Improving the Effective Range of a Through the Soil Long Range Wireless Power Transfer System Using a Marx Inverter Topology

Christopher S. Johnson[2], *Student Member*, Michael Tidwell[1], *Student Member*,
Tyler Marcrum[1], *Student Member*, William Stump[1], *Student Member*,
C. W. Van Neste[2], *Senior Member*,
[1]Center for Energy Systems Research
[2]Electrical and Computer Engineering Department
Tennessee Technological University
Cookeville, TN, 38505
csjohnson43@tntech.edu

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***Abstract*—With the growing research into Through the Soil wireless power transfer systems, power supply design research is necessary for determining a suitable topology capable of supplying high current density. A modified Marx inverter is chosen to complete this task due to the extremely high voltages produced. The presented analysis shows that TTS system performance metrics greatly improve with increased current density and high operating frequency. Finally, the inverter is used to operate a Through the Soil wireless power transfer system and its performance is assessed.**

***Index Terms*—DC-AC, switched capacitor, TTS**

I. INTRODUCTION

Challenges in power delivery often emerge in applications located in remote environments. Traditional solutions such as photovoltaics or wind turbines tackle many of these challenges, however, can be intrusive to the working environment. Addressing these limitations has led to extensive research in the field of Long-range Wireless Power Transfer (LR-WPT). LR-WPT technologies, including laser power beaming and RF microwave power transfer (MPT), have been explored in depth [1]–[3]. These systems are line-of-sight dependent and require complex rectenna arrays to enhance safety during transmission. Neither of these LR-WPT systems would be suitable for powering systems in extremely remote locations.

A promising LR-WPT approach, known as a Through-the-Soil (TTS) wireless power transfer system utilizes conduction currents in the soil as a method of power delivery [4], [5]. An illustartion of how a TTS transmitter (Tx) operates is shown in Fig. 1 as a dipole approximation [4]. The proposed method is not line of sight dependent and viable for diverse environments. According to previous work conducted on TTS system's, performance relies heavily on the power supply design. System efficiency is directly tied to the magnitude of current being supplied to the Tx. Due to this crucial design point, it is of upmost importance for research into adaptive DC-AC converters able to produce the desired large magnitudes of current needed for an effective TTS system.

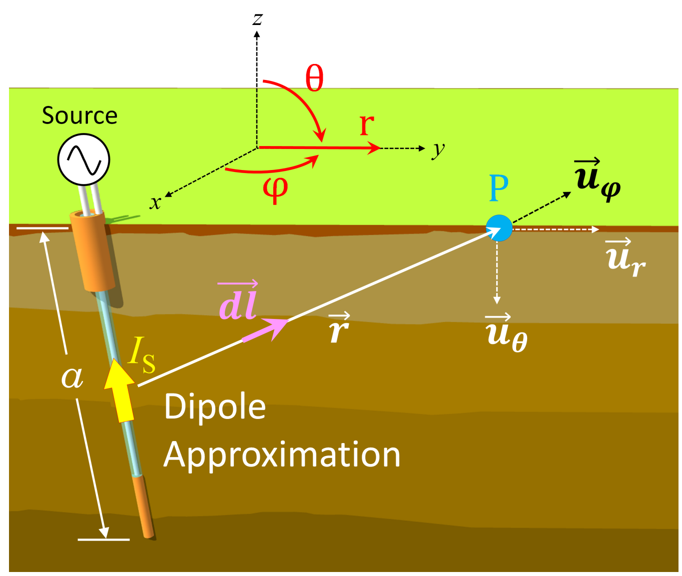

Fig. 1: Overview of a traditional TTS system courtesy of [4] where point P corresponds to the point of measurement.

An inverter design well-suited for this application are those utilizing switching of charged capacitor banks within a circuit [6], [7]. One of the earliest examples of this circuit is known as a Marx Generator. The circuit operates by charging the capacitor banks in parallel and discharging them in series through the use of spark gaps. (Fig. 2).

