Electrical Characterization of Wetted Substrates

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Abstract—**An interface system for measuring water-content and water conductivity of artificial soils (substrates) is presented. It is intended for measuring impedances that can be modeled as a parallel combination of a capacitance C_p and a resistance R_p. In the particular application, the capacitance varies from 1 pF to 100 pF and the resistance can be in the range from few tens of ohms up to 5 kΩ. The measurements are conducted with a sinusoidal signal having a frequency of 20 MHz. At this frequency the full-scale error for C_p doesn't exceed 3,5% for a 100 pF range. The full-scale error for the measured R_p remains below 3,7% for a full-scale value of 5 kΩ. With the presented measurement principle resolution better than 0,2% can be achieved for both measured components.**

Keywords—**Admittance-measurement system; Wetted substrates; Conductivity; Permittivity;**

I. INTRODUCTION

Nowadays agriculture widely applies artificial soils (substrates) instead of natural soil. Such a substrate supports easily plant growth thanks to its water-holding capacity. When the substrate is dry it contains approximately 97% air. It is cheap and easy to fabricate. However, for optimizing the growing process, continuous control of the amount of water in the substrate is needed. The conductivity of the water can be informative as well. The current article presents an interface system for measuring both water-content and water conductivity of wetted substrates.

The best approach to measure the water-content of a substrate is to sense the specific dielectric constant of the material [1][2][3]. A dry substrate has a relative dielectric constant ε_r around 1,05 and water of about 80, thus the overall relative dielectric constant of the material varies from 1,05 to approximately 80, depending on the water-content. Usually we are talking about permittivity instead of dielectric constant, because the specific dielectric constant is a parameter specified for zero frequency. The permittivity is defined as

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad (1)$$

where the real part of the permittivity ε', is a measure of the total polarisability, including non-polar and dipolar polarization of the material constituents. The imaginary part of the permittivity ε'', represents the total energy absorption or energy loss.

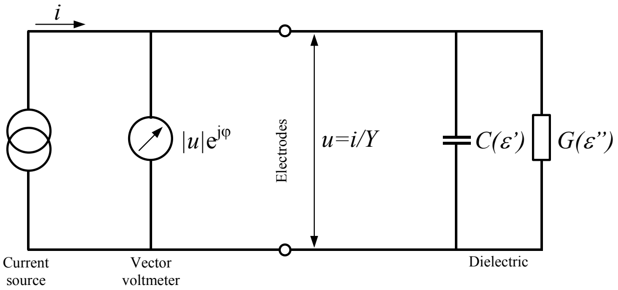

Fig. 1. Electrical model for measuring the dielectric properties of materials.

The electrical parameters of a substrate can be measured with a two or a four-electrode setup [3][4][5]. By applying a sinusoidal current and measuring the voltage between the electrodes (Fig. 1) the total complex admittance can be extracted

$$Y = 1/Z = G + j\omega C \qquad (2)$$

From (2) the real and imaginary part of the permittivity can be found

$$\varepsilon' = \frac{C}{\varepsilon_0 k} \qquad (3)$$

$$\varepsilon'' = \frac{G}{\omega \varepsilon_0 k} \qquad (4)$$

where k is the geometry factor of the electrode structure and ω is the angular frequency.

II. PRINCIPLE OF OPERATION OF THE MEASUREMENT SYSTEM

To implement the measurement principle shown in Figure 1 a set-up based on the principle applied in the RLC instruments can be used [3][4][8]. Figure 2 shows the block diagram of the measurement system. The sinusoidal voltage U_s is converted to a current i by the OTA (operational transconductance amplifier). The current passes through the unknown impedance Z_x and the resistor R_i. A differential amplifier A2 monitors the

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unknown voltage drop U_z across Z_x directly at the terminals U and I. To eliminate the effects of the nonidealities of the current source and the current-to-voltage converter A1, the current i is monitored, by measuring the voltage U_i across R_i. The impedance is found as the ratio of the voltage to current reading, which equals

$$Z_x = \frac{U_z}{U_i} R_i \qquad (5)$$

With this principle a ratio measurement with a common voltage-meter is performed, so the gain and phase characteristics of the voltage-meter circuits are cancelled in the final result.

