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LAND VEHICLE-BASED WIRELESS POWER TRANSFER THROUGH SOIL FOR ENABLING BATTERYLESS UNDERGROUND SOIL MOISTURE SENSING APPLICATION

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ABSTRACT

This paper reports the design and field demonstration of a land vehicle-based wireless power transfer system that can enable a batteryless underground soil moisture sensing application. The wireless power transfer system consists of a tuned primary coil exhibiting a 40cm-diameter with 2-turn, which is inductively coupled to a secondary coil buried in the soil, tuned to the same frequency at 2MHz, exhibiting 6cm-diameter and 1-turn while being interposed between two ferrite layers. The prototype system is optimized to transmit 20mW over 20cm distance (18cm-deep soil with a 2cm air gap above the ground) to energize an underground soil moisture sensor.

KEYWORDS

Wireless power transfer, Inductive power transfer, Underground power transfer, Soil moisture sensor, Irrigation, Agriculture.

INTRODUCTION

As the global demand for food production increases, technology advancements are needed to enable efficient resource use for sustainable agriculture. Soil moisture sensing technology can increase water-use efficiency, but conventional above-ground instrumentations render current systems impractical. Wireless underground *in-situ* systems are desirable by allowing agricultural processes without obstruction. In this work, we aim to develop and demonstrate a land vehicle-based wireless power transfer system that can enable a batteryless underground soil moisture sensing application as depicted in Figure 1, where a land vehicle can wirelessly power or recharge an underground sensor module as well as communicate with the sensor for data telemetry. Sensor data can include soil moisture, salinity, temperature, pH, etc., which are indicative of soil conditions.

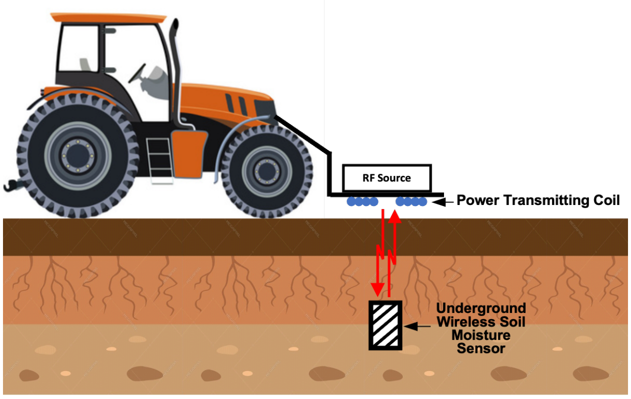

Figure 1: Land vehicle-based wireless and batteryless underground soil moisture sensing application.

Inductively-coupled radio-frequency (RF) power transfer techniques have been widely employed for biomedical, industrial, and consumer electronics applications [1-3]. Our recent research demonstrated wireless power transfer through the soil to energize a prototype soil moisture sensor [4] reliably in a lab environment [5]. This paper reports a further improved design and field demonstration of a land vehicle-based wireless power transfer system, which can wirelessly transmit 20mW over a 20cm distance (18cm-deep soil with 2cm air gap above the ground) to energize an underground soil moisture sensor. The power transfer system consists of a tuned primary coil exhibiting a 40cm-diameter, which is inductively coupled to a secondary coil buried in the soil, tuned to the same frequency, with a 6cm-diameter while being interposed between two ferrite layers.

DESIGN OF INDUCTIVELY-COUPLED WIRELESS POWER TRANSFER THROUGH SOIL

Figure 2 presents an inductively-coupled wireless power transfer system architecture. The system consists of a pair of tuned LC tank circuits, where an input RF power is coupled to the secondary coil, L_2, from the primary coil, L_1, tuned to the same frequency through the mutual inductance, M. It should be noted that the secondary coil represents an underground coil, whereas the primary coil is above the ground. The received RF power exhibits an AC voltage swing, V_{out}, across a load resistance, R_{Load}, which models an electrical system to be powered by the received RF power. The AC voltage swing can be further rectified and filtered to produce a DC voltage to energize an underground soil moisture sensor in this application.

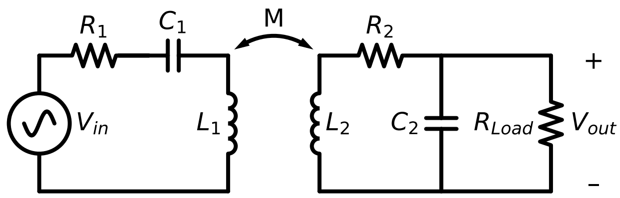

Figure 2: Inductively-coupled wireless power transfer system architecture.

