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Development of A Wireless Power Transmission System for Agriculture Sensor Devices

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***Abstract*—The integration of wireless power technology in large sensor networks is highly sought for in many applications, including agriculture. This is due to the accessibility and lack of wiring complexity such technologies have to offer. In an agricultural setting, the working environment can be harsh on sensing equipment due to factors that include weather, constant deconstruction and re-installation with the changing plant cycles, and vehicle traffic. Since many agriculture plots reside in difficult to access locations, the use of self-sufficient energy capturing methods have become popular. These contemporary methods generally rely on the collection of solar, wind, or ambient radio waves to charge battery banks connected to the sensing device. These methods have major limitations as sunlight can be shadowed as crops mature, wind creates obstacles for equipment to navigate, and radio frequencies do not penetrate well through soil or plants. This ultimately reduces the quantity of sensors that can be instrumented throughout a field. To address such limitations, a new wireless power transfer method will be presented that utilizes a buried transmitter to generate conduction currents through the soil to power distant sensing devices scattered throughout a field. Impedance spectra of the soil is used to determine the optimal depth of the transmitter. The power capabilities of the system are demonstrated by operating, without a battery, a moisture sensor connected to a microcontroller at a 10 m distance from the transmitter.**

Keywords—Wireless power transmission, Conduction theory, agricultural sensing device

I. Introduction

Outdoor environmental data collection and monitoring are vital in agriculture. Much of this monitoring takes place in secluded areas where electrical power is expensive or otherwise difficult to deliver. Present wireless power transfer techniques utilize electric or magnetic field coupling that does not have the ability to transfer power at the ranges required for agricultural applications, as they would need to produce incredibly high field magnitudes.[1]–[3]

Some research has focused on using energy harvesting technology where each sensor in a network is connected directly to an energy harvester such as an array of solar panels.[4], [5] The energy harvester is placed in the center or off to the side of the research plot to decrease the cost of wires and other electronics. The sensor network is typically installed and then dissembled between planting cycles to save the electronics from damage while farming equipment is in use. Another popular sensor power supply is a small battery which is attached directly to the various devices. This allows for the sensor to be randomly placed throughout the field. However, problems arise when the battery needs to be replaced.

This paper presents an innovative wireless power transfer system that is located on the outer edge of a 13-acres agricultural research field. The system will utilize the “conduction theory of radio” to send power signals using the soil as a conductive path directly to a sensor device which is placed within the field. The impedance characteristics of the transmitter at various soil depths will be analyzed to determine the optimal depth of the buried electrode. The system is then observed over a 4-month period to determine seasonal effects the climate will have on the impedance of the transmitter. Next, the power signal magnitudes with distance and at various current inputs are presented. Lastly, a capacitive moisture sensor (ASIN#B07SYBSHGX) attached to an Arduino Pro Mini is operated without a battery to show proof of concept power transfer capabilities of the system at approximately 10m from the transmitter.

II. Theory and Derivations

A. Conduction Theory

The basis of the WPT system is derived from the *conduction theory of radio*, which was a methodology utilized in the very early 1900’s for wireless communication. The technique uses a transmitter and receiver placed into the soil and separated by some distance, as shown in Figure 1. Both transmitter and

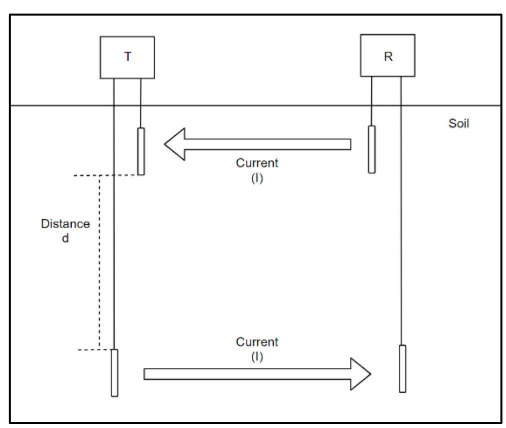

Fig. 1: Transmitter and receiver diagram to show flow of current.

