Investigating an Alternative System of Transmission of Electrical Energy

by
Alexander O'Sullivan

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Electrical and Computer Engineering
(Honors Scholar)

Presented May 13, 2024
Commencement June 2024

AN ABSTRACT OF THE THESIS OF

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Abstract approved:____

Roger Traylor

The famous electrical engineer Nikola Tesla developed a patent for a wireless power transmission system, designed to transfer large amounts of power across large distances. This technology has heretofore been only marginally explored, and such explorations have focused on circuit and impedance analyses rather than power transmission analyses. A variation of this patent, designed for a low power and high frequency input, was prototyped with a focus on mirroring the original patent diagram as much as possible. Experiments were then conducted on this prototype to determine the power transmission capabilities of the system and derive trends. The results of these experiments were as follows: (I) The transmitted voltage decays in a 1/D^1.57 relationship at short range (where D is the distance between the transmitter and receiver), but then rapidly increases and fluctuates at mid-range, before eventually decaying slowly and linearly at long range; (II) The power transfer efficiency of the system is low, with an average of 16.6%. These results demonstrate that this wireless power transmission system design is functional, but is not viable in its current state. Further research needs to be conducted on a larger scale in order to make it more viable, particularly with regards to the mechanism of transmission, which is still unknown.

Keywords: wireless power transmission, WPT system, energy systems, Nikola Tesla

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Honors Baccalaureate of Science in Electrical and Computer Engineering project of Alexander O'Sullivan presented on May 13, 2024.

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Alexander O'Sullivan, Author

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Introduction

Background

Nikola Tesla

Nikola Tesla (1856-1943) was a Serbian-born American electrical engineering who pioneered several inventions that have shaped our modern society. Such inventions include alternating current power generation and distribution, hydroelectric power (e.g. Niagara Falls), three phase electric power, brushless high speed induction motors, radio transmission, and fluorescent lighting, just to name a few. During his life, Tesla was regarded as a celebrity due to his inventions, lighting the 1893 Chicago World Far, and having a unit of measure named after him as a testament to the impact he made within the field of electrical engineering. One high school textbook of the era [1] (published while Tesla was alive and in his 40's) even dedicated an entire section to Tesla's inventions. In stark contrast, today, if a high school student were to be asked regarding the name Tesla, they would most likely think of Elon Musk's electric car company rather than the man. Thus, as impactful as his life and works have been, Tesla and his work have fallen into obscurity in the public consciousness.

As transformative as some of Tesla's inventions have been, there are many other of his inventions that have been largely forgotten that range from the mundane to the incredulous: aquarium installations [2], novel fountain designs [3], unidirectional valve-less fluid conduits [4], vertical take-off and landing aircraft [5], remote controlled boats [6], automatic ship's log devices [7], etc. Among these patents can be found a series detailing the wireless transmission of electric power.

Tesla's Wireless Power Transmission (WPT) System

In 1897, Tesla applied to the U.S government for a patent [8] detailing a means of transmitting electrical power wirelessly across a large distance. His 1899-1900 Colorado Springs engineering notes [9] detail experiments and observations made with a series of prototypes for this invention. These notes include, among other things, photographs of large coils of varying designs and, perhaps most notably, light bulbs out in a field being lit only by energy supplied through one of these coils (the transmitter being miles away in his laboratory).

If the wireless power transmission (WPT) system works as Tesla described, then this invention is remarkable for a number of reasons.

- The wireless transmission of energy would reduce the environmental impact and cost of a wired power grid network.
- Transmitting power from a remote location to any other desired point would provide a huge benefit into the transmission and distribution of renewable energy sources such as wind and solar, which necessarily must be located wherever sunshine or wind is available.
- The possibility of transmitting power directly to appliances such as an electric vehicle or device would reduce or outright remove the reliance on environmentally harmful batteries.

Objectives

Sufficiently motivated by the potential benefits, it is first necessary to investigate whether or not Tesla's WPT system has any merit at all. Is it capable of long distance, efficient power transmission without the use of wires? This thesis will test the viability of this WPT system design by recreating a scaled version of this system and testing its transmission range and power transfer efficiency.