It can be shown that the voltage gain from V_{in} to V_{out} and the AC power transfer efficiency can be expressed by Equations (1) and (2), respectively, under a weak coupling condition,

$$A_v \cong Q_1 Q_2 \frac{k}{1+\beta}\sqrt{\frac{L_2}{L_1}} \tag{1}$$

$$\eta_{coupling} \cong \frac{\beta k^2}{(1+\beta)^2} Q_1 Q_2 \tag{2}$$

where Q_1 and Q_2 are the loaded quality factor of the primary coil and unloaded quality factor of the secondary coil, respectively, k is the coupling factor between the coils, and β is the impedance ratio between an equivalent parallel resistance of $\frac{(\omega L_2)^2}{R_2}$ associated with the secondary coil and the load resistance, R_{Load}, which can be expressed as $\beta = \frac{(\omega L_2)^2}{R_{Load} R_2}$ [1]. For our prototype system design, an RF coil implemented by litz wire (1162 strands of AWG #46 wire exhibiting an approximately 2mm-diameter) with a 6cm-diameter and 1-turn is chosen for a compact underground system implementation. The choice of 1-turn is based on the consideration of obtaining a nearly matched load condition under system operation. Further, the coil is interposed between two ferrite layers, where each ferrite layer exhibits a thickness of 2.5mm with a relative permeability (μ_r) of 120, to achieve an enhanced inductance value of approximately 300nH and a maximum quality factor (Q_2) of 90 around 2.5MHz. This condition results in an equivalent parallel resistance of approximately 390Ω associated with the secondary coil, corresponding to a β value of 1.4, representing a nearly matched load condition for a custom-designed soil moisture sensor dissipating 20mW from a 3.3V power supply [4].

Equations (1) and (2) indicate that a large coupling factor can achieve an increased voltage gain and power transfer efficiency. To enable a reliable field operation for a land vehicle-based wireless power transfer system, a number of power transmitting coils exhibiting a diameter ranging from 10cm to 50cm were investigated for their coupling factor to a 6cm-diameter power receiving coil positioned at 20cm away, which represents a typical cultivation layer thickness. In a practical application, it is difficult to ensure a center-to-center alignment between the power transmitting coil and receiving coil. Therefore, measurements were conducted under various axial offset distances. Figure 3 presents the measured coupling factor versus offset distance for different diameters of the power transmitting coils. The measurement data reveals that below 10cm offset, the coupling factors for all coils except the 10cm-ϕ coil are approximately the same. Between 10cm and 20cm offset, the 40cm-ϕ coil outperforms all other designs. Therefore, the 40cm-ϕ coil is chosen as an optimal configuration for the prototype system implementation.

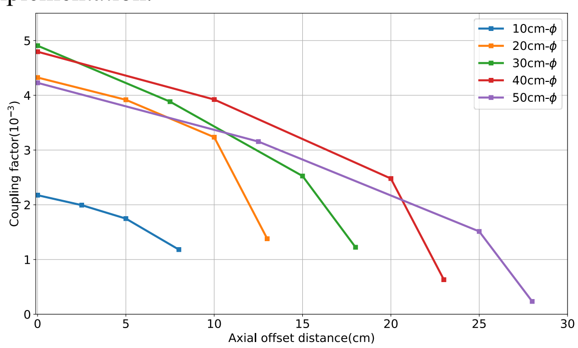

Figure 3: Measured coupling factor versus axial offset distance for different diameters of power transmitting coil.

To further investigate the effect of geometry on the power transmitting coil, a number of 40cm-diameter coils were built using the same litz wire with different number of turns and characterized for their performance. Figure 4 presents the measured inductance value and quality factor versus frequency, which reveals that the 3-turn coil design achieves a peak Q factor of 313 around 2MHz. Figure 5 further presents the calculated power transfer efficiency and voltage gain using the measured coils' inductance value and quality factor, as well as the coupling factor between the coils. The analytical results show that the 40cm-diameter and 1-turn power transmitting coil can achieve a high voltage gain but exhibits a low power transfer efficiency due to its low quality factor and low inductance value. The other three coil designs (2-turn, 3-turn, and 4-turn) achieve increased comparable efficiencies with the 2-turn design exhibiting a higher voltage gain than the 3-turn and 4-turn alternatives. The plots indicate that the 40cm-diameter and 2-turn power transmitting coil can achieve a maximum power transfer efficiency over 8% with a voltage gain of 11 around 2MHz.

