A New Soil Water Content Sensor with Temperature Compensation Design

SHI GE, LI QING
College of Electrical & Mechanical Engineering
China Jiliang University
XueYuan Street, Xia Sha Economic Development Zone, Hangzhou
CHINA
ishige@126.com http://www.cjlu.edu.cn

Abstract: The design and construction of a soil water content sensor with temperature compensation using the piecewise linear interpolation method was presented in this paper. The sensor out put often influenced by temperature, so temperature compensation must be given. This work presents the design, construction, and circuitry system, method of temperature compensation and preliminary results of experiment. The result of experiment indicates that the sensor could effectively reduce the influence of the soil type and temperature change. It is applicable to the geological disaster early warning and the agronomic research activities.

Key-Words: Soil water content sensor; Circuitry system; Temperature compensation; Piecewise linear interpolation method; Geological disaster

1 Introduction

For prevention the collapse, landslides, mud-rock flows, etc geological disasters, the various geological conditions monitoring is necessary. And soil water content monitoring is one of the most important parts, especially the depth of soil water content measurements. The results of monitoring are important data for early warning of geological disasters. Another concern, knowledge of soil water content is essential for evaluation and selection of agro-system, and planning the rational use of water resources. The soil water content has important implications for a number of parameter affecting plant growth, soil penetration hardness and soil micro-biological activity. Therefore, water content measurements are a common and required practice for agronomic research activities.

There are two soil water content definitions: gravimetric percentage and volumetric percentage[5]. Gravimetric measurements refer to the relationship between water mass content divided by total mass of the soil sample, dried at 105℃ until the sample attains a constant weight. Volumetric water content measurements refer to the volume of water contained in a given volume of soil sample. At present, the soil water content measurement methods can be basically divided into three categories: gravimetric, nucleonic and electromagnetic techniques. The gravimetric method is probably the most accurate method for soil water content measurement since the soil sample is taken to the laboratory and can then be carefully and extensively analyzed. But it destroyed the soil structure and can not obtain the real-time information of the soil. Nucleonic method has more accurate calibration results, but it is unsafe to organism. Recent and current advances in electronics instrumentation have contributed to the widespread use of electromagnetic soil water measurement methods. The TDR[1][4] (Time Domain Reflectometry) and Capacitance methods are the preferred electromagnetic sensing methods because they permit obtaining measurements in situ[6]. These soil water content measurement technique is based on the concept that the dielectric constant of a dry material consisting of soil particles and air is relatively small

(1.5 to 4), whereas the dielectric constant for water is very much larger (80 at room temperature). Therefore, even small amounts of water in a soil cause the dielectric constant of the resultant soil--water-air mixture to exhibit a composite dielectric constant that can be related to the soil water content through a simple calibration procedure[1]. Still, the relatively high cost of TDR devices precludes the widespread use such instrument by producers. A lower cost alternative is the capacitance method which has recently gained popularity amongst researchers. Still, there is the need to develop reliable and affordable water content measurement instrumentation.

This work presents the design, construction, and circuitry system, method of temperature compensation and preliminary results of experiment. The result of experiment indicates that the sensor could effectively reduce the influence of the soil type and temperature change. It is applicable to the geological disaster early warning and the agronomic research activities.

2 Principle of operation

2.1 Electrode structure and impedance analysis

The sensor's electrodes using two-rod parallel probe (Fig.1.a). And, the insulated stainless steel electrodes with length, L, and diameter a, are held at a distance d, by means of a non-conductive (Epoxy resin) electrode mount assembly. The probe electrodes are insulated by polyolefin tubing, and the tubing's thickness is (b-a)/2(Fig.1.b). Measurement system directly connected to the electrodes for reduces the external signal interference and remote multipoint data transmission by RS-485 communications channel.