Reconstruction will be on a smaller scale due to available time, equipment, and resources. Because of this, this thesis will not be a full verification of Tesla's patent specifically. Tesla's patent and related claims focused on high voltage and low frequency signal transmission; reconstructing that system and verifying Tesla's claims in relation to a high-voltage input is not reproducible with available time and resources. This thesis will instead focus on low voltage, high frequency transmission. Justification for this focus is detailed in the Design section.

Past Studies

There have been several studies that covered the nature of wireless power transmission systems, especially systems that involve resonant induction like Tesla's patent, and explore various facets of implementation.

Plaizier

An example of such a study is one done by Gregory Plaizier from University of Utah [10], who focused on designing and building a WPT system to power electronics at range. Specifically, they simulated and constructed a resonant inductive coupling WPT system to power a drone while it was hovering in the air. They were able to successfully accomplish this, and the drone was able to hover 114mm in the air while remaining wirelessly powered. This study is one of many similar studies to focus on resonant inductive coupling between coils as the primary form of wireless power transferal. This is a valid line of study, and Tesla's WPT system does utilize similar principles, but it is not a full exploration of Tesla's system.

Keskin

In terms of exploring Tesla's patent specifically, there has been some research into it. A common trend among these studies, however, is a focus on circuit and impedance analysis. An example of circuit analysis is a study conducted by Nurcan Keskin from Oregon State University [11], who conducted an analysis of the RF properties of Tesla's WPT system. Keskin condensed Tesla's patent into an equivalent circuit, and then conducted tests and simulations to determine the effects of capacitor tuning on that circuit, designed a suitable class E amplifier for the system, and designed a suitable antenna array. This is a useful analysis, but it's on a very small scale, with distances of a few inches. There was no analysis of transmission over any distance.

Tucker

An example of impedance analysis is a study conducted by C.A Tucker from University of Reading [12]. Much like Keskin, they created an equivalent circuit and even built a prototype of Tesla's system. He focused heavily on calculating and measuring the impedances of the WPT system, as well as plotting the magnetic field intensity and flux density using simulation tools. This is great research, but the focus is exclusively on impedance and efficiency. Their measurements are all within 2 meters and it is unclear what their input power is or what their construction process is, which makes it hard to gauge the efficiency.

Based on the trends reflected by these studies, while there is significant interest in WPT systems, there is minimal research on Tesla's WPT system specifically, and such research tends to be focused on small-scale capabilities of the system, with low range and low power. There is very little accessible research about Tesla's patent that focuses on the range and power capabilities of his WPT system. This exposes a gap in current research, a gap that this thesis shall attempt to fill.

Design

Patent Analysis

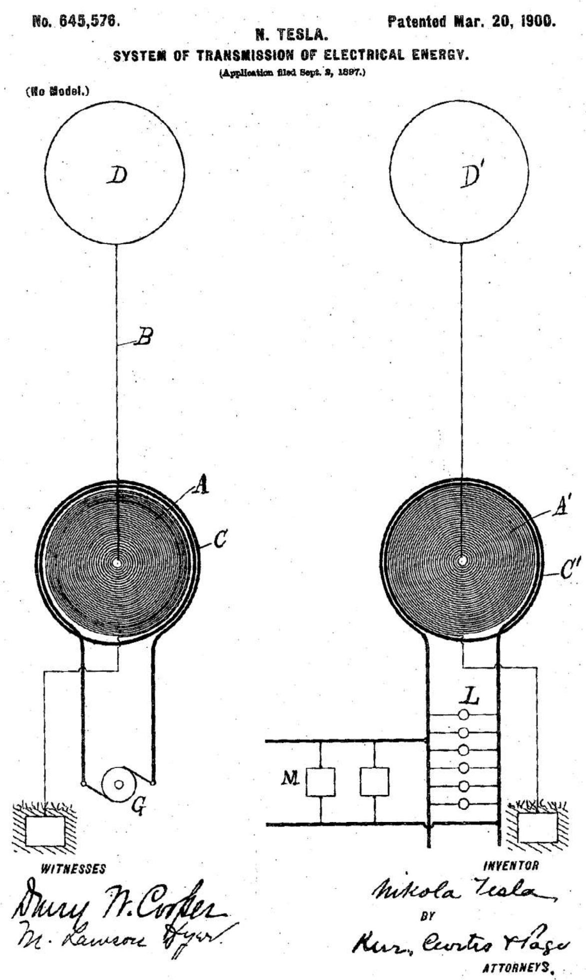

Figure 1: Nikola Tesla's Patent No. 645576

Figure 1 is a conceptual diagram of the WPT system proposed by Nikola Tesla. It is an apparatus consisting of two nearly resonant induction systems, one on the left-hand side and the other on the right, drawn as the mirror image of the first.