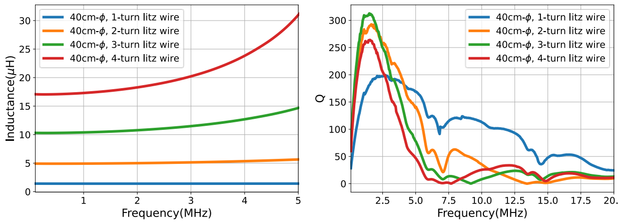

Figure 4: Measured primary litz wire coils' inductance (left) and quality factor (right) with different number of turns.

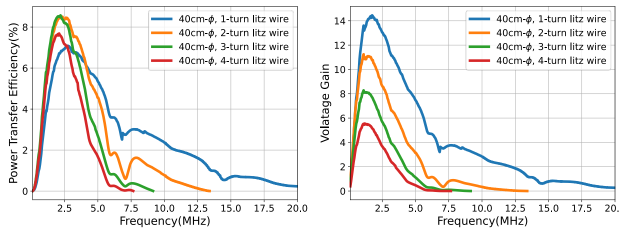

Figure 5: Calculated power transfer efficiency (left) and voltage gain (right) vs. frequency with different number of turns for litz wire coils.

An additional performance comparison was conducted by employing power transmitting coils implemented with copper wire (AWG #11 wire with an approximately 2.4mm-diameter). Figure 6 presents the characterization results of the copper wire coils. Figure 7 plots the calculated power transfer efficiency and voltage gain, which reveal that the power transmitting coil with a 40cm-diameter and 4-turn can achieve a high efficiency close to 10% around 2.5MHz with a voltage gain of 6. Therefore, two power transmitting coils (one implemented using litz wire with a 40cm-diameter and 2-turn, and another one implemented using copper wire with a 40cm-

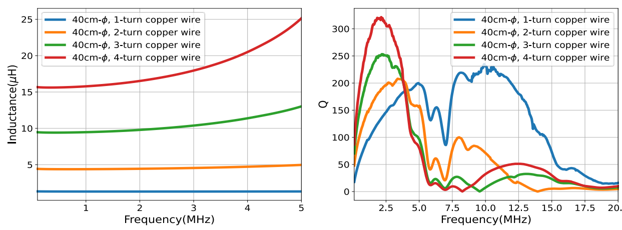

Figure 6: Measured primary copper wire coils' inductance (left) and quality factor (right) with different number of turns.

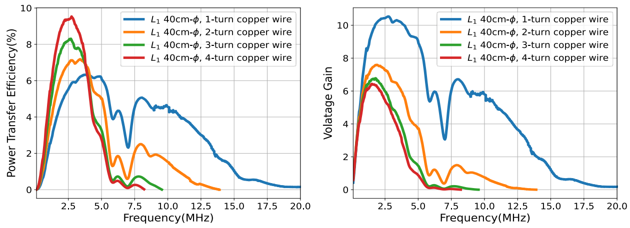

Figure 7: Calculated power transfer efficiency (left) and voltage gain (right) vs. frequency with different number of turns for copper wire coils.

diameter and 4-turn) were selected for wireless power transfer demonstration in the laboratory as well as in the field, which will be described in the following sections. It should be noted that our measurement equipment exhibited certain artifacts between 5MHz and 7.5MHz as shown in Figures 6 and 7.

LABORATORY EXPERIMENTS

Figure 8 presents the laboratory experimental setup for wireless power transfer in air. A tuned primary coil implemented using litz wire exhibiting a 40cm-diameter and 2-turn is positioned above a ferrite-layers-interposed secondary coil with a 20cm air gap in between. The secondary coil will be encapsulated in a 3D-printed package with a sufficient clearance to ensure its high-Q performance when buried in soil [6], which is critical for minimizing potential degradation of wireless power transfer through the soil. Further, high-Q capacitors are employed for implementing the LC tank circuits to minimize system losses.

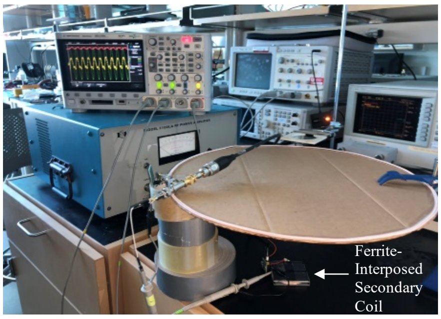

Figure 8: Experimental setup for wireless power transfer characterization across 20cm in air by employing a 40cm-diameter and 2-turn primary litz wire coil.