receiver have a pair of 2 electrodes that are placed at different vertical depths within the soil, one being near the surface of the soil and the second at a depth of d from the surface electrode. This allows current to form a looping path underground, by using the soil as a conductive medium between the top and bottom electrode pairs.[6]–[8] The vertical configuration of the electrodes for both the transmitter and receiver results in the highest flow of current for long range applications. In previous work [9], horizontal and vertical electrode configurations were explored. The results found that horizontal configurations for the transmitter produced a higher resistance between the 2 electrode connections. The electric field orientation within the soil was also vastly different than with the vertical electrode structure, with the vertical structure possessing unique properties. Prior literature on vertical electrode configurations have also been described in [8]. The equation for the potential difference between the vertical electrodes can be approximated as

$$V_V \cong \frac{9I*d^4}{4\pi\sigma r^5} \tag{1}$$

where the I is the current that is being injected from the top to the bottom electrode, σ is the conductivity of the soil surrounding the system, r is the distance between the transmitter and receiving circuits and d is the distance between the top and bottom electrodes of the transmitter and receiver.

B. Simulation Results

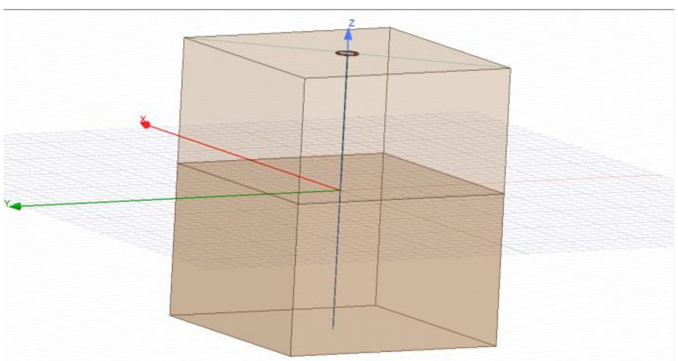

Fig. 2: Simulation diagram of the transmitter systems.

The transmitter system was simulated in Ansys, Maxwell with a 3.6kV 60Hz signal for better understanding of the distances and voltage levels which the system may achieve. The conductivity of the soil is applied to the surrounding area of the transmitter, shown in Figure 2. The simulated system was scaled down by a factor of 1000 to adhere to the processing limits of the computer. Figure 3 shows the resulting differential voltage curve of the signal as it propagates through the soil. The differential voltage was taken at 3.048m distances between the transmitter and receiver for each point in the model. All differential voltage curves follow the structure of depreciation, but the rate of attenuation is reduced substantially depending on the voltage supplied to the system. This matches the same shape of curve as shown in the experimental measurements.

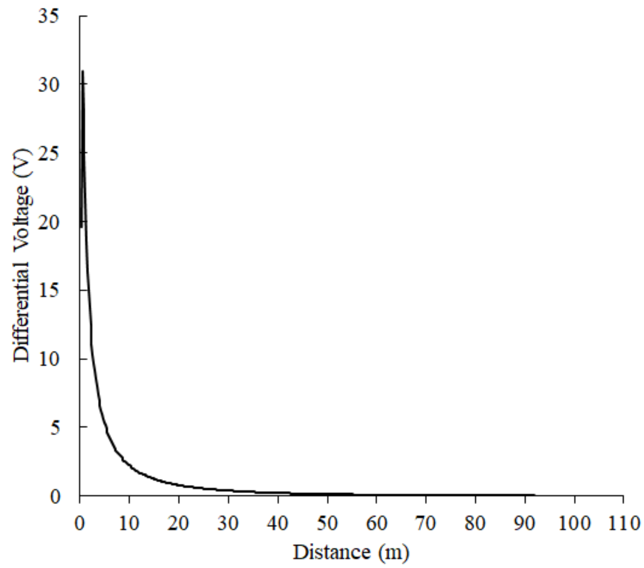

Fig. 3: Potential response with a continuous AC power supply applied to the transmitter.

