Computers and Electronics in Agriculture 148 (2018) 148–159

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Original papers

Design and implementation of a low cost photovoltaic soil moisture monitoring station for irrigation scheduling with different frequency domain analysis probe structures

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ARTICLE INFO

Keywords:
Frequency domain
Irrigation management
Sensor probe
PV monitoring station
Soil moisture sensors

ABSTRACT

Frequency Domain Analysis (FDA), as an approach, has been developed for the measurement of soil dielectric constants. As it stands, the standard dielectric of dry soil is much less than the dielectric of soil exposed to water, and the volume of water present significantly affects the propagation of electromagnetic waves. With this in mind, this paper proposes a plan for the design and implementation of two distinct isolated probe structures for the measurement of water contents within the soil at different levels. Accordingly, Probe A is used to determine the water level present in soil at four different depths. Probe A does this by utilizing pairs of parabolic copper sections fixed horizontally and isolated over the outer surface of an access tube. Probe B, on the other hand, makes use of two steel rings buried vertically inside of an access tube, and is used to determine the water contents of soil on two levels. To do so, a fixed frequency square-wave is transmitted to measure the soil capacitance in which the probe sensors are connected to an Arduino microcontroller which also included air humidity, air temperature, and soil temperature sensors. During the experimental assessment of both probes, the results are loaded onto an SD memory card and are then compared with the results of other commercial sensors installed in the same irrigated plot. The soil moisture monitoring station used is powered by a photovoltaic (PV) module of 10 W 12 V and a storage battery of 12 Ah. The experimental monitoring station used to assess the efficiency of both probe designs was set up in a Mediterranean semiarid zone in the Southeast of Spain.

1. Introduction

Agriculture and climate change are indissolubly linked: crop yield, water use, soil health and biodiversity are directly affected by climate change. Agriculture uses more than 75% of available freshwater resources worldwide, and this percentage will continue to increase proportionately with population growth and the increased demand for food in the years to come (Regan et al., 2017; Capra and Mannino, 2015; Jury and Vaux, 2005).

Efficient and effective irrigation scheduling is key to improving agricultural practices and crop yields the world over. In order to improve the effectiveness of irrigation scheduling, several methods for irrigation scheduling calculations has been used (agrometheorological stations for indirect calculation of evapotranspiration, lysimetric methods, monitoring of soil moisture, among others). All of them calculate the water balance in a crop. In this case, the monitoring of soil moisture method has been employed. Although this method is extended all over the world, the novelty in this case is the use of low cost sensors and programming methods (low cost hardware and software). Making use of an automatic soil moisture monitoring station is both an innovative and time saving method to effectively monitor and irrigate soil as needed. In this regard, the use of an automatic moisture monitoring station can (i) help facilitate effective irrigation scheduling, (ii) lead to the efficient management of water resources, (iii) reduce various costs associated with irrigation, and (iv) can contribute to greater crop yields and increased profit from agricultural activities.

A pivotal aspect of farming irrigation is the management of soil moisture. Appropriate levels of water within the irrigated soil must be kept between targeted upper and lower limits of availability to the plant while simultaneously accounting for soil evaporation, crop water use, regular irrigation, drainage, and rainfall (Zhang et al., 2017; Ley et al., 1994).

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https://doi.org/10.1016/j.compag.2017.12.038
Received 14 March 2017; Received in revised form 9 October 2017; Accepted 25 December 2017
0168-1699/

There are numerous techniques of soil moisture measurement currently in use, and the suitability of each technique depends on the cost efficiency, accuracy, durability, and response time of each technique. Other factors to consider also include installation, intended use, and ease of management. The most widely adopted techniques include neutron probes (Stirzaker et al., 2017; Ward and Wittman, 2009; Falleiros et al., 1993), the dual probe heat pulse (DPHP) (Liu et al., 2016; Ochsner et al., 2003), gravimetric sampling (Algeo et al., 2016; Reynolds, 1970), and dielectric sensors (Shan et al., 2016; Lee, 2005; Zazueta and Jiannong, 1994; Chilar and Ulaby, 1974). The use of soil dielectric sensors to measure the soil dielectric constant has been adopted in a number of ways that include: The time domain reflectometry (TDR) method (Kanzari et al., 2012; Seyfried and Murdock, 2004; Robinson et al., 2003), the time domain transmissometry (Will and Rolfes, 2014), the frequency domain reflectometry (FDR) (Choi et al., 2016; Skierucha and Wilczek, 2010), the resistance method (Dias et al., 2016; Tyagi et al., 2011) and the capacitance method (Solar and Solar, 2016; Mander and Arora, 2014; Evett and Cepuder, 2008; Johnson et al., 2002; Dean et al., 1987).

In discussing the various dielectric sensor mechanisms, Aravind et al., 2015 stated that the use of capacitive and resistive sensors consume less than half of the electricity consumed by DPHP sensors. Moreover, Valente et al., 1998 states that soil moisture can be determined by measuring the capacitance between two electrodes buried in the soil and that utilizing this method results in faster response times and requires a lower cost of implementation.

By definition, the dielectric constant of a material measures its capacity to conduct electric energy. In a composite material such as soil that contains minerals, air and water, the water content is determined by measuring the velocity of an electromagnetic wave or pulse as it travels through the soil. As such, the dielectric constant of dry soil varies between 2 and 5 while the dielectric constant of water is about 80. There are two approaches currently in practice that are used to measure the dielectric constant of water present in soil, the time domain approach and the frequency domain approach (Cristi et al., 2016; Bouksila et al., 2010; Paige and Keefer, 2008; Kelleners et al., 2005; Schmugge et al., 1979).

