Design, development and performance study of a polymer coated capacitive sensor for measuring moisture content of soil

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Abstract

In this study a new type of capacitive sensor coated with a polymer material, named as "DQN-70" has been used to measure the moisture content of the soil. Three different polymers PMMA, BPDA-mPD and DQN-70 are taken as the coating material and their impedance performance has been evaluated to select the proper coating material. Among these three materials- DQN-70 shows the repeatable and reliable output and hence, used for further study. The change in capacitance of the probe is measured at different moisture level and converted to voltage signal. Thermo-gravimetric method is used to calibrate the sensor performance. The probe was inside the soil for more than three months and produced consistent output.

Keywords: Soil moisture measurement; DQN-70 polymer; Polymer coated electrode; capacitive sensing; Thermo-gravimetric method

1. Introduction

Measurement of soil moisture is an integral part of “Water Management”, and became an important area of research in the field of agriculture, hydrology, agronomy, and meteorology [1–3]. Irrigation water management requires timely application of the right amount of water. Apart from that com- petition for water, high pumping costs, and concerns for the environment are important for good water management [4]. Reliable, robust and automated techniques for the measurement of soil moisture content can be extremely useful for sustainable growth [5].

Literature shows an wide number of reports on soil moisture meter and their critical review [6]. Among these, thermo- gravimetric method is the oldest one and still used for calibration purpose, but not an automated techniques and also labor intensive [5]. Modern soil moisture measurement techniques employ electrical properties of the soil (such as, soil resistivity, dielectric constant, impedance, and capacitance), soil moisture potential, infrared rays, and radioactive techniques such as neutron scattering, gamma attenuation and optical techniques [6]. All the measurement methods have their own advantages and disadvantages in terms of performance, portability, deployment, cost and automation.

Capacitive measurement technique meets many of the above mentioned performance parameters. It is precise, simple, fast, low cost, easy to install. It provides electrical output
which can be integrated to a sensor network for data analyses and necessary action [7].
Most of the capacitive techniques uses two separate probes where the capacitance between
them changes with the moisture content of soil [8].

In this paper, a new type of capacitive sensor coated with polymer is proposed which is
a single probe cut from a double sided copper (Cu) clad PCB board used in electronic
circuit fabrication. The polymer coating on the electrodes make the probe sensitive to the
moisture content and at the same time protect the electrodes from the hostile environmental
condition [9], [10].

The paper is organized in five sections. Section-I is 'Introduction'. In Section-II,
characterization of the probes, signal transduction circuit and the test result are provided.
Section-III discusses the result and conclusion is in Section-IV.

2. Fabrication, characterization and test result

It is already mentioned that the sensors are cut from double side Cu clad PCB board
which makes it rigid and can be easily pushed inside the soil bed. Cu layers are on the
largest
faces of the blocks and lead wires are soldered to them. The dimension of the sensors are
8 cm × 0.6 cm × 0.16 cm
with one side knife edged as shown in the Fig. 1(a). The probes are then coated with three
different types of polymer

(i) polymethul-methaacrylate (PMMA) [9]; (ii) BPADA-mPD which is a composition of
4,4-(4,4-isopropylidene diphenox) bis (phthalic anhydride) (BPADA) and m-
phenylenediamine (mPD) [11]; and with (iii) DQN-70 which is a proton exchange type
polymer comprises of Naphthalene dianhydride (NTDA) based semifluorinated sulfonated
copoly(ether imide)s [12].

A. Experimental Procedure

In a laboratory setup, natural soil is used in three hollow cylinders made of metals
and placed on a permeable plate

![Fig. 1. (a) Schematic of the sensor in soil bed (b) Laboratory setup to characterize the sensors](image-url)
which allows water percolation downwards, and enclosed in a tub (Fig. 1(b)). The three different probes coated with three different polymers are inserted inside the soil. Three liters of water is put into the bath and after one hour water comes out to upper level of soil from downwards. Then rest of the water remained in the bath is thrown out. After another 15 hours the experimentation started. Readings were taken using precision Impedance Analyzer (Agilent 4294A). The input of the sensor is sinusoidal signal whose frequency was varied from 20 Hz to 2 MHz to identify the most sensitive and repeatable range of operation of the sensor. The characterization was carried out at regular interval.