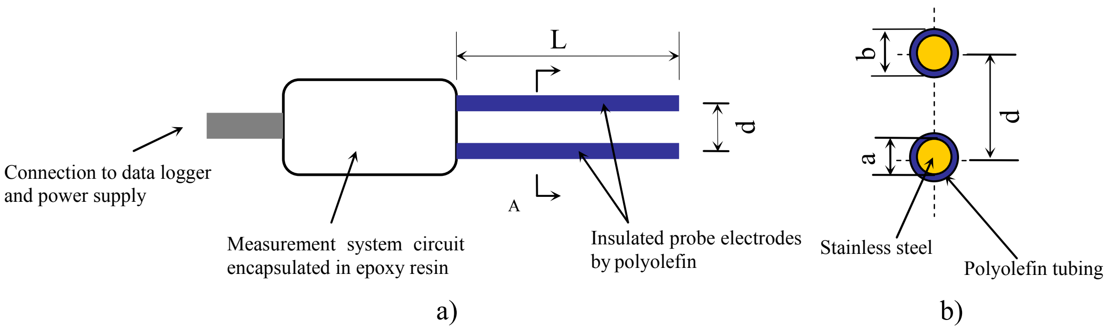

Fig.1. Schematic diagram of the sensor structure.

a) A pair of Insulated Stainless Steel electrodes with length, L, and diameter a, are held at a distance d, by means of a non-conductive (Epoxy resin) electrode mount assembly.

b) Enlarged section of A, the stainless steel probes are insulated by polyolefin tubing, and the tubing's thickness is (b-a)/2.

The stainless steel probes insulated by polyolefin tubing for permanent burial deeply and reduce the serious error in a highly saline soil. Since salt water is so highly conductive, the presence of salt in any appreciable amount causes the probe to read just the resistance of the soil, or worse, the inductance of the null inductor, since the capacitance of the probe is shorted out by the low resistance of the salt water. And the insulated stainless steel electrodes are held by means of a non-conductive (Epoxy resin) electrode mount assembly. The following is the pertinent electrical data for each material:

Polyolefin: Dielectric constant at 1 MHz: 2.5
Volume resistivity: $10^{15}\ \Omega \cdot \text{cm}$
Epoxy resin: Dielectric constant at 100 kHz 3.8
Volume resistivity: $4.2 \times 10^{16}\ \Omega \cdot \text{cm}$

The impedance of a soil sample is a complex topic that depends on a number of variables: soil temperature, soil water content, type of soil, chemical and mineral content, pore size, etc. [2][3] The choice of electrode size and shape also influences the electromagnetic properties of the measurement technique. When a pair of electrodes of length L and diameter a, separated a distance d, are inserted in the soil sample for impedance measurements, it is possible to obtain an approximated electrical model of the resulting assembly (Fig.2).

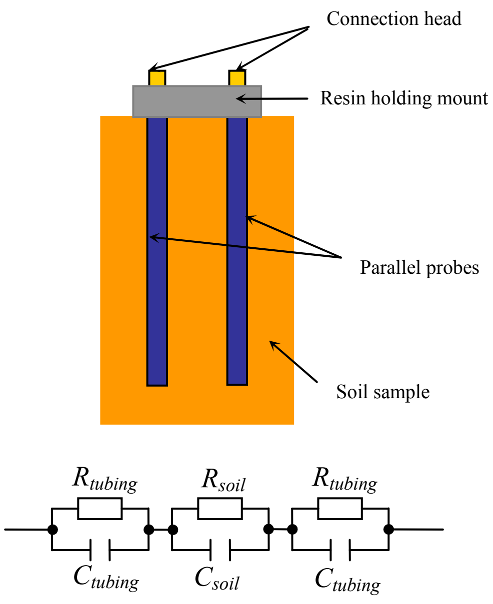

Fig.2. Electrical equivalent model impedances when the Parallel probes inserted in the soil sample.

Polyolefin is a very good insulating material, so the R_{tubing} is a very high resistance. We can ignore its conductive effect. The insulated probe may be the only solution for a water content measurement in a highly saline soil. If there is no insulated polyolefin tubing, the contact impedance of the electrodes with the soil sample must be taken into account. Electrodes inserted in sandy soil would have a good conducting path when water is present in the soil sample. In contrast, for sandy soil there could be poor contact due to large pore size when there is no water in the sample. In the case of clay-type soils, the compactness of the sample would also provide good contact means when there is water in the soil sample. And, cracks in the soil can reduce the contact area of the electrode with the sample.