The concept of the Marx Generator has been studied using modern power electronics known as a Series/Parallel switched capacitor (SPSC) inverters [8]–[10]. While Marx generators are known for generating extremely high voltages, the low repetition rate of the pulses produced are not fast enough to be applied to modern wireless power systems. SPSCs seek to mitigate this drawback by utilizing solid state transistors and gate drivers to increase the operating frequency, allowing for

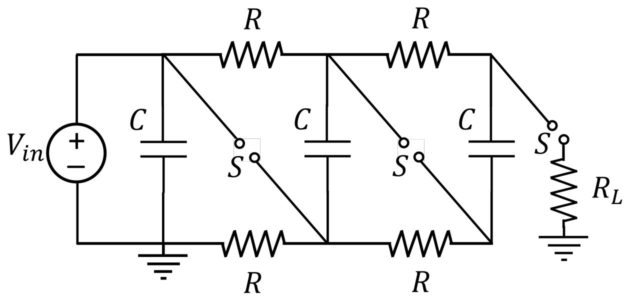

Fig. 2: Analog Marx generator circuit where R_L is the load and S represents a spark gap.

more adaptive power supply designs.

In this work, a closer investigation of a solid state Marx inverter topology applied to a TTS system will be presented. It will be found that the generation of high amplitude voltage waveforms allows for increased power transmission from the Tx. An investigation into the frequency dependency of a TTS system will be presented. A combination of these two ideas will result in an overall improvement to system performance parameters.

II. THEORY AND OPERATION

The voltage distribution produced radially around the Tx is fully derived in [4], therefore only the key parameters of the resultant equations will be discussed here. It should be noted before proceeding that the perceived separation of the point charges must be modified from the standard dipole. This change is reflected in (1)

$$d = 2\pi a \tag{1}$$

where a is the physical distance between the Tx electrodes. The radial voltage distribution measured in the soil is given as:

$$\Phi(r) = -\frac{I_S d}{4\pi\left(\sigma^2 + (\omega\varepsilon)^2\right)}\left(\frac{\sigma\beta}{(r)} + \frac{\omega\varepsilon}{(r)^2}\right) \tag{2}$$

where I_s is the supplied current, d is seperation of the perceived point charges of a dipole, σ is the conductivity of the medium, ω is the angular frequency, ϵ is the permittivity of the medium, β is the phase constant, and r is the distance from the center of the transmitting electodes.

For an established TTS system, it is a reasonable assumption that the soil parameters such as the permittivity ϵ and the conductivity σ are fixed and not easily modified. Therefore, the key parameters easily changed that greatly impact the radial voltage distribution will be ω and I_S, the angular frequency and supplied current of the Tx respectively. Thus, a solid state Marx inverter is determined to be a suitable power supply to drive the system due to the capability to produce high voltages and their inherent fast rise times that allow for faster switching than traditional power inverters. Fig. 3 showcases an inverter topology inspired by traditional Marx inverters used in an ideal TTS system where V_{dc} is the input DC voltage,

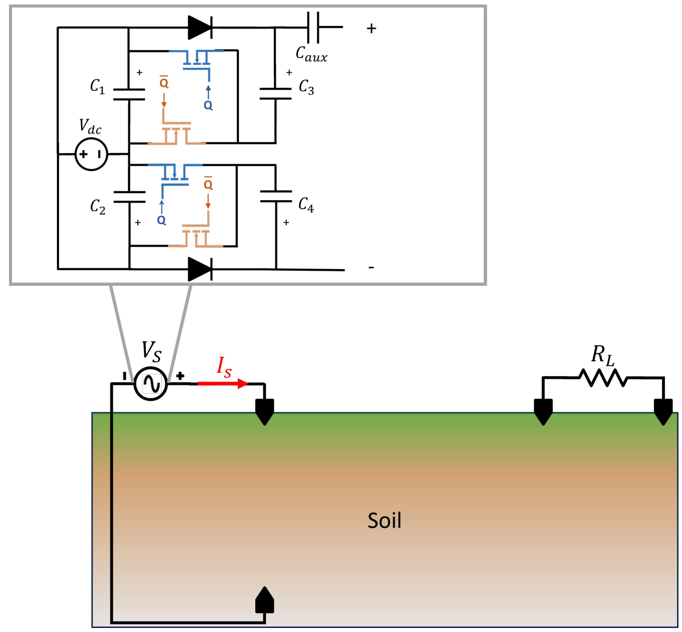

Fig. 3: Ideal TTS System with Marx Inverter as Input Voltage Source

$C_1 - C_4$ are the capacitors switched in between series and parallel configurations, Q is the switching signal, and C_{aux} is an auxiliary capacitance that influences the output waveform. Details about the influence of the auxiliary capacitance and its impact on converter design will be communicated at a later date.