An examination of the diagram and the accompanying text reveals a design with many unique characteristics. First, the coils of each resonant induction system consist of a primary (labeled C) and secondary coil (labeled A). Both coils appear to be flat, wound as an Archimedean spiral, of many turns. Adjacent to the secondary is an outer primary coil (C), also flat and Archimedean in nature, but of only a few turns. This appears to be a variation on the classic set of cylindrical/solenoid coils found in standard transformers (see Figure 2 for a visual depiction). Why Tesla specifically chose flat spiral coils rather than cylindrical coils is not clear, and the patent provides little explanation. The primary coil (C) is connected directly to a source of alternating current (G). The secondary (A) is connected from the center of the spiral up a long wire (B) to a terminal suspended above the ground, and, at the other end, from the outer ring of the secondary coil down to a connection to earth.

This apparatus is then mirrored in a second almost identical system, composed of primary (C') and secondary (A') coils, wire (B') and terminal (D'). The terminal (D') runs down through the wire (B') to a coil of many turns (A', identical in geometry to the secondary described earlier A), and then to earth; next to this coil is a coil of fewer turns (C', identical in geometry to the primary described earlier C), which then drives several loads represented in the diagram as lamps (L) and motors (M).

At first glance, this WPT system utilizes resonant inductive coupling. Applying an alternating current in the primary coil (C) induces, through magnetic induction, a stepped-up voltage in the secondary coil (A). Somehow, and by a means not explained, Tesla claims that a current will be induced in the remote coil (A') by a form of sympathetic resonance (between A and A'), which, after inducing an alternating current in the smaller coil (C'), is stepped down to drive the remote loads. The common earth is the important third component that makes the resonance circuit complete.

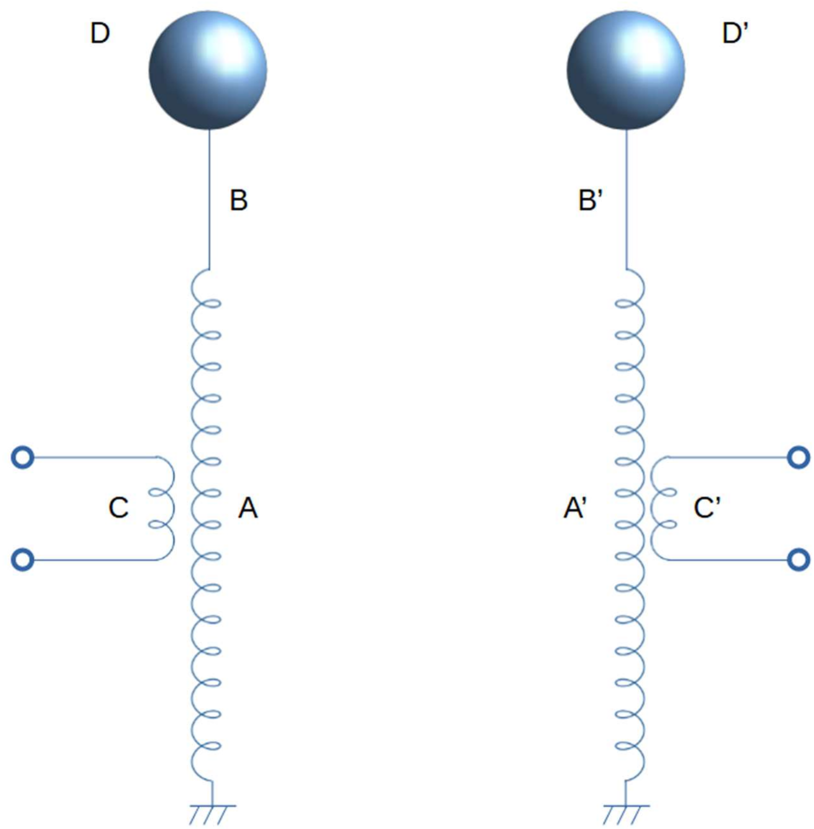

Figure 2: WPT System with redrawn primary and secondary coils to reflect transformers.