The C_{tubing} is decided by the dielectric constant of insulating material and the tubing's thickness, and the thickness is (b-a)/2. The dielectric constant of polyolefin is relatively small as the soil particles as. The C_{tubing} is related with the thickness of tubing, the thinner the thickness when the higher capacitance value.

$$Z_{tubing} = R_{tubing} \parallel \frac{1}{j\omega C_{tubing}}$$

(1)

Z_{tubing} is the impedance of tubing in the frequency domain, equal to the capacitive effect of the tubing between the electrode and soil (C_{tubing}), in parallel with the resistance of the tubing ($\boldsymbol{R_{tubing}}$). Since the $\boldsymbol{R_{tubing}}$ is a very high resistance. We can consider only the capacitive effect of Z_{tubing}. So, Z_{tubing}≈$(1/j\omega C_{tubing})$.

$$Z_{soil} = R_{soil} \parallel \frac{1}{j\omega C_{soil}}$$

(2)

Z_{soil} is the impedance of soil in the frequency domain, equal to the capacitive effect of the soil between the tubing (C_{soil}), in parallel with the resistance of the soil ($\boldsymbol{R_{soil}}$). The number of ions of the soil and the soil water content decide the resistance. The more soil water content the lower resistance, the more ions of the soil the lower resistance too. Krauss (1984) consider including the electric conductivity (EC) of the equivalent dielectric constant (ε_{eff}) expression:

$$\varepsilon_{eff}(f) = \varepsilon'(f) - j\left(\varepsilon''(f) + \frac{EC}{2\pi f \varepsilon_0}\right) \qquad (3)$$

Where ε_0 is the vacuum dielectric constant(8.854 ×10^{-12}Fm^{-1}). EC is the electrical conductivity of soil, equivalent to $1/\boldsymbol{R_{soil}}$. ε' is the real part of dielectric constant, dielectric materials reflect electromagnetic fields and the polarization degree of energy storage, ε'' is the imaginary part of dielectric constant, reflecting the dielectric material under external electromagnetic field energy loss (Santamarina2001). f is the frequency of external electric field.

From the Formula (3) can be seen that as the frequency increases, the conductivity of the energy loss caused by the imaginary part of the equivalent to

ISSN: 1790-5117

ISBN: 978-960-474-076-5

reduce the impact. So, Increase the frequency of external electric field (f)can be a very good way to reduce the impact of saline soil water content test. We choose the 100MHz external electric field signal, experimental results show that effectively reduce the impact of the saline.

So the impedance of this parallel probes can be consider simply as a total capacitance (C_{tot}):

$$\frac{1}{C_{tot}} = \frac{1}{C_{tubing}} + \frac{1}{C_{soil}} + \frac{1}{C_{tubing}} \quad (4)$$

From the Formula (4) can be seen that if want to reduce the impact of C_{tubing} , then tubing's thickness (b-a)/2 should be <<d, and a<<d, and Increase the frequency of external electric field (f). And while the resolution of the measurement may be reduced for the existence of C_{tubing} , but the accuracy may still be acceptable after data process.

2.2 Capacitance measurements and the effect of frequency

Considering that the capacitance is mainly formed by the combined dielectric of soil and water content. The equivalent capacitance constituted by the electrode array inserted in the soil sample can be shown to be Formula (5):

$$C_{soil} = \frac{\pi\varepsilon_0 L}{\ln(\frac{d-a}{a})}(\varepsilon_{soil} + x(\varepsilon_{water} - \varepsilon_{soil})) \quad (5)$$

Where ε_{soil} (from 2 to 4) is the soil dielectric constant, ε_{water} is the water dielectric constant and x is the percentage of water in the sample. In addition, the real part of the impedance has to be taken into account as well. Therefore, the instrumentation circuitry has to be able to measure the real and complex parts of the resulting impedance.