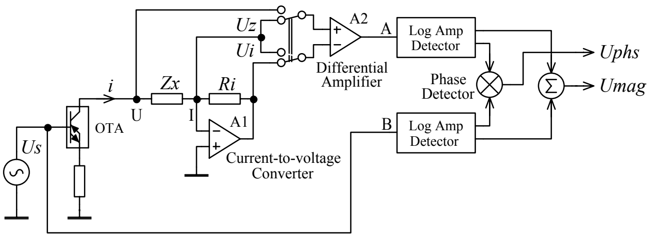

Fig. 2. Block diagram of the measurement system.

The vector voltmeter shown in Figure 1 is realized with two well-matched logarithmic amplifiers (see Fig. 2). By taking the difference of their outputs, a measurement of the magnitude ratio between the two input signals at terminals A and B is available. To determine the absolute signal level of the unknown signals U_z and U_i at terminal A, we apply an AC reference signal at terminal B. A phase detector of the multiplier type is used to measure the phases φ_{Uz} and φ_{Ui} of the two unknown voltages (Fig. 3).

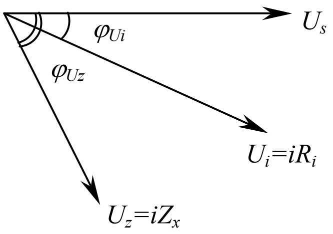

Fig. 3. Vector diagram of the measured voltages.

Two DC output voltages U_{mag} and U_{phs} are available for measurement of respectively the amplitude ratio of the signals at terminals A and B over a ±30 dB range, scaled to U_{slpM}=30 mV/dB, and the phase difference between the two signals over a 0°-180° range, scaled to U_{slpP}=10 mV/degree, according to the equations

$$U_{mag} = U_{slpM} 20\lg(U_A / U_B) \qquad (5)$$

$$U_{phs} = U_{slpP}(\varphi_A - \varphi_B) \qquad (6)$$

where U_A and U_B are the AC input voltages at terminals A and B, and φ_A and φ_B their phases.

Two steps are needed to measure the unknown impedance. During the first step, the voltage across the impedance is measured. With a reference signal U_s applied to terminal B, it holds that

$$U_{z,mag} = U_{slpM} 20\lg\frac{U_z}{U_s} \qquad (7)$$

$$U_{z,phs} = U_{slpP}\varphi_{U_z} \qquad (8)$$

During the second step, the current i is monitored

$$U_{i,mag} = U_{slpM} 20\lg\frac{U_i}{U_s} \qquad (9)$$

$$U_{i,phs} = U_{slpP}\varphi_{U_i} \qquad (10)$$

From (7) and (9) the module of the impedance $|Z_x|$ can be derived

$$|Z_x| = R_i 10^{\frac{1}{20U_{slpM}}\left(U_{z,mag} - U_{i,mag}\right)} = R_i \frac{U_z}{U_i} = R_i \frac{Z_x}{R_i} \qquad (11)$$

The phase φ_z is calculated from (8) and (10)

$$\varphi_z = \frac{1}{U_{slpP}}\left(U_{z,phs} - U_{i,iphs}\right) = \varphi_{U_z} - \varphi_{U_i} \qquad (12)$$

If the structure of the impedance is known, the value of its components can be calculated. For the particular application we assume to have two components C_p and R_p in parallel. The resistance R_p is calculated from

$$\frac{1}{R_p} = \mathrm{Re}[Y_x] = \frac{1}{|Z_x|}\cos(\varphi_z) \qquad (13)$$

The capacitive component is calculated from

$$C_p = \frac{1}{\omega}\mathrm{Im}[Y_x] = \frac{1}{\omega}\frac{1}{|Z_x|}\sin(\varphi_z) \qquad (14)$$

III. EXPERIMENTAL RESULTS

In our particular application with special electrodes for measuring the water-content of a substrate, the capacitance C_p varies in the range from 1 pF to 100 pF and the parallel resistance R_p from a few tens of ohms to 5 kΩ. Experiments were carried out with the circuit shown in Figure 2. The sinusoidal voltage U_s is converted to a current with constant amplitude of 1 mA by an operational transconductance amplifier OPA660AU (Burr Brown). It is preferable to work with an excitation current with constant amplitude because of the electrode polarization impedance. This impedance depends on the current density, the temperature, the type and the concentration of the dissolved ions etc. We need to reduce its influence or to keep its value as stable as possible.