Approach

With this design in mind, the first goal was to reconstruct a prototype that matched this WPT system design as accurately as possible. If this WPT system design had any merit, then a prototype that matched Tesla's design would be capable of transmitting power, even if just for a low power application such as lighting a couple of LEDs. The next goal would be to conduct further tests to determine the system transmission range and power transfer efficiency, and thus determine the viability of this WPT system design. If this WPT system design did not have any merit, and it was incapable of any power transfer, then further experiments would not be necessary, and this WPT system design could be classified as non-functional.

Due to available resources and measuring equipment, the focus of this research was based on lower voltage, lower power, higher frequency input signals. The exact outcome of this approach was unknown when construction and testing began. While Tesla made several claims based on a high-power, high-voltage input for industrial applications, there are several elements of the system (such as the resonant frequency, which will be detailed in the Construction section) that are scalable to a smaller system. As such, an open-minded approach was adopted.

Construction

For the sake of external verification, the exact construction process of the prototype is documented below.

The first challenge in construction is to recreate coils matching those in the Tesla patent. Naturally, Tesla's design focuses on high power and low frequency transmission, where the coils consist of many hundreds of meters of windings. This is not feasible for the scope of this thesis, but higher frequency coils, like the ones developed for the prototype, would be much smaller and thus more feasible to develop. The challenge posed is how to reliably and repeatedly construct two secondary windings (A and A') of matching inductance, along with two matching outer primary windings (C and C').

Physical wire windings present a significant difficulty. Holding the wires precisely in place both during construction and use wis a feat that would need to be achieved twice. The "fiddly" nature of handling loose wires and the human errors introduced as a result would adversely impact accuracy and repeatability. It was desired to reduce variance between the two coils as much as possible. Therefore, after some fruitless attempts, a different strategy was determined: a printed circuit board. Using lithographic techniques, a coil design could be reliably and accurately reproduced as many times as needed.

The A and C coils in the patent have a 10:1 coil turn ratio, as there were 20 turns of the A coil compared to 2 turns of the C coil. The design doubled these values, so the A coil would have 40 turns and the C coil would have 4 turns, which maintains the 10:1 ratio. A design for this coil was then made with this information in mind.

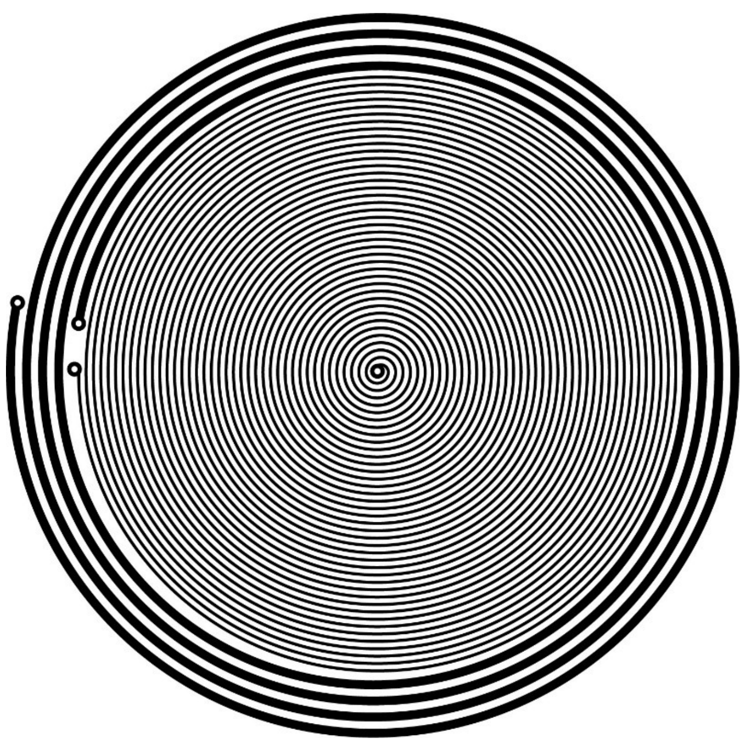

Figure 3: The primary and secondary coil artwork.