III. Experimental Setup

A. The Transmitter

The transmitting device is located at Tennessee Technological University's Shipley Farm research site on the edge of a 13-acre hay field, as shown in Figure 4. The test site has a covered trailer at the edge of the field for storing test equipment. The trailer is powered through an isolated, off-grid, solar panel array that has eight 100W panels attached to a 48V battery bank. The transmitter was a 167.6m deep bore hole with a 0.1524m diameter, similar to a water well, which consisted of five 1.83m long brass pipes that were separated by 30.48m increments of insolating plastic tubing sections. Each brass pipe was connected to the surface by a 12awg highly insulated

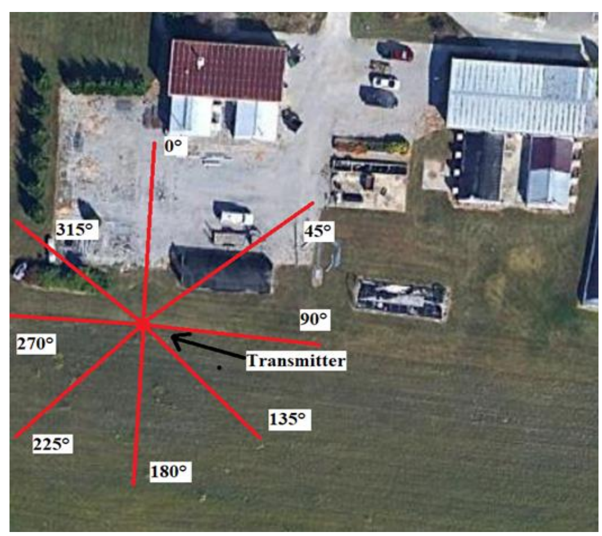

Fig. 4: Aerial view of the testing site provided by Google maps.

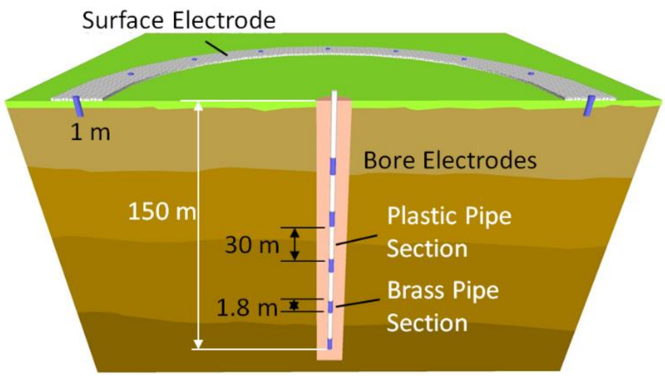

Fig. 5: A 3D illustration of the entire transmitter system placed into the soil.

copper wire. The depths of each brass pipe is shown in Fig. 5 and includes 45.72m, 76.2m, 106.68m, 137.16m and 167.64m. The transmitter bore hole surrounding the tubing was back filled with bentonite clay in order to protect the water table from contaminants. A surface electrode was constructed using a galvanized steel mesh that was 0.914m in length and located approximately 9.144m from the transmitter center.

Two experiments were conducted with the transmitter system. The first experiment was to determine the optimal depth in which the transmitter operates, based on impedance measurements and distant signal intensity, and the second was to determine the power signal propagation magnitudes of the system versus distance. For the first experiment, the impedance was measured with a THS3014 Tektronix Oscilloscope for the 5 electrodes over a frequency range of 1k-800kHz. The range followed a logarithmic scale increase until 100kHz was reached. At 100kHz, the intervals were increased to 50kHz per point until reaching 800kHz in frequency. The frequency sweep was tested with all 5 leads during a 4-month period at intervals of approximately 2 weeks between each measurement.

The second experiment was conducted to determine the omnidirectional power signal characteristics of the transmitter in a full 360-degree radius at 45-degree increments (shown in Fig. 4). The changes of the receiver output signal at variable current inputs was also recorded. The experiment used two 0.91m long steel rods that were placed at 3.048m increments between 6.096m to 30.48m from the transmitter. The power supplied was from a Model 3PN1010B 60Hz variable transform (VARIAC) connected to a Model PICOGLF20W24V120VR solar inverter within the trailer. The current input to the transmitter began at 0.5A and was incremented by 0.25A until a maximum of 1.84A input current was achieved.