**B. Characterization and selection of the sensor**

To develop proposed soil moisture sensing system, we first study characteristics of different types of probes with respect to moisture over time. Primary objectives of such study are: (a) To understand which type of sensing is more appropriate, resistive or capacitive. (b) To determine the optimum operating frequency for signal transduction. (c) To determine which is the best suitable probe among DQN-70 type, BPADA-mPD type and PMMA type.

(a) Selecting the mode of sensing:

First, impedance between two lead wires (Fig. 1(a)) are measured using an LCR meter (Agilent 4980A) at 4 different frequencies (200 Hz, 2 kHz, 20 kHz, and 200 kHz) in CP – RP mode. In each testing iteration, resistance and capacitance values across the lead wire are recorded for 4-5 days, and characteristic curves are drawn with respect to time. As time increases, the soil moisture decreases. Hence, a probe characteristic with respect to time is an indirect representation of probe characteristic with respect to moisture.

In Fig. 2(a), the capacitance with respect to time have been plotted for different operating frequencies and in Fig. 2(b), the resistances with respect to time have been plotted. Both the figures present data for three different iterations carried out with DQN-70 coated probe. The above figures depicts that capacitive sensing is more reliable than resistive sensing. We see, in case of capacitance measurement, the values of different iterations are close to each other for each operating frequency. But, in case of resistive measurement, the values from different iterations of different frequencies jumble up together and show no specific trend. So, it is clear that the capacitive measurement has better repeatability. Hence, it is more reliable and selected for final sensing system. [Similar trends
are seen for BPAD- mPD coated and PMMA coated probes also, but those figures are not shown here for the sake of comprehensibility and compactness.

(b) Choice of operating frequency:

TABLE I. AVERAGE RMSE IN LINEAR FIT OF CAPACITANCE VERSUS TIME CURVES FOR DQN-70 COATED PROBE AT DIFFERENT OPERATING FREQUENCY

<table>
<thead>
<tr>
<th>Serial number</th>
<th>Frequency</th>
<th>Average RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200 Hz</td>
<td>0.0743</td>
</tr>
<tr>
<td>2</td>
<td>2 kHz</td>
<td>0.0506</td>
</tr>
<tr>
<td>3</td>
<td>20 kHz</td>
<td>0.0338</td>
</tr>
<tr>
<td>4</td>
<td>200 kHz</td>
<td>0.0268</td>
</tr>
</tbody>
</table>

As we study the probe capacitance with time at different frequencies, we see that response repeatability is better at higher operating frequency than the lower ones. E.g. in Fig. 2(a), we see that capacitance versus time curves are almost linear in log-log plane. Once each of the curves is fitted to a best fitting straight line, we can find out the RMSE (root mean square error) for each such fitting. The average RMSEs (averaging over different iterations) for each frequency are shown in Table. I (for DQN-70 coated probes). We see average RMSE is least in the case of 200 kHz operating frequency and most for 200 Hz frequency. This indicates that response is more repeatable at 200 kHz and least in 200 Hz. However, signal transduction at 200 kHz frequency is costly and complicated, so this work has optimally chosen 20 kHz as the operating frequency (average RMSE at 20 kHz is not much high than that at 200 kHz). Again, similar trend is observed for BPADA- mPD and PMMA coated probes.

(c) Choice of the coating polymer:

In Fig. 3(a)- 3(c), the change of capacitance (C) versus time (t) for three different probes (coated with DQN-70, BPDA- mPD and PMMA) are presented respectively. In each figure responses from three different iterations have been included. From Fig. 3, it is apparent that the DQN-70 coated probes are more suitable than the other two types of probes. The reasons are: (i) DQN-70 coated probe has better repeatability; their C versus t curves are more closely packed than those of other two probes. Hence, DQN-70 probes are more reliable. (ii) Response curves for DQN-70 coated probe are more linear (in log-log plane, Fig. 3(a)) compared to others. (iii) Response from BPADA-mPD and PMMA is oscillatory (ref. Fig. 3(b)- 3(c)) compared to that of DQN-70 coated probes. (iv) Finally, it is found that probe life is more for DQN-70 coated probes. It is already reported that DQN-70 polymer coating is stable over a year in moist ambiance [10]. Hence, in this work sensing is done using capacitive response of DQN-70 coated probe at 20 kHz frequency.