The patent includes an equation relating the resonance frequency to the length of the inner coil (A and A'). Explicitly, this equation is [8]:

$$l = \frac{\lambda}{8} = \frac{c}{8f}, or\ f = \frac{c}{8l} \tag{1}$$

In this equation, l = inner coil length in meters, λ = wavelength in meters, c = speed of light ($3 * 10^8$ m/s), and f = resonant frequency in Hz. This equation is slightly modified compared to the original equation, which claimed that $l = \frac{\lambda}{4}$. Tesla's patent uses "cycles" as a unit of frequency, which was the common conception of frequency during that time [13]. In comparison to Hertz, 1 Hz would equal 2 "cycles" [14]. Hence, the equation was modified accordingly.

This is a scalable equation, and thus should still be applicable for this design, which is essentially a scaled down version of Tesla's patent. A simple test was done after prototype construction to verify this, which is detailed at the end of this section.
The length of the inner coil can be calculated by using this equation [15]:

$$l = \pi * N * \frac{(OD + ID)}{2} \tag{2}$$

In this equation, N = number of turns, OD = outer diameter of the coil, and ID = inner diameter of the thin coil. The inner diameter of the thin coil for this design was measured to be about 2.5mm, the outer diameter was measured to be 101.6mm, and there are 40 turns. Using Equation 2, the length of the thin wire coil was found to be:

$$l = 40\pi * \frac{101.6mm + 2.5mm}{2} = 6540.8mm = 6.5408\ meters \tag{3}$$

This value was verified by using a vector graphics application, which has a feature to perform this calculation automatically, giving 6.5404m, which is a negligible deviation. Plugging this value into Equation 1, the resonant frequency was calculated to be:

$$f = \frac{3 * 10^8\ m/s}{8(6.5408)\ m} = 5.729MHz \tag{4}$$

Figure 4: Coil design imprinting.