B. The Moisture Sensor

The microcontroller currently used for the sensor system is an Arduino Pro Mini, as shown in Figure 6. The soil moisture sensor is the (ASIN#B07SYBSHGX) Capacitive Soil Moisture Sensor. Together these two devices form a sensor node. The capacitance value is read by the microcontroller and linearized to a voltage value that indicates the soil moisture content. The data is currently stored locally on an SD card to be accessed later. Future systems are underway to replace the Arduino with an ESP32 microcontroller, having integrated WiFi capability.

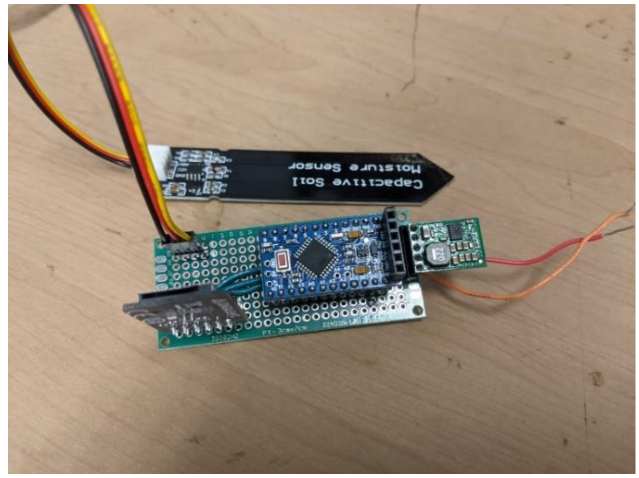

Fig. 6: Photo of the Arduino Pro Mini circuit attached to the capacitive moisture sensor (ASIN#B07SYBSHGX).

The sensor node receives power through the step potential generated in the soil which is then rectified and fed into a Buck converter to further filter and stabilize the rectified DC. The construction of the capacitive soil moisture sensor consists of a conducting plate and a ground plate placed near each other inside the PCB. The capacitive moisture sensor uses the plates to measure the changes in capacitance caused by changes in the soil. As it is not measuring the water in the soil directly, a change in ions within the soil will cause the resistivity in the soil to decrease, altering the capacitance. The sensor uses a 555-timer circuit that produces a voltage that is proportionate to the capacitance changes seen by the sensor.

IV. Results and Discussion

A. Physical Characteristics Of The Transmitter

Figure 7 shows the impedance spectra between the surface electrode and the bottom electrodes for all 5 leads. The 45.72m,

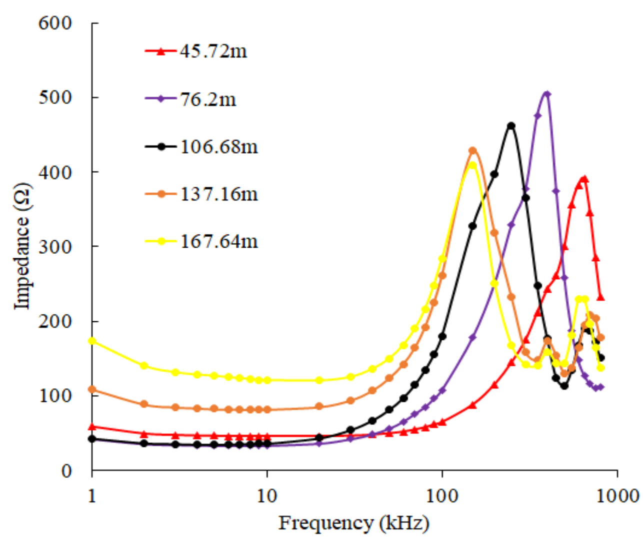

Fig. 7: Impedance measurements at various depths.