The selection of the operating frequency of external electric field can impact on the measured dielectric. The relaxation time (period in which a particle can no longer orientate itself with the induced field due to large frequency, τ) is determined by Stokes' Law as (6):

$$\tau = \frac{4\pi\eta r_m^{\ 3}}{kT} \quad (6)$$

Where η is the viscosity in relation to a liquid; T is the temperature (°K); K Boltzmann's constant (≈ 1.38062×10^{-23}); and r_m is the molecular radius (White & Zegelin, 1995). For water it can be shown that the relaxation frequency (1/τ) is around 10 GHz. At frequencies below 10 GHz, for water ε' >> ε'' as shown in Figure 3.

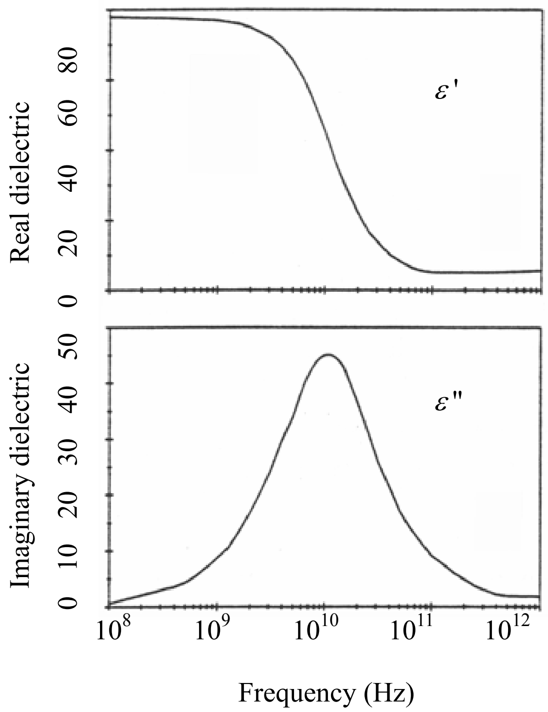

Fig.3. The effect of frequency on the real (ε') and imaginary (ε'') dielectric (after White & Zegelin, 1995).

From Fig.3. ε' is at a maximum (≈ 80) between 100 MHz and 1 GHz. Corresponding to this maximum dielectric loss is small (ε'' < 5). So, operation at larger frequencies can reduce the effect of the imaginary component as well as the influence of EC . We choose the 100MHz external electric field signal in this work.

2.3 Signal processing circuitry design

Modeling of the impedance components allows the design of a voltage division circuit of the series impedance for measuring the impedance changes of the electrode array due to changes in water content of the soil sample. Fig.4 shows the schematic diagram of the signal processing circuitry.

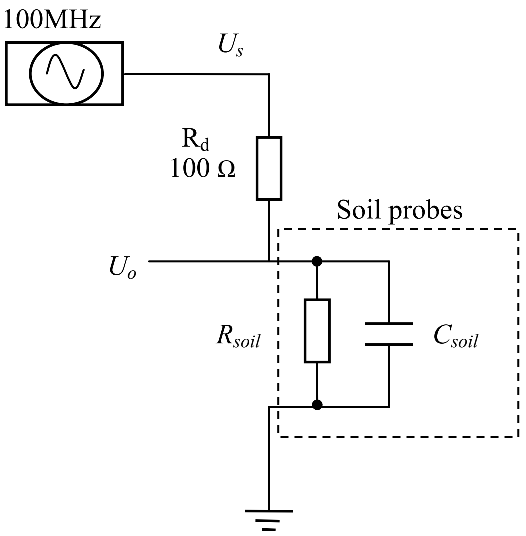

Fig.4 Simplified circuit diagram of the voltage division circuit of the series impedance

An oscillator generator adjusted to produce a 100MHz signal U_s (5 volts pp. amplitude) is used to excite the electrodes. One electrode is connected to one leg of the signal source through a 100 Ω resistor (R_d), and another electrode is connected to GND. The U_o is an output of the voltage division circuit of the series impedance. The resulting signal is measured with an RMS-to-DC converter circuit.