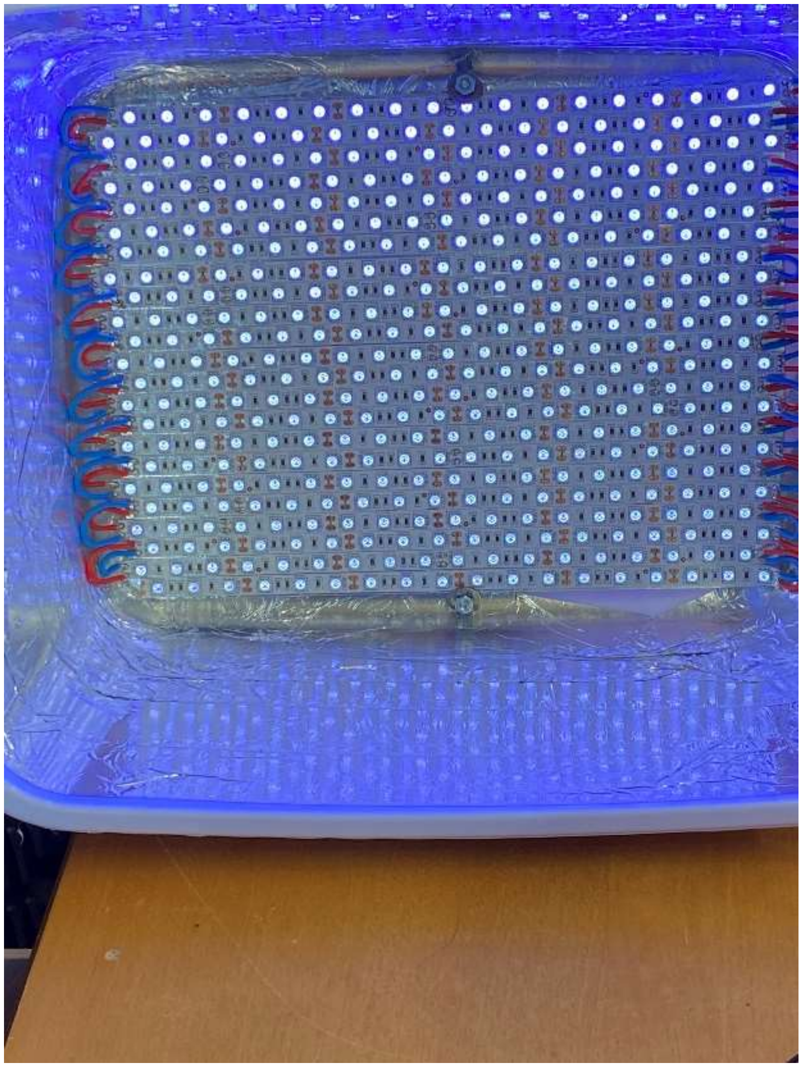

Figure 5: UV radiation chamber used for lithographic exposure.

The design in Figure 3 was printed onto a transparency using a Canon ink jet printer, with maximum contrast and application of black ink. A single sided copper clad board coated in a UV light sensitive lacquer was used. The artwork (Figure 4) was pressed down on the board with a glass panel. The board was then placed into a rudimentary ultraviolet radiation chamber (Figure 5) and exposed for 90 seconds. After this, the board was submerged into the positive developer for a few seconds before being rinsed in water. The board was then submerged into ferric chloride to etch the design into the board. Finally, the board (Figure 6) was rubbed with acetone and then cleaned again. This process etched the coil into the circuit board, successfully constructing the coil design.

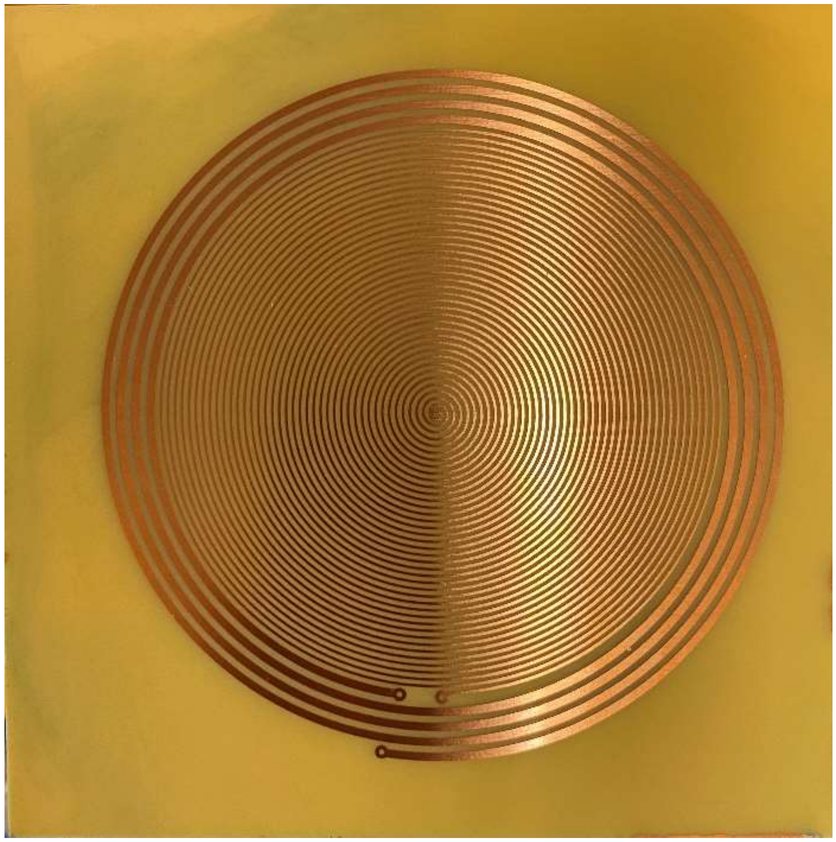

Figure 6: Constructed coil.

This process was then repeated with a flipped design to match the mirrored network. Following this process resulted in two identically mirrored coils, labeled sections A and A'. These coils consist of the inner/thin wire coil (A and A' in the patent) and the outer/thick wire coil (C and C' in the patent).

With the coils designed, attention was then directed to the terminals. Tesla's patent shows spherical terminals (D and D') connected to the inner coils by wire (B and B'). Hollow metal spheres with a diameter of 10 centimeters were acquired [16]. The wires were attached to the spheres with self-tapping screws.