Figure 9 presents the measured voltage waveforms at the input and output terminals of the wireless power transfer system. The prototype system demonstrates that an output voltage amplitude of 7.88V_{pp} (corresponding to 28mW developed over a load resistance of 275Ω) can be achieved under an input driving voltage amplitude of 0.96V_{pp}, which corresponds to a voltage gain of 8.2 and power transfer efficiency of 7.9%. The measured performance is closely matched to the analytical result. A similar experiment was conducted by employing a primary coil implemented using copper wire exhibiting a 40cm-diameter and 4-turn. Figures 10 and 11 present the experimental setup and measured voltage waveforms, respectively. The system demonstrates a power transfer efficiency of 9.2% with a voltage gain of 5.4. The received RF power is further rectified by a voltage regulator to deliver a stable 3.3V DC supply to energize a custom-designed soil moisture sensor. Figure 12 presents the overall system design architecture. The soil moisture sensor outputs a pulse width modulated signal with its average value varying between 1.08V and 1.54V, corresponding to a soil moisture level controlled between 46% and 26%.

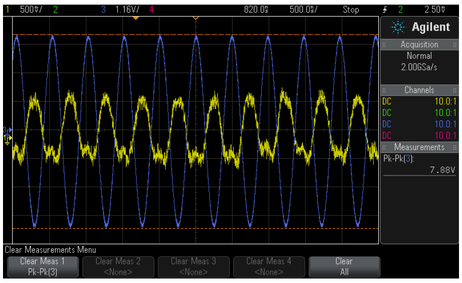

Figure 9: Measured input and output voltage waveforms.

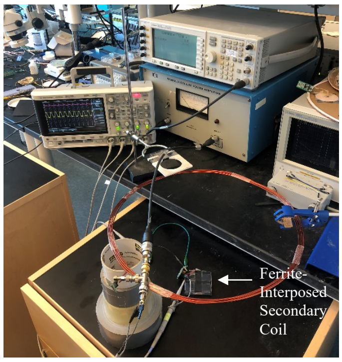

Figure 10: Experimental setup for wireless power transfer characterization across 20cm in air by employing a 40cm-diameter and 4-turn primary copper wire coil.

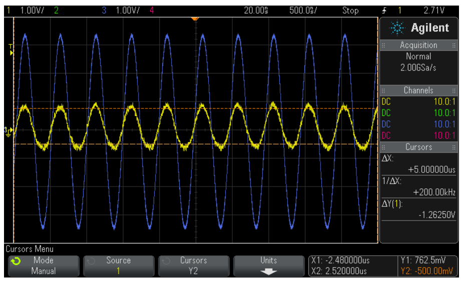

Figure 11: Measured input and output voltage waveforms.

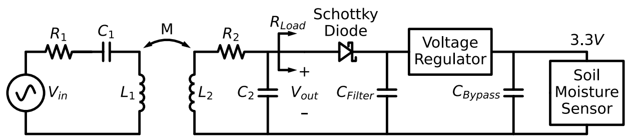

Figure 12: System design architecture for wirelessly powering soil moisture sensor.

FIELD DEMONSTRATION

Figure 13 presents the field demonstration setup for a land vehicle-based wireless power transfer system. Figure 13(a) shows a 40cm-diameter and 2-turn primary litz wire coil mounted onto a wood frame attached to a metal 3-point tractor implement, which was anchored to a tractor as shown in Figure 13(b). The entire apparatus can be vertically moved and positioned above the ground with 2cm clearance. A tuned 6cm-diameter and 1-turn secondary coil is positioned 18cm below the soil surface. Figure 13(c) shows the entire packaged underground

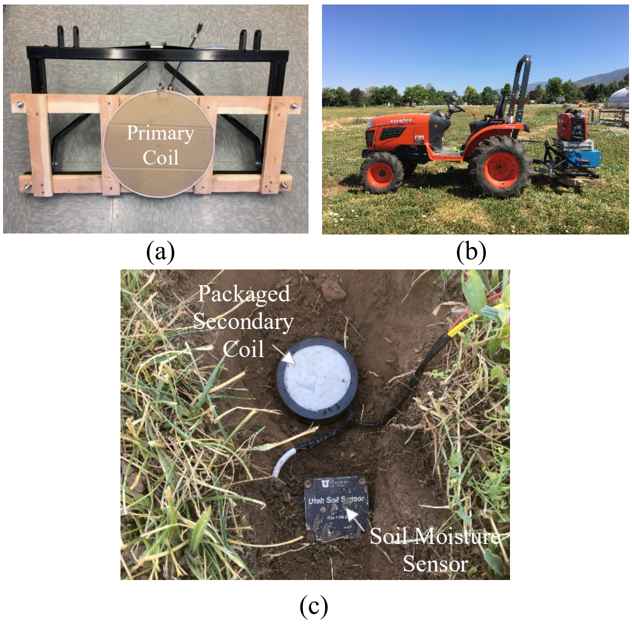

Figure 13: Field demonstration setup for a land vehicle-based wireless power transfer system.