According to [4]. the theoretical efficiency of a TTS system is given by:

$$\eta = \frac{P_L}{P_{IN}} = \frac{R_L u_e^2}{(Z_{Tx}(Z_{Rx} + R_L) + (u_e)^2)(R_L + Z_{Rx})} \tag{3}$$

where u_e is the lumped ”Earth impedance” which is dependent on the distance from the T_x, R_L is the load resistance, Z_{Tx} is the transmitter contact impedance, and Z_{Rx} is the receiver contact impedance. It can be seen that the contact impedance of the transmitter and receiver, Z_{Tx} and Z_{Rx}, greatly impact the power transmission range of a TTS system. Using various methods for improving electrode grounding, the measured impedance of both the T_x and the R_x can be drastically lowered leading to a significant improvement in system performance.

III. EXPERIMENTAL SYSTEM AND RESULTS

It is important to be able to validate the theoretical results of previous work in TTS systems, therefore, a prototype inverter was constructed to drive a TTS Tx and is shown in Fig. 4. While more work is needed before the inverter is fully functional, preliminary data was collected investigate the parameters discussed previously.

A. Field Voltage Gradient of a TTS Tx

To verify the impact of running a TTS system at an optimal frequency, several data points were collected radially around

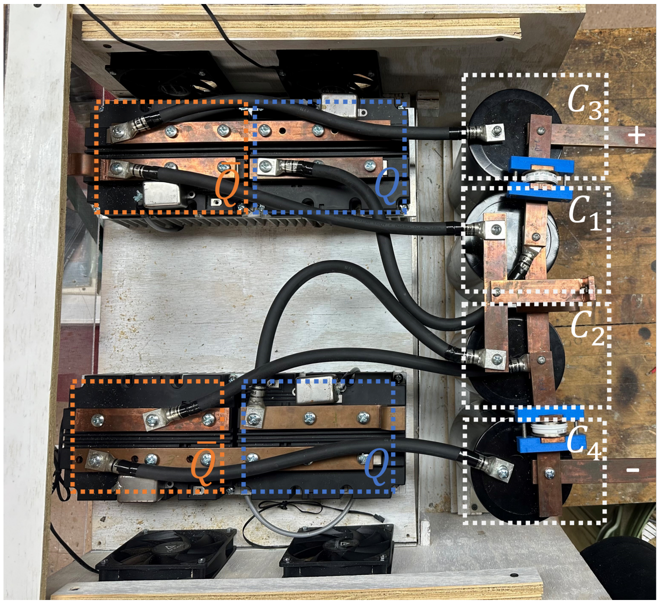

Fig. 4: Experimental prototype of the proposed Marx inverter topology shown in the inset of Fig. 3.

TABLE I: Soil Parameters

Parameters	Values
σ	0.8 mS/m
ϵ_r	4
μ_r	1

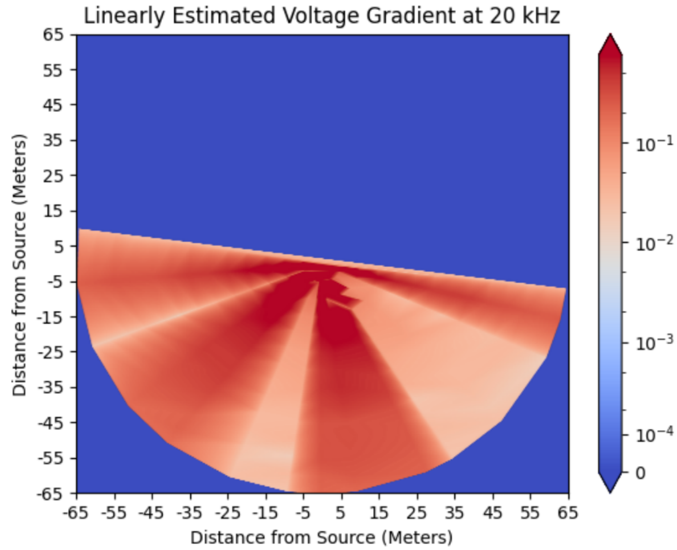

Fig. 5: Field Voltage Gradient at 20 kHz from [11] measured in a 180 degree arc around Tx.