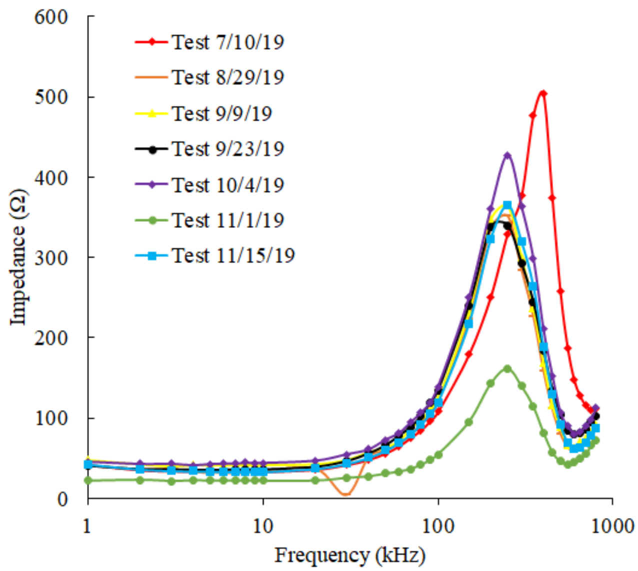

Fig. 8: The impedance taken over a 4-month period.

76,2m and 106.68m electrodes are similar values of impedance at the lower frequency spectrum, below 20kHz. The other 2 electrodes show a greater impedance as the depth increases into the Earth which could be caused by the water table levels, conductive properties or material composition of the soil at the further depths. For optimal impedance values, the 76.2m and 106.68m electrodes were used in further experiments due to the 45.72m having slightly higher impedance at the operational ranges, which include all frequencies lower than 10kHz, for the equipment used in later testing.

The changing in weather patterns did not have a large effect on the transmitter within the operational range of 1k-20kHz, as shown in Figure 8. The differences in the impedance curve for the month of June showed lower impedance prior to 250kHz, but the later half of the spectrum showed substantially higher impedance of the soil. In early November there were higher levels of precipitation than any other monthly measurements. The corresponding impedance curve showed a lower value for the entire spectrum. Comparing this data to that collected in Alberta Canada [9], it can be seen that the impedance of the soil below 20kHz appears quite consistent, at least in these two, vastly different locations.

B. *Power Capacities*

The transmitter produces a consistant energy signal in 360° omnidirectional spread through the soil. The effects of the soil contents is minimal when transmitting a low frequency signal as shown in Figure 9. The signal in all 5 directions show similar potential differences as the receiver changed locations. There was a small variance at 45° due to a building structure (seen in Fig. 4). The structure did have a slight increase in potential voltage around it in comparison to the other directions at that distance, but this is not a confirmed consist trend in the reaction of impedance around building structures, so more investigation is needed.

Figure 10, shows varying current inputs into the transmitter. The energy of the signal increases in amplitude and distance as the transmitted signal increases. This is very important when trying to find the optimal current that is necessary for powering sensing devices that are placed in the field. At further distances, as in 100m or more from the mesh, a substantially higher voltage source will be required to produce the waveform, as shown previously in the simulation results. The maximum distance that is shown to power small sensing devices and LED lights is approximately 12m from the transmitting structure for a 5A injection. The shape and characteristics of the waveform stay consistent with the simulation results. We are currently investigating changes in the duty cycle of the power waveforms

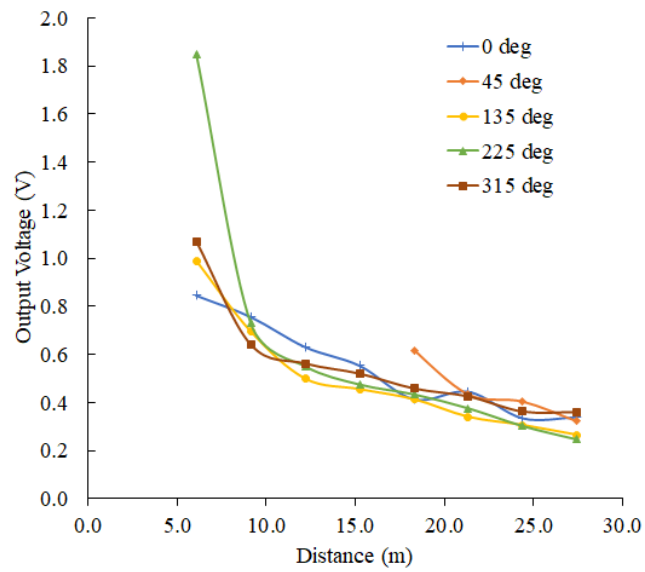

Fig. 9: The differential voltage measured at 3.048m increments in omnidirectional path.