The current-to-voltage converter and the differential amplifier were realised with the voltage feedback amplifier AD8055 (Analog Devices). The vector voltmeter was realized with the gain/phase detector AD8302 (Analog Devices). Tests were conducted for capacitors and resistors at a frequency 20 MHz. The frequency of the applied signal is an important parameter because of the physical nature of the water molecule and the dissolved ions. It has been found that for measuring moisture, the highest sensitivity for the presence of water molecules can be achieved at around 20 MHz [1][6][7].

The results were compared with measurements made with a Hewlett Packard HP4294A precision impedance analyser which has an accuracy between 1% and 3% at 20 MHz. The voltages U_{mag} and U_{phs} were measured with a Hewlett Packard HP34401A digital voltmeter (DVM). Its resolution was set to be 0,01 mV.

Table 1 shows the values of the measured capacitance C_p for different values of R_p.

Table 1. The value of the measured capacitance C_p for different values of the resistance R_p.

Cp, pF HP analys.	*Rp*=∞	*Rp*=4,7kΩ	*Rp*=1,5kΩ	*Rp*=470Ω	*Rp*=100Ω
1,842	1,963	1,968	1,938	1,939	1,113
2,879	2,934	2,97	2,947	2,961	2,131
5,633	5,615	5,661	5,64	5,686	4,927
9,994	9,887	9,965	9,958	10,027	9,385
17,959	17,783	17,915	17,916	17,967	17,546
33,14	32,83	33,08	33,08	33,16	33,13
56,39	56,18	56,62	56,65	56,82	57,26
81,76	81,98	82,59	82,67	83,03	83,8
100,35	100,99	101,79	101,9	102,18	103,39

It can be calculated that the full-scale error doesn't exceed 3,5% for a 100 pF scale. The inaccuracy for the measured capacitive component is mainly caused by the nonlinearity in the phase measurement circuitry. Also because of the limited gain of A1, at the current terminal I a non-zero voltage appears. Through the input differential impedance of the amplifier flows mainly reactive current, which is added to the current i flowing through R_i. This effect is dominant for R_p with very low resistance and resembles additional capacitance for the measured C_p.

Table 2 shows the values of the measured resistance R_p for different values of C_p.

Table 2. The value of the measured resistance R_p for different values of the capacitance C_p.

Rp, Ω HP analys.	*Cp*=0pF	*Cp*=1,8pF	*Cp*=10pF	*Cp*=33pF	*Cp*=56pF	*Cp*=100pF
99,341	98,58	98,53	98,28	97,77	97,42	97,04
219,08	219,82	219,69	219,27	218,33	217,7	219,18
467,69	473,54	472,94	470,4	467,31	467,34	479,08
994,74	1015,72	1013,19	1002,12	988,67	993,89	1066,8
1493,91	1529,6	1522,09	1500,65	1474,26	1495,11	
2691,76	2755,5	2734,39	2678,97	2630,14	2731	
4686,39	4657,9	4721,31	4583,04	4507,8	4825	

It can be seen that for a 5 kΩ scale the full-scale error doesn't exceed 3,7%. The presence of a reactive parasitic component C_i, which the resistor R_i carries, causes the main error for the measured R_p.

The resolution of the digital voltmeter that measures the signals U_{mag} and U_{phs} is important for the resolution of the overall system. Experiments were conducted with two different resolutions of the DVM – 0,1 mV and 0,01 mV by measuring an impedance consists of 1,8 pF capacitor and 220 Ω resistor (Fig. 4), and an impedance consists of 100 pF capacitor and 220 Ω resistor (Fig. 5).