2.4 Soil water content measurement system

Fig.5 shows the schematic diagram of the measurement system device. The prototype is built around the MSP430F1232 microcontroller. The module operates with a +9V DC power. There is an interface connection: RS-485 for data transfer between the module and the host data logger. RS-485 is an electrical specification of a two-wire, half-duplex, multipoint serial communications channel. Since it uses a differential balanced line over twisted pair, it can span relatively large distances (up to 4,000 feet (1,200 m)). There is a set of three terminals (+3.3V, GND, Data), for connecting DS18B20. The DS18B20 digital thermometer provides 9-bit to 12-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18B20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microcontroller. It has an operating temperature range of -55°C to +125°C and is accurate to ±0.5°C over the range of -10°C to +85°C.

A electrode is connected to one leg of the signal source through a 100 Ω resistor (R_d), and another electrode is connected to GND as described in section 2.3. The 100MHz oscillator generation and signal conditioning sections are included in the module.

The module can operate in data logger mode recording temperature and soil water content data at fixed intervals (10 minutes, 20 minutes, etc.) or determined by the host's command. Data is stored in the microcontroller's flash memory. Currently, temperature compensation is programmed in the microcontroller. A VB program that can also be used for receiving and plotting data acquired in host PC.

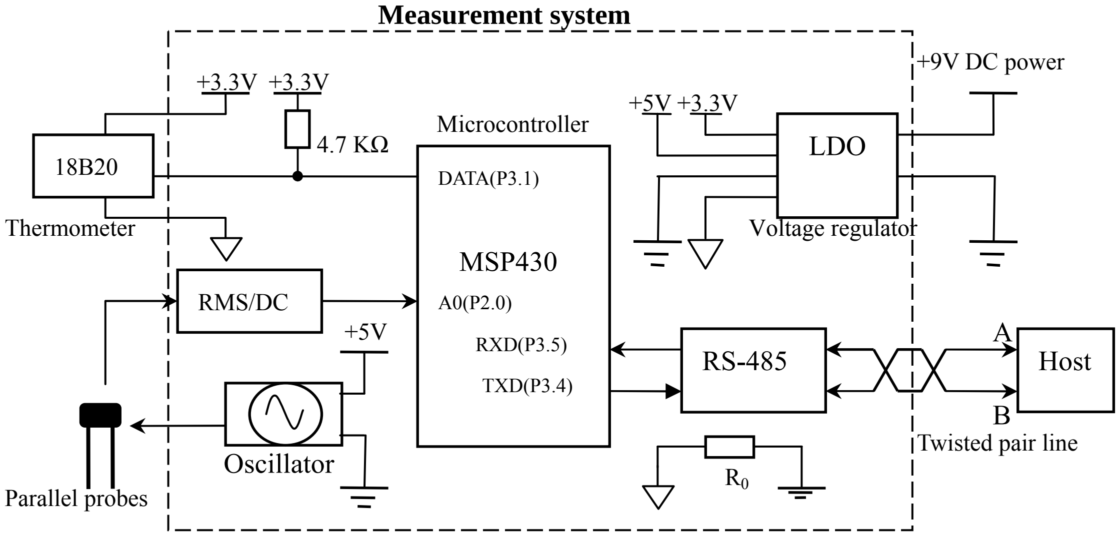

Fig.5. Schematic diagram of the soil water content measurement system.

3 Testing and analysis

3.1 Test of soil water content sensor in lab

In order to verify the performance of the sensor, Reference to the “Determination of forest soil water content” (GB 7833 - 87) and “Forest soil analysis methods”(LY/T 1210~1275-1999), we designed the test method in lab, follow these steps:

a). Soil water samples by the heat of the oven 105 □ to constant quality in drying.

b). Filtrate the dry soil Particles by sieve which the mesh is 3mm, for remove large stones.

c). Take six equal size sealed glass bottles. The same quality dry soil to each bottle, and made of the same six soil samples.

d). Buried the sensor in to the soil samples.

e). Vibration machine is used to make the sensor work surface full contact with the soil and to ensure that the in same volume of soil samples.

f). Then add a different quality of water in to the different samples, and then sealed.

g). Six samples would be set on the thermostat at 95□ oven heating in 5 hours, to accelerate the spread of the movement of water molecules in soil, and then natural cooling, holding 1 hours, repeat the above step 3 times for water infiltration in the uniform.

We select several typical soil (sandy soil, loam and clay) to tests the sensors to investigate the efects of different soil. The experiment temperature is 20□. Fig.6. shows result of experiments.

