Wireless Power Transfer Through Soil for Energizing an Underground Soil Moisture Sensor

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***Abstract*—This paper presents the design and measurement result of an inductively coupled power transfer system, which can wirelessly transmit 20mW through a 15cm-deep soil to energize a soil moisture sensor. The power transfer system consists of a tuned primary coil exhibiting 6cm-diameter and 9-turn, which is inductively coupled to a secondary coil, tuned to the same frequency of 2.5MHz, exhibiting 6cm-diameter and 1-turn while being sandwiched between two ferrite sheets. Ferrite materials are employed to enhance the secondary coil's inductance value and quality factor, which are critical for wireless power transfer. A soil moisture level varied between 31% and 46% under a controlled manner was detected by the soil moisture sensor under wireless powering.**

Keywords—wireless power transfer; power transfer through soil; inductive coupling; ferrite; soil moisture sensor; soil moisture monitoring; underground sensing

I. Introduction

The world's population is expected to surpass 9 billion by 2050, thus calling for an increased demand for food production, which in turn can degrade soil and threaten food security [1]. Sustaining high levels of food production depends on healthy soil. Therefore, there is a strong and urgent need to develop low-cost, long-term, wireless, and in-situ sensing technologies for monitoring soil health to ensure future sustainable agriculture. In this work, we aim to develop a wireless underground in-situ soil sensing network, as depicted in Fig. 1, where autonomous vehicles, both ground and aerial, can potentially power or recharge an underground sensor module or network in a wireless manner as well as communicate with the sensor for data telemetry [2, 3, 4]. Sensor data can include soil moisture, salinity, temperature, pH, etc., which are indications of soil conditions. Autonomous vehicles can transfer radio-frequency (RF) power to the sensor from a power source incorporated as a part of the vehicles, as shown in Fig. 1.

Inductively-coupled RF power transfer techniques have been widely employed for biomedical, industrial, and consumer electronics applications [5-17]. Recent research demonstrated that power could also be wirelessly transmitted through soil via inductive coupling over a soil depth between 15cm to 30cm, which represents a typical cultivation layer thickness [18, 19]. However, the received power was limited between 0.56mW and 0.13mW, respectively, under a developed voltage of 2.1V$_{RMS}$. A custom-designed soil moisture sensor was reported recently with a power dissipation of approximately 20mW from a 3.3V DC supply [20]. The work presented in this paper focuses on developing and demonstrating an enhanced wireless power transfer through soil to energize the prototype soil moisture sensor reliably. Optimal coil design considerations incorporating ferrite materials are investigated to achieve a sufficient power transfer for the proposed sensing application.

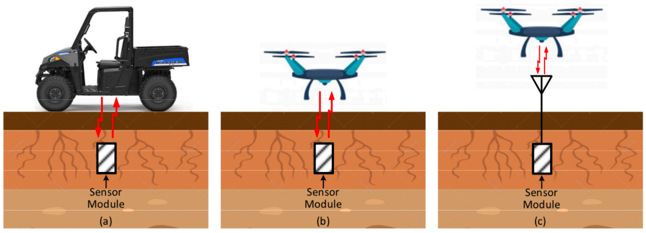


Fig. 1. Wireless underground in-situ soil sensing network architecture.

II. Design of Inductively-Coupled Wireless Power Transfer Through Soil

Fig. 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}. The AC voltage swing can be further rectified and filtered to produce a DC voltage to energize an underground soil moisture sensor.

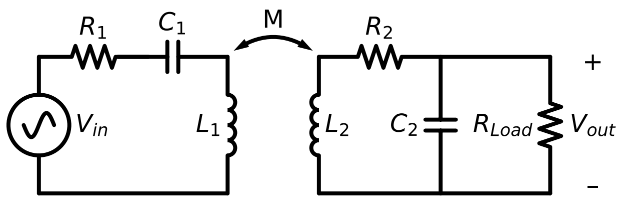


Fig. 2. Inductively-coupled wireless power transfer system.

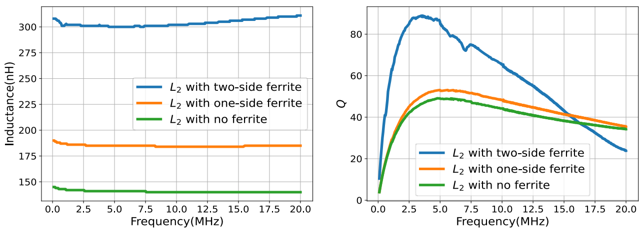
It can be shown that the voltage gain from V_{in} to V_{out} and AC power transfer efficiency can be expressed by Equations (1) and (2) under a weakly coupled condition, respectively,

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

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

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 $\beta = \frac{(\omega L_2)^2}{R_{Load} R_2}$ [21]. It can be further shown that an optimal design in terms of voltage gain and efficiency can be achieved when β is approximately equal to unity, corresponding to a matched load condition [21].