It was concluded that the DVM causes the main restrictions for the resolution of the overall system. Yet, we achieved a resolution better than 0,2% for *Rp*. For C_p it is 0,1 % at the upper end of the measurement range and around 1,2 % for capacitance in order of few picofarads.

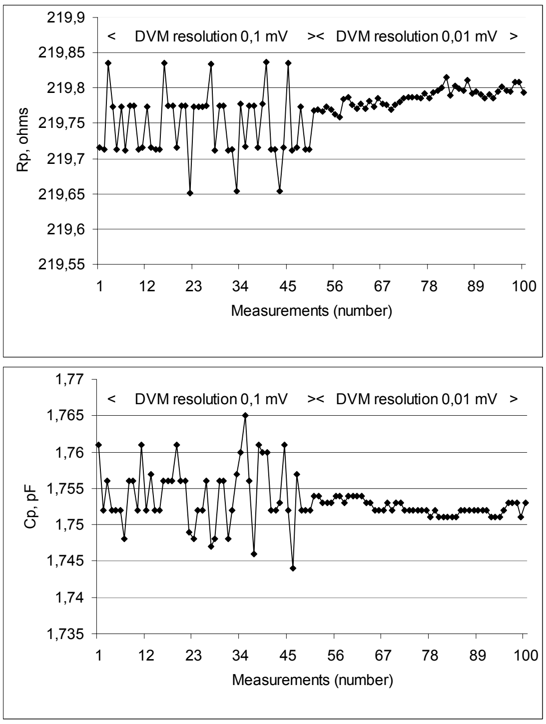

Fig. 4. A consecutive measurement for impedance consists of 1,8 pF capacitor in parallel with 220 Ω resistor for two different resolutions of the analog-to-digital converter - 0,1 mV and 0,01 mV.

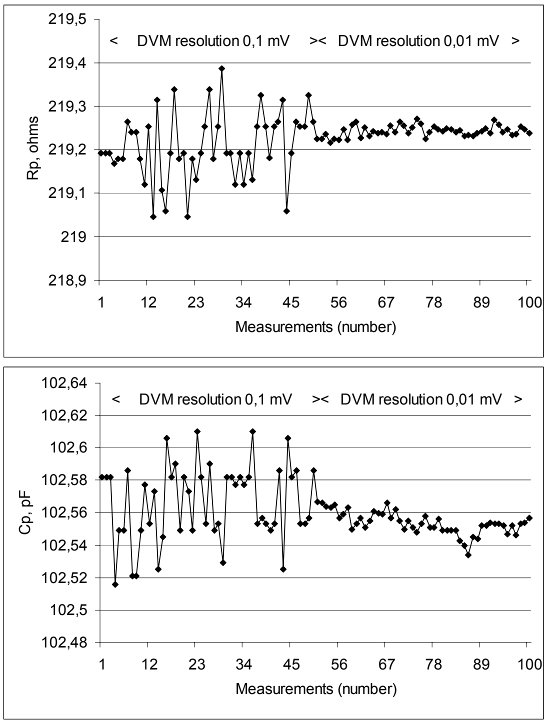

Fig. 5. A consecutive measurement for impedance consists of 100 pF capacitor in parallel with 220 Ω resistor for two different resolutions of the analog-to-digital converter - 0,1 mV and 0,01 mV.

IV. CONCLUSIONS

An interface system for measuring water-content and water conductivity if wetted substrates is presented. It is a system based on the measurement principles applied in the RLC instruments and designed to work with impedance that can be modeled as a parallel combination of a capacitance C_p and a resistance R_p. In the particular application, the capacitance can vary from 1 pF to 100 pF and the resistance from a few tens of ohms to 5 kΩ. The measurements are performed with a sinusoidal signal having a frequency of 20 MHz. At this frequency the full-scale error for C_p doesn't exceed 3,5% for a 100 pF scale. The full-scale error for the measured R_p remains below 3,7% for a 5 kΩ scale. With the presented measurement principle a resolution better than 0,2% can be achieved for both measured components.

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