C. Signal transduction

The capacitance of the DQN-70 coated probe varies in the range 100 pF to 600 pF, as obtained from the measurements taken by the impedance analyzer. A sample capacitance measuring circuit is designed to convert the change in capacitance to voltage (Fig. 4). In this circuit, one end of the DQN-70 coated sensor is connected in series with a 10 nF ($C_2$) capacitor and the other to the output of the
buffer amplifier. This circuit is excited with a sinusoidal wave of 4.0 peak to peak volt at 20 kHz frequency, generated from a sinusoidal signal generator using XR2206.

The following equations gives the relationship between the

![Graph](image1)

(a).

![Graph](image2)

(b).

![Graph](image3)

(c).

Fig. 3: Capacitance versus time at 20 kHz, for different iterations for a) DQN-70 coated probe, b) BPADA-mPD coated probe and c) PMMA coated probe

![Circuit Diagram](image4)

Fig. 4: Capacitance measuring circuit
sense capacitance and the output voltage.

\[ V_{\text{out}} = \frac{V_{\text{in}} \times 1/sC_1}{R_1 + sC_1 + sC_2} \]  

(1)

The magnitude of the output voltage can be written as

\[ |V_{\text{out}}| = \frac{V_{\text{in}} \times C_1/C_2}{(1 + C_1/C_2)^2 + (\omega C_2 R_1)^2} \]  

(2)

At 20 kHz frequency, with \( C_2 = 10 \text{ nF}, \ C_1 \) in the range of \( \text{pF} \) and with and \( R_1 = 1 \text{ k}\Omega \) we can approximate the above equation as:

\[ |V_{\text{out}}| \approx \frac{V_{\text{in}} \times C_1/C_2}{1 + C_1/C_2} \]  

(3)

Expanding in Taylor’s series and neglecting the higher order terms the above equation gives

\[ |V_{\text{out}}| \approx V_{\text{in}} \times C_1/C_2 \times [1 - (C_1/C_2) + (C_1/C_2)^2 + \ldots \ldots] \]  

(4)

\[ |V_{\text{out}}| \approx C_1/C_2 \]  

(5)

Which means that a change in sensor capacitance \( (C_1) \) due to the moisture content of the soil will give proportional change in the output voltage as \( C_2 \) is constant. The RMS voltage across \( C_2 \) was measured using Oscilloscope for four days at certain interval of time. Simultaneously, soil was taken from the same soil bed and moisture content was measured using thermo gravimetric method.

3. DISCUSSION

Literature reports that determining the dielectric constant by measuring capacitance directly rather than through the use of time domain reflectometry (TDR) systems is a relatively new approach to soil moisture measurement [4]. In this study, to develop the capacitive soil-moisture meter, three different probes are chosen which are coated with three different poly- mers i.e. DQN-70, BPDA-mPD and PMMA. From Fig. 2, it can be seen that for all the probes capacitance decreases with the time and resistance increases as expected. With the time the soil gets dried and the dielectric constant decrease resulting decrease in the capacitance; whereas, depletion of water decreases the conductivity and so resistance increases.
Among these three polymers, DQN-70 gives better repeatability as can be seen in the Fig. 3 and hence, chosen for further study. 20 kHz frequency is chosen looking at the stability in designing signal transduction circuit. Moreover, signal transduction circuit is designed to measure the change in capacitance. Similar can be also done in resistive mode, but as capacitive mode gives better performance (Fig. 2(a) and 2(b)), for the preliminary study we have chosen capacitive mode.

Plots of Fig. 5 shows that the output voltage of the signal transduction circuit faithfully follows the moisture content of the soil which has been measured by thermo-gravimetric.

In this paper, performance of a polymer coated capacitive probe in measuring moisture content of soil is presented. First three different polymers (DQN-70, BPDA-mPD and PMMA) are taken for coating the probe and after systematic characterization of the probes DQN-70 material is chosen.

A simple capacitive circuit is used to measure the change of capacitance of the probe with the change of soil moisture. Results show that the output voltage of the system follows the moisture level of the soil measured by thermo-gravimetric method. In higher level of moisture, the output
voltage has a linear relationship with the moisture level. In lower moisture level a higher deviation is observed may be due to the non-homogeneity of the soil. Further study is required in this direction by making the soil bed with higher moisture level.

The signal conditioning circuit gives output in voltage and hence, can be easily automated and integrated with wireless sensor network to get the data for analysis and necessary action. Further research work is going on in this direction.

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