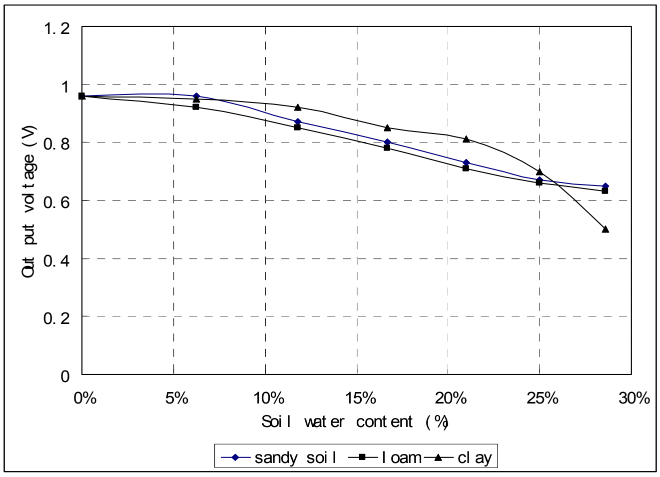

Fig.6. Results of the sensor test for various type soil and different water content

The result of experiment indicates that the sensor could effectively reduce the influence of the soil type in lab test. Through the piecewise linear interpolation method can be calibrated for each sensor so that the measurement results and closer to the actual water content.

3.2 Temperature change test

The dielectric constant of water changed in different temperature. The temperature of the soil should be determined and used. Typically ε_{water} is 80 at room temperature, but the actual value for any temperature may be found Table 1.

Table 1. Dielectric constant of water

T(□)	ε_{water}	T(□)	ε_{water}
0	88□00	40	73□28
5	86□40	45	71□59
10	84□11	50	69□94
15	82□22	60	66□74
20	80□36	70	63□68
25	78□54	80	60□78
30	76□75	80	57□98
35	75□00	100	55□33

Therefore, the temperature characteristics of soil water content sensor to be tested. We designed the test method: put soil water content sensor into the standard soil samples (20%), then the soil samples be sealed. connect the Sensor's RS485 interface to host PC. Wait for stable data, put the soil sample into a constant temperature box, and change the temperature of the incubator so that soil temperature changes, record the temperature of soil samples and measuring the sensor data. We received a total of 9000 data; Fig.6 shows result of the Temperature change test.

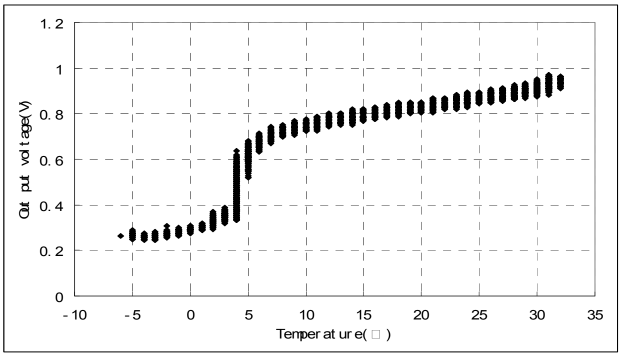

Fig.6. Experimental results of the sensor for various temperatures

As the Fig.6 shown, the sensor output voltage decreased with decrease of temperature, relationship of voltage and temperature of 5 □ ~ 35 □ can be regarded as essentially linear. At 4□, there is a rapid decline, may be in the course of the density of water molecules at this temperature is biggest reasons. at 3 □ ~ -10□, the voltage and temperature can be regarded as essentially linear and the slope basic the same of the 5□ ~35□ scope.

Due to the depth of the soil temperature range is normally between 10□~30□ degrees, so we can ignore the changes in the 4□, and the output has a non-linear zone when less than 10□, so we gave up the temperature compensation below the 10□.

4. Temperature compensation using the piecewise linear interpolation method

Since relationship between the sensor output voltage and the soil water content is non-linear. Through the piecewise linear interpolation method can be calibrated for each sensor so that the measurement results and closer to the actual water content. The more interpolation points, the more accurate for calculation of water content to real. Between two interpolation points, we assume that the relationship between input and output is linear. Based on pre-given data under normal temperature, deduced the temperature compensation sensor input and output relations when temperature changed.