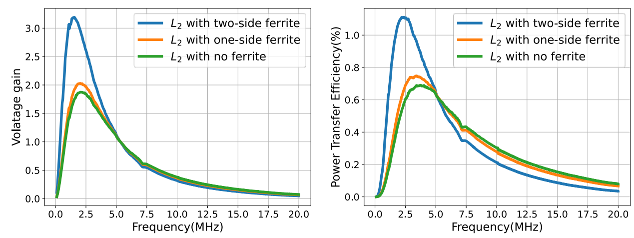
Our prototype soil moisture sensor dissipates approximately 20mW from a 3.3V DC supply, thus corresponding to an equivalent load resistance around 275Ω presented to the L_2C_2 tank circuit, assuming a half-wave rectifier is employed to convert the developed AC voltage swing, V_{out}, to a DC voltage of 3.3V energizing the sensor. Equation (1) suggests that enhancing the inductance value of L_2 for a higher quality factor is beneficial for boosting the voltage gain while simultaneously improving the AC power transfer efficiency. For our prototype system design, an RF coil with 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 sandwiched between two ferrite sheets, where each ferrite sheet exhibits a thickness of 2.5mm with a relative permeability (μ_r) of 120, to achieve an inductance value of approximately 300nH and a maximum quality factor (Q_2) of 90 around 2.5MHz, thus resulting in an equivalent parallel resistance of approximately 390Ω associated with the secondary coil, corresponding to a β value of 1.37 that represents a nearly matched load condition. Experimental investigation reveals that increasing ferrite sheet thickness and relative permeability of the ferrite material can enhance the coil's quality factor. However, an optimal performance occurs with a thickness of 2.5mm with μ_r of 120. Fig. 3 presents the measured secondary coil's inductance value and quality factor versus frequency under different ferrite arrangements, which reveal that the coil incorporated with two-side ferrite sheets achieves a higher inductance value and a higher quality factor compared to the configuration without employing any ferrite sheet or employing a one side ferrite sheet. The primary coil, L_1, is designed with a diameter of 6cm for the prototype demonstration. A small size coil will result in a reduced coupling factor while an excessive large coil size would also degrade the coupling factor. Experimental investigation determines that a coil with 6cm-diameter and 9-turn, constructed using litz wire, can achieve an inductance value of 3.8μH with a quality factor (Q_1) of approximately 240 and 200 at 2.5MHz in air and in soil across a range of moisture level, respectively [19]. Reducing the number of turns decreases both the inductance value and quality factor, compromising the voltage gain and power transfer efficiency. Incorporating ferrite material with the primary coil enhances the inductance and quality factor,



(a) (b)

Fig. 3. Measured secondary coil's inductance (a) and quality factor (b) under different ferrite arrangements.

but with a penalty of reduced coupling factor (due to shielding the magnetic field from reaching the secondary coil), thus undesirable for wireless power transfer. Our prototype design was first simulated, revealing a maximum power transfer efficiency of 1.1% at 2.5MHz with a voltage gain of roughly 3 across a soil depth of 15cm. Fig. 4 plots the simulated gain and efficiency versus frequency under different ferrite arrangements for the secondary coil. Based on the simulation results, it is expected that an RF power of 20mW can be received across a load resistance of 275Ω by driving the primary tank circuit with a sinusoidal signal exhibiting a peak-to-peak amplitude of 2.55V at 2.5MHz and sandwiching the secondary coil with ferrite sheets.



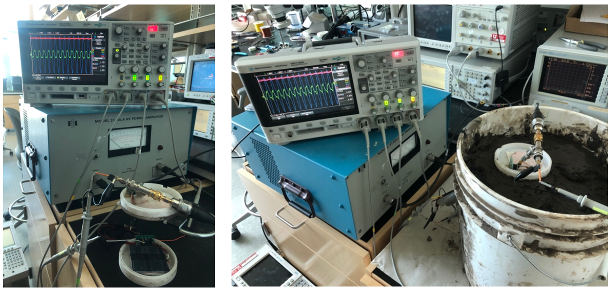
(a) (b)

Fig. 4. Simulated gain (a) and efficiency (b) vs. frequency under different ferrite arrangements.

Additional simulations were performed with a load resistance ranging from 100Ω to 400Ω, demonstrating a similar performance and the advantage of employing ferrite materials for the secondary coil. It is also anticipated that a larger primary coil than the current prototype version can achieve a higher coupling factor and an increased quality factor, thus improving the voltage gain and efficiency, which is planned as the next step.

III. Experimental Demonstration of Wireless Power Transfer Through Soil

Fig. 5 presents the experimental setup for wireless power transfer through soil. Fig. 5(a) shows that a tuned primary coil is positioned above a ferrite-sheets-sandwiched secondary coil with a 15cm air gap in between. The secondary coil is then encapsulated in a 3D-printed package with a 1cm air gap clearance to maintain its high-Q performance when buried in soil [19]. A similar packaging scheme was used for the primary coil to minimize capacitive coupling to the soil, thus ensuring its high quality factor. Fig. 5(b) shows a soil-based experimental setup, where the primary coil is positioned at the soil surface with the tuned secondary coil buried 15cm below the soil surface. High-Q capacitors are employed for implementing the LC tank circuits in order to minimize system losses.