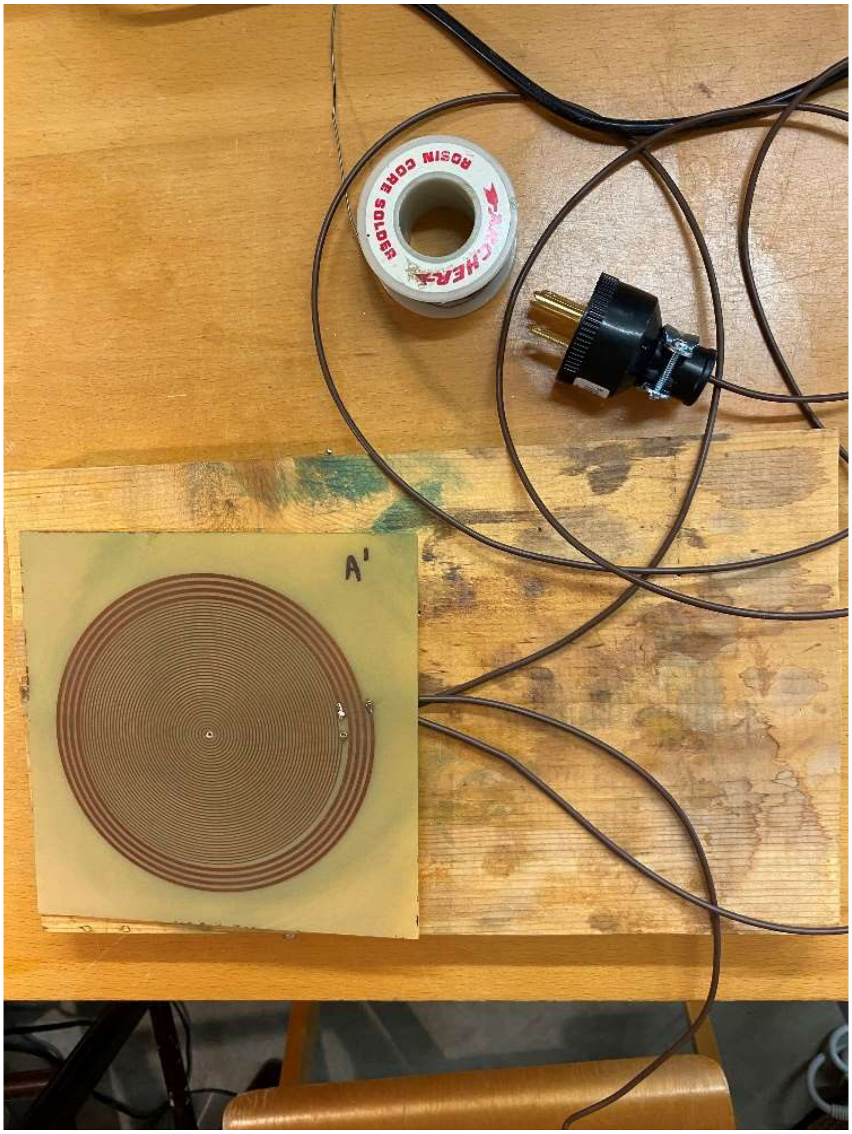

Figure 7: Wire connections to coil.

Wire was used to connect these spheres to the inner coils. Likewise, wire was soldered to the outer coil connections to allow for load and input attachment. Tesla's patent specifies that the thin wire coils should be connected to common ground. A direct earth connection was not possible in the main testing environment, so a wire was used to create an artificial groundline between the coils. This eliminated any potential complications from the system not having a common ground (as detailed in the Distance Tests section). This resulted in a completed prototype, shown in Figure 8.

With the WPT system constructed, a simple test was conducted to determine if it was functional. Two LEDs were connected together in parallel so that they would light up regardless of current direction. The signal generator was then connected to the primary coil of the transmitter board of the WPT system, while the LEDs were connected to the primary coil of the receiver board. The terminals of the "transmitter" and the "receiver" were placed about 2 meters apart, and a frequency sweep was performed until the LEDs lit up brightly. This occurred at about 5.7MHz, which matched the calculated resonant frequency found in Equation 4 and thus verifies the scalability of Equation 1.

Figure 8: Final constructed system.