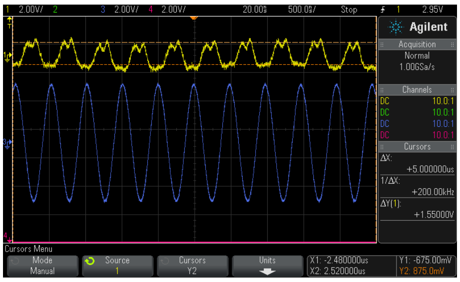

Figure 14: Measured input and output voltage waveforms.

batteryless sensing system to be buried in loamy soil. To investigate the soil effect on the wireless power transfer performance, three tests were performed under different conditions: (1) with no soil cover, (2) with dry soil cover, and (3) with wet soil cover. An impedance characterization reveals that the primary coil's loss at 2MHz increases from 216mΩ with no soil cover to 276mΩ with dry soil cover and ultimately reaches 375mΩ with wet soil cover. Figure 14 presents the measured voltage waveforms at the input and output terminals of the system, demonstrating that an output voltage amplitude of 7.8V_{pp} can be developed under an input driving voltage amplitude of 1.55V_{pp}. The prototype system, therefore, can wirelessly energize a soil moisture sensor across 20cm distance (18cm-deep soil with a 2cm air gap above the ground) with an efficiency of approximately 4.5% due to the additional loss on the primary coil contributed by the surrounding wet soil. A similar test was conducted using a 40cm-diameter and 4-turn primary copper wire coil. Measurement results reveal that the wet soil introduced a more pronounced loss to the primary coil due to its wider (4-turn) coil width; hence, a larger surface area for a more enhanced coupling between the coil and the surrounding soil. The power transfer efficiency was reduced to approximately 2.3%, which suggests that an increased air gap above the ground is necessary to minimize the coil's loss contributed by the soil but with an expense of a reduced soil depth to be covered by wireless power transfer. A complete underground soil moisture sensor with wireless powering and data telemetry capability will be designed and demonstrated as the next step.

CONCLUSION

A wireless power transfer system is designed and demonstrated to transmit 20mW through 18cm-deep soil with a 2cm air gap above the ground. The prototype system consists of a tuned primary coil exhibiting a 40cm-diameter with 2-turn, which is inductively coupled to a secondary coil buried in the soil, tuned to the same frequency at 2MHz, exhibiting a 6cm-diameter with 1-turn while being interposed between two ferrite layers. The system is designed to maximize the achievable power transfer efficiency given constraints on the coils' size and coupling distance by optimizing the coils' geometry; hence, the quality factor, inductance value, as well as tolerance with respect to an axial offset for a practical consideration. The wirelessly transferred power is sufficient to energize an underground custom-designed soil moisture sensor operated in a batteryless manner. Field testing further reveals that an adequate air gap between the primary coil and soil surface is critical for minimizing additional coil loss due to the surrounding soil, thus presenting a trade-off between efficiency and soil depth that can be covered by wireless power transfer.

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REFERENCES

[1] D. J. Young, P. Cong, M. A. Suster, and M. Damaser, "Implantable wireless battery recharging system for bladder pressure chronic monitoring," Lab on a Chip, DOI: 10.1039/C5LC00821B, 2015, 15, 4338-4347.

[2] N. Chaimanonart and D. J. Young, "Remote RF powering for industrial strain sensing microsystem," IEEE Sensors Journal, Volume 6, Issue 2, April, pp. 484 – 489, 2006.

[3] P. D. Mitcheson, David Boyle, George Kkelis, David Yates, Juan Arteaga Saenz, Samer Aldhaher, and Eric Yeatman, "Energy-autonomous sensing systems using drones," IEEE Sensors Conference, 2017, pp. 1-3.

[4] J. Sanchez, A. Dahal, C. Zesiger, R. Goel, D. Young, and S. Roundy, "Design and Characterization of a Low-Power Moisture Sensor from Commercially Available Electronics," IEEE Sensors Conference, October, 2021.

[5] S. Ding, J. Sanchez, A. Jackson, S. Roundy, R. Goel, C. Zesiger, D. Young, "Wireless Power Transfer Through Soil for Energizing an Underground Soil Moisture Sensor," IEEE Sensors Conference, October, 2022.

[6] W. Luo, A. Jackson, J. Sorensen, A. Dahal, R. Goel, S. Roundy, C. Zesiger, D. Young, "Wireless Power Transfer Through Soil Over a Range of Moisture Levels for In-Situ Soil Health Monitoring," IEEE Sensors Conference, October, 2021.