The main compensation of sensor is a linear compensation of offset volume and the sensitivity, assume the be measured value sensor is "θ", and offset is "a", the sensitivity is "b". The sensor output at room temperature:

$$U_o = a_0 + b_0 * \theta ; \quad (7)$$

At a temperature of t, without compensation sensor output as follows:

$$U_t = a_t + b_t * \theta ; \quad (8)$$

Where:

$$a_t = a_0 + \alpha(t - t_0) * Y(FS)$$

$$b_t = b_0 + \beta(t - t_0) * Y(FS) ; \quad (9)$$

In the Formula (9), α is the coefficient of the offset.

$$\alpha = \Delta a / (\Delta T * Y(FS)) ; \quad (10)$$

Here Δa is the greatest value of offset changed in the scope of temperature changed. ΔT is the scope of temperature changed.

In the Formula (9), β is the coefficient of the sensitivity.

$$\beta = \Delta b / (\Delta T * Y(FS)) ; \quad (11)$$

Based on Formula (7) ,(8),(9), we can get:

$$\theta = \frac{U_t - [a_0 + \alpha(t - t0) * Y(FS)]}{b_0 + \beta(t - t_0) * Y(FS)}; \qquad (12)$$

Put Formula (12) into the Formula (7), we can get the compensated out put of the sensor:

$$U_t' = a_0 + \frac{U_t - [a_0 + \alpha(t - t0) * Y(FS)]}{b_0 + \beta(t - t_0) * Y(FS)} * b_0 \quad ;$$

(13)

The a_0 , b_0 , α and β can be get by the Experimental of temperature. When we get the out put of sensor U_t, put it into the Formula (13), the compensated out put U_t' could be get.

From the above analysis we can see: By the temperature compensation algorithm, the error of temperature can be lowered a lot.

5. Conclusions

The current trend towards sustainable development requires appropriate use of water resources at all levels. Thus the availability of a measurement instrument that can provide accurate and reliable information of the soil water content can have important implications for improving soil irrigation practices. Throughout this paper, the design and construction of a novel soil water content measurement prototype was described. The design is based on impedance measurements. The temperature effect on impedance measurements was investigated. Experiments were conducted to determine a suitable procedure for correcting the measurements. A piecewise linear interpolation method was proposed and used for correcting the soil water content information using soil temperature data. The resulting prototype was tested and the results suggest that the measurement module can provide reliable information so as to determine the soil water content.

References:

[1] Topp, G.C., J.L. Davis, and Annan.. Electromagnetic Determination of Soil Water Content Measurement in Coaxial Lines. *Water Resour*. Res. Vol. 16, 1980, pp.574-582.

[2] Rhoades, J.D., P.A.C. Raats and R.J. Prather. Effects of Liquid-Phase Electrical Conductivity, WaterContent and Surface Conductivity on Bulk Soil Electrical Conductivity. *Soil Sci*. Soc. Am. J. Vol. 40, 1976, pp. 650-653.

[3] Filho, S.V. and C.M. Portela. Investigation of Soil as a Lossy Dielectric. Properties and Applications of Dielectric Materials *In Proc. 2nd International Conference on Properties and Applications*, Vol 2, 12-6 Sept. 1988, pp. 515-518.

[4] F. N. Dalton and M. Van Genuchten. The TimeDomain Reflectometry Method for Measuring Soil Water Content and Salinity. *Geoderma* 38, 1986, pp237-250.

[5] Kelleners, T.J., D.A. Robinson, P.J. Shouse, J.E. Ayars, and T.H. Skaggs. 2005. Frequency dependence of the complex permittivity and its impact on dielectric sensor calibration in soils. *Soil Sci*. Soc. Am. J. Vol. 69, 2005, pp. 67-76.

[6] Regalado C. M, Ritter A, Rodríguez-González R. M. “Performance of the Commercial WET Capacitance Sensor as Compared with Time Domain Reflectometry in Volcanic Soils”. *Vadose Zone* J. Vol. 6, 2007, pp. 244–254.