(a) (b)

Fig. 5. Experimental setup for wireless power transfer: (a) across 15cm in air and (b) through 15cm loamy soil.

Fig. 6 presents the measured voltage waveform at the input and output terminals of the system, demonstrating that an output voltage swing with $6.95V_{pp}$ amplitude (corresponding to 18mW developed over a load resistance of 275Ω) can be achieved under an input driving voltage of $2.61V_{pp}$. The demonstrated performance is closely matched

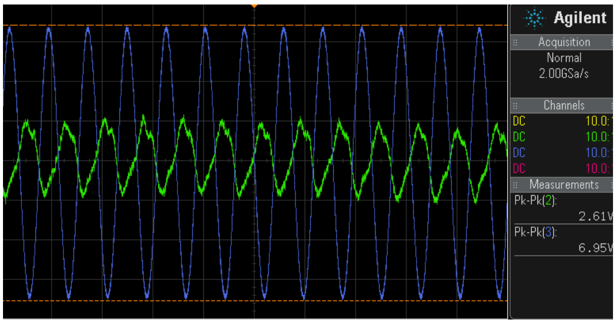


Fig. 6. Measured input and output voltage waveform demonstrating power transfer through soil.

to the simulation results (measured gain of 2.7 vs simulated gain of 3). A similar performance was obtained with the loamy soil's volumetric moisture level varied between approximately 36% and 46%. Experiments also reveal that the prototype system can receive a maximum power of 45mW, limited by the prototype power source driving capacity and potential heating of the circuit components. An offset of 3cm between coils can result in a reduced voltage gain by approximately 20%.

The received RF power is further rectified, followed by a voltage regulator to deliver a stable 3.3V DC supply to energize the soil moisture sensor. Fig. 7 presents a corresponding system design architecture for wirelessly

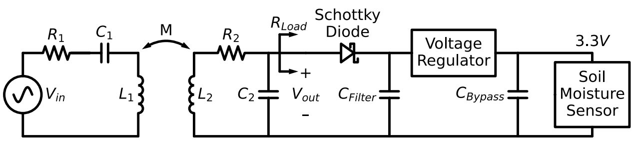


Fig. 7. Design architecture for wirelessly powering the soil moisture sensor.

powering an underground soil moisture sensor. Fig. 8 presents a secondary coil sandwiched in between ferrite sheets, further interfaced with a packaged soil moisture sensor. Fig. 9 shows the entire packaged underground system, which is to be buried in loamy soil. The buried system can be energized through inductively coupled RF power at 2.5MHz, thus enabling an underground battery-less operation, as shown in Fig. 10. It should be noted that the current system outputs an analog voltage ranging between 1.1V to 1.4V, corresponding to a soil moisture level varied from 46% to 31%, through a wired connection. Wireless signal telemetry will be designed as the next step to enable a fully wireless and battery-less underground sensing operation.

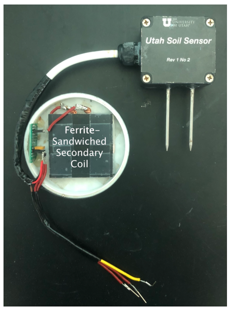


Fig. 8. Secondary coil sandwiched in ferrite sheets interfaced with soil moisture sensor.

Fig. 9. Packaged underground system.

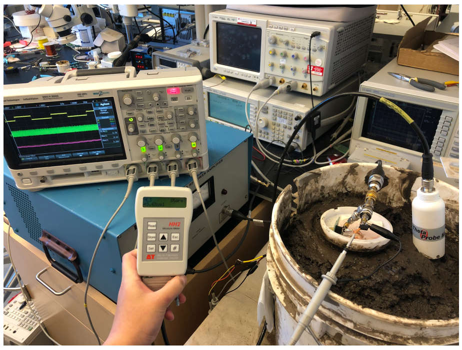


Fig. 10. Soil moisture test with wireless powering.

IV. Conclusion

A wireless power transfer of 20mW through 15cm-deep loamy soil was demonstrated over a typical soil moisture level ranging from 36% to 46%. This performance was achieved through inductive coupling from a tuned primary coil exhibiting 6cm-diameter and 9-turn to a secondary coil, tuned to the same frequency of 2.5MHz, exhibiting 6cm-diameter and 1-turn while being sandwiched between two ferrite sheets. A primary coil with an increased dimension is expected to further improve the performance. The received RF power was sufficient to energize a soil moisture sensor, thus enabling an underground battery-less sensing operation. A soil moisture level varied between 31% and 46% under a controlled manner was detected by the soil moisture sensor under wireless powering.

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