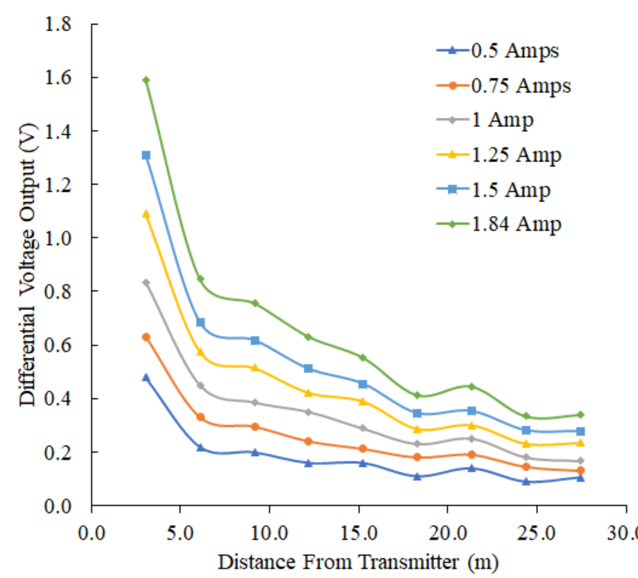

Fig. 10: The differential voltage measured at 3.048m increments with various current inputs.

injected into the transmitter to control the power dissipated in the soil. This should allow us to produce large signal magnitudes that offer greater power reception at distance, but with far less power dissipation in the soil.

C. Sensor Data

The soil moisture data was gathered over 120 seconds while the sensor was powered by the transmitter through the soil. No batteries or large capacitors were used. The sensor node was operated strictly from currents propagated within the soil. The reading was taken approximately 10m from the transmitter. Figure 11 was plotted using the analog output voltage of the sensor.

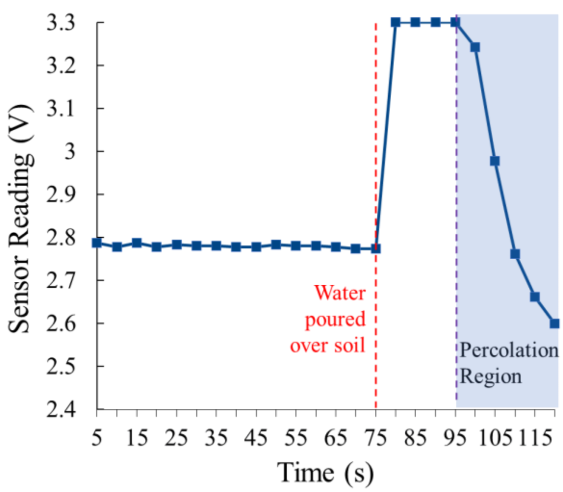

Fig. 11 Soil moisture data from sensor powered wirelessly through the soil. At 75 seconds, water was poured around the sensor which indicated a rapid rise in the moisture – saturating the sensor.

V. Conclusion

In conclusion, the transmitter and receiver structure shown has the power capabilities to operate small low-powered sensors through the soil by conduction. The system offers an omnidirectional wireless power transmission alternative to the current energy harvesting systems used in agriculture research. The system has the potential of powering sensing devices at extremely long distances as indicated in the simulation, but the tested limits thus far is approximately 12m from the transmitter for a 5A charge injection into the soil. Future work will include improved distances by changing the inverter design for a high energy signal output at low duty cycle and triangulating the signal by adding multiple transmitters to the system. We will also incorporate telemetry into the receiver to enable data to be wirelessly transmitted to the solar trailer for analysis.

Acknowledgment

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