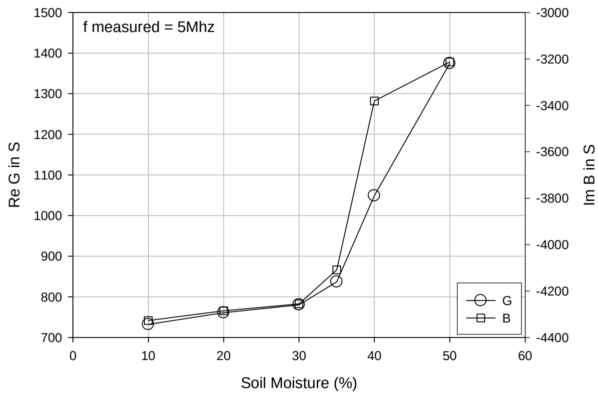

Figure 6. The Real G and imaginary part B of soil impedance shown dependency of soil moisture

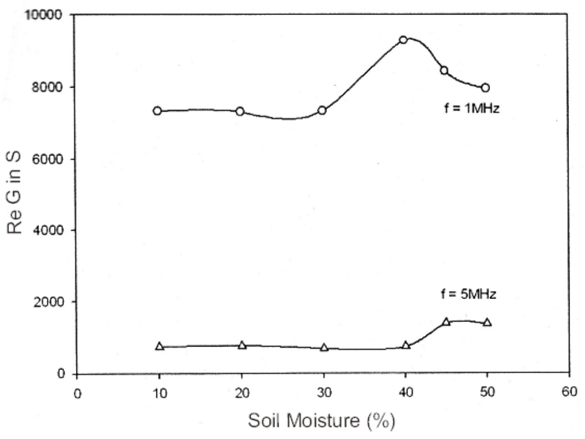

Figure 7. Relative changes of model parameters in comparison of their values at different frequency

As we seen, the real part of the soil impedance changes slightly with the increasing of the soil moisture. We have chosen two different frequencies 1 MHz and 5 MHz in order to observe the sensor sensitivity and implicate to simplify the electronic circuit instead the impedance analysator for the future purpose. The sensitivity of model parameter on soil moisture is significant and let us expects a good calculability of soil moisture.

5. CONCLUSION

The measurement of soil moisture is very important for an adequate irrigation taking into account the real vegetation demands. Nevertheless, commonly used methods need regular calibration processes and therefore high maintenance expenditure. This leads to high costs and prevent the wide use of soil moisture sensors.

A soil moisture measurement based on impedance spectroscopy was proposed. The basic idea thereby is to measure the complex impedance of a soil sample at different frequencies and to subject them to adequate signal processing.

The soil investigated especially in this paper is local soil in Sumatera. The main reasons thereby are that several soil moisture sensors have specially difficulties with it and because it is almost composed of pure wet soil with organic parts and therefore an interesting special case.

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