To detect the level of water present in soil, soil moisture sensors are an essential tool when managing the irrigation of farmland. Since soil water sensors are relatively small and only sensitive to the soil immediately surrounding them, it is important to have at least two or more sensors installed at different depths. This not only increases accuracy but also enables a clear understanding of changes in soil moisture in response to irrigation and crop water uptake (Aguilar et al., 2015; Helmer et al., 2005).

The dielectic properties of materials utilized in agriculture are affected and influenced by a number of factors that include: (i) water content, (ii) temperature, (iii) the density of the materials, and (iv) any applied radio frequency and/or microwave electric fields (Hardin et al., 2013; Nelson and Trabelsi, 2012). The resulting measurement of soil moisture can also sometimes be negatively affected by other factors. The length of the probes and the temperature of the soil, among other things, can result in misleading readings of soil moisture (Oates et al., 2015). With these things in mind, two low-cost techniques can be used to accurately determine soil moisture content. The first technique involves the use of soil capacitance in association with a low pass filter that measures the attenuation of a fixed frequency signal. The second technique makes use of the soil capacitance as a controlling component in the variable frequency oscillator (Oates et al., 2017a).

The advantages of making use of the frequency domain signal is that it is inexpensive, uses a low frequency standard circuit, has no radiation hazard, provides a fast response time, is logging capable, and is portable. However, the frequency domain signal has an increased sensitivity to insulation and tends to be more sensitive to air gaps than the time domain signal (Cui et al., 2015; Maughan et al., 2015; Kolekova and Schmid, 2011).

Comparatively, field studies that assessed soil water sensors that were inserted into an access tube yielded readings of soil water content at different levels (Dao, 2016; Evett, 2007). These sensors featured an electronic circuit in which two rings, plates, or rods made of metal were connected to an oscillator to form a capacitor to determine the soil dielectric. The changes in the circuit frequency are then directly related to the changes in soil moisture.

The frequency domain (FD) based on capacitance of a capacitor is proportional to the bulk permittivity of the soil and it typically operates at lower frequencies. When the capacitor that made of parallel metal plates or rods embedded in the soil is connected to an oscillator getting an electrical circuit, the changes in soil moisture produce variations of the circuit operating frequency. In FD capacitance sensors, the permittivity is determined by measuring the charging time of a capacitor while the FDR sensors control the oscillator frequency within a specified range to record the resonant frequency at which the amplitude is greatest, that indicates the water present in the surrounding soil (Miras-Avalos et al., 2016; Visconti et al., 2016; Evett, 2009).

The most renowned probe structure that makes use of capacitance measurements in the market is EnviroSCAN® (Sentek Pty., Ltd., Australia). EnvironSCAN® is noted to be suitable for varying soil types, utilizing installations, but is unfortunately expensive ranging in price around2000 Euros (Sentek, 2010). With this probe is possible monitoring soil water content (SWC). EnviroSCAN® multi-sensor capacitance probes have proved to deliver reliable readings that allow sufficient interpretation of SWC as basis for irrigation management (Noltz et al., 2016). EnviroSCAN® capacitance sensors operate based on the FDR principle, where a high-frequency electric field is induced in a certain volume of soil by means of a capacitor. The frequency of oscillation is proportional to the ratio of air and water in the soil (Paltineanu and Starr, 1997). As a cost-efficient solution to many energy related problems, solar energy is the most abundant and readily available source of energy in the world. Solar power is not only an answer to today's energy crisis, providing free electricity generation, but also an environmentally friendly form of energy (Munoz-Garcia et al., 2013; Shindy and Wandre, 2015; Kabir and Chowdhury, 2012). Moreover, the global module prices for this source of energy has declined by roughly 95% from about \$60/W to about \$2/W between 1976 and 2010 (SunShot, 2012). The module prices have fallen to even lower prices in recent years ranging between \$0.65/W and \$0.70/W in 2015.

With this source of energy in mind, the purpose of this paper is to design and implement a low-cost PV soil moisture monitoring station with an optimum FDA probe structure. The station is designed to determine soil temperature, air temperature, air humidity, and soil moisture content at different depths in high silica content clay soil.

2. Materials and methods

The PV monitoring station consists of soil moisture sensors present in two different probe structures installed at different depths. Probe A is used to detect the water content of soil at 4 depths: 7, 17, 32, and 42 cm. while probe B is used to detect the water content of soil at 2 depths: 12, and 42 cm. The two probe sensors are connected to an Arduino microcontroller along with soil temperature, air humidity, and air temperature sensors. The temperature of soil is measured by using a waterproof DS18B20 sensor that is buried into the soil at depth of 5 cm. the air temperature and outdoor humidity ratio are detected by using the DHT11 sensor that is installed 1 m above the ground. A PV panel of 10 W 12 V is used to power the standalone Arduino and the excess power can then be transferred to another load by using a solar charge controller with a USB regulator of 5 V. The station is employed 24 h per day by the partial connection of a 12 V 12 Ah battery (see Fig. 1).

The solar powered, 5 V USB regulator includes three converters, the panel buck converter, the load buck converter, and the bidirectional boost converter. The first buck converter is used to convert the voltage from the solar panel of 17.3 V maximum power voltage and 0.58 A