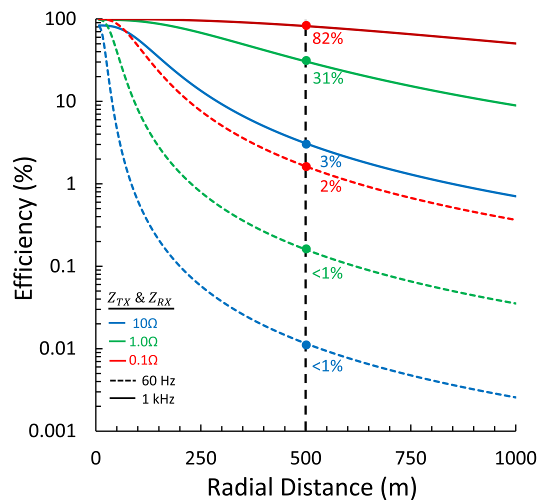

Fig. 6: Theoretical power transfer efficiency with varying impedance and drive frequency for perfectly matched Tx and Rx. Electrode separation and soil parameters are modeled after the TTS test site in [4].

the Tx using a horizontal Rx topology. The Rx electrodes were spaced 3m apart with the measurements taken at multiple angles out to a distance of 65m. The TTS system was driven at 50V peak-to-peak with at 20 kHz with the results shown in Fig. 5. Using the measurement method showcased in [11], the collected data was interpolated to produce a voltage gradient across the surface of the soil. Due to the location of the test site, only data could be recorded in a 180 degree arc around the Tx. The field voltage gradient produced highlights the impact frequency has on TTS system performance. Optimal TTS system frequencies are signals in the very low frequency (VLF) band and it can be seen that the 20 kHz drive signal produces a radial gradient that matches the theoretical model but doesn't suffer from extreme attenuation from changes in impedance. Future work seeks to continue this method of data collection for mulitple frequencies in an attempt to find the optimal drive frequency and these details will be communicated at a later date.

B. Theoretical Efficiency Improvements

For any given method of power transmission, efficiency remains one of the most important parameters to optimize. Looking into (3), the theoretical efficiency of a TTS system can be explored through simulation in order to extrapolate the future potential for a TTS system by changing the key parameters discussed previously. The circuit parameters used in the model are shown in Table 1. These circuit parameters closely matched the test site which consists of a limestone rich soil. Fig. 6 plots the efficiency as the radial distance away from the center of the TTS Tx increases. For the simulation, the current test site Tx parameters found in [4] were used and it was assumed that the Tx and Rx would be perfectly matched in impedance, topology, and electrode seperation. A load value of 50Ω was assumed for convenience. Fig. 6 illustrates how lowering the contact impedance of the Tx and Rx greatly improve power transfer efficiency for any given frequency, but increasing the drive frequency also shows significant improvements. A combination of these two methods provides the highest theoretical efficiency, with the model showing 82% efficiency at 500m away from the Tx when the contact impedance is lowered significantly and driven at 1 kHz.

IV. CONCLUSIONS

The performance characteristics of a Through the Soil (TTS) system were expanded upon and thoroughly investigated for validity. Switching converters based off of conventional Marx inverters give the ability for large supplied current magnitudes to be produced at ideal switching frequencies for TTS systems.

The Marx inspired inverter was developed and tested on an established TTS wireless power transfer system to increase the effective power transmission range. Future works seeks to verify the performance of TTS systems at different testing location to verify if similar performance parameters can be obtained and to increase the supplied current to discover the outer limits for similar systems.

V. ACKNOWLEDGMENTS

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