Experimentation

With promising results in the initial test of the prototype's functionality, further experiments were devised to test the transmission range and power transfer efficiency. These tests are as follows:

1. Distance Tests: Explore how the power transmission varies with distance between the transmitter and receiver.
2. Power Tests: Determine the power transfer efficiency of the system.

Distance Tests

Objective: Test the effective range of the scaled WPT system and its ability to transmit useful power over distance.

Procedure:

The transmitter and receiver of the scaled WPT system were initially positioned 10cm from each other. Once positioned, the A coil was connected to the signal generator, while the A' coil was connected to the oscilloscope. The signal generator was set to perform an automatic frequency sweep using a 10-volt peak-to-peak (10Vpp) signal, ranging from 1kHz to 20MHz. The results of this frequency sweep were captured by the oscilloscope. Maximum voltage and approximate resonant frequency were noted. The transmitter and receiver were then moved 20cm apart, and the experiment was repeated. The tests were repeated at 10cm intervals to 1m. After 1m, the terminals were moved in 1m steps. This continued until 20m. This maximum distance was determined by the following factors:

a. It was discovered early in testing that if the WPT system didn't have a shared ground, then there would be no power transmission. The easiest way to guarantee a common ground connection between the transmitter and the receiver was to establish a representative groundline with a single length of copper wire. 20 meters was the longest length of wire readily available. This wire had a resistance of about 0.66Ω at DC and about 3.3Ω at 5.7MHz due to the skin effect of AC current, which was considered negligible.
b. The tests were carried out indoors, and 20 meters was the maximum reachable distance without too much line-of-sight obstruction. A clear line of sight means an unobstructed path between the terminals (no walls or doors or other obstacles, only open air).

Results:

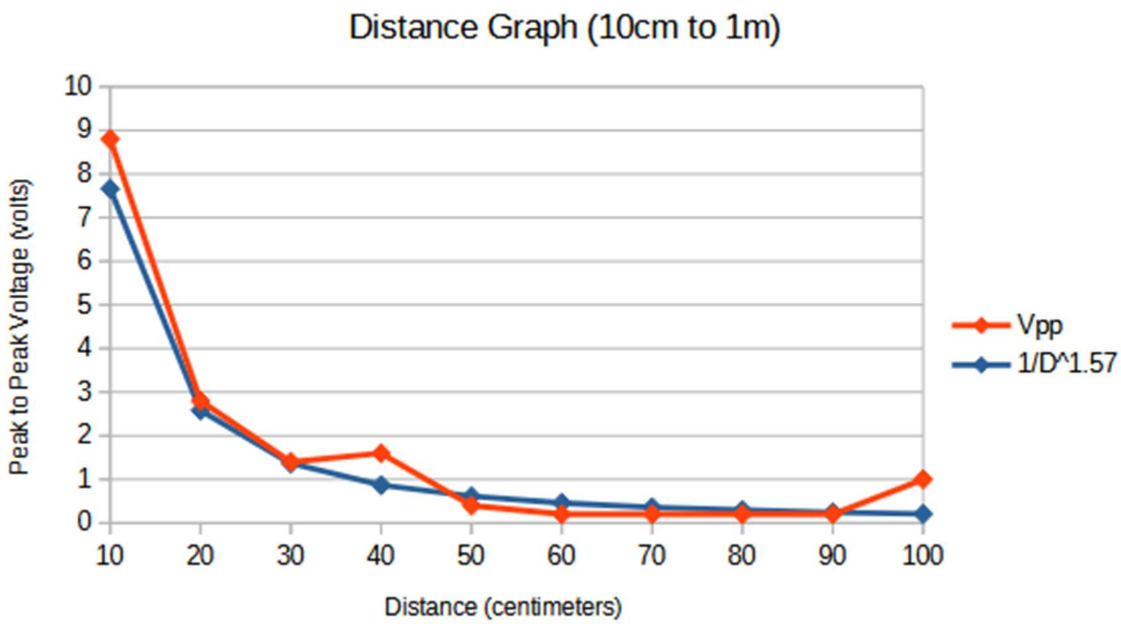

Figure 9. Distance Graph (10 to 100cm) compared to a power regression analysis that represents a 1/D^1.57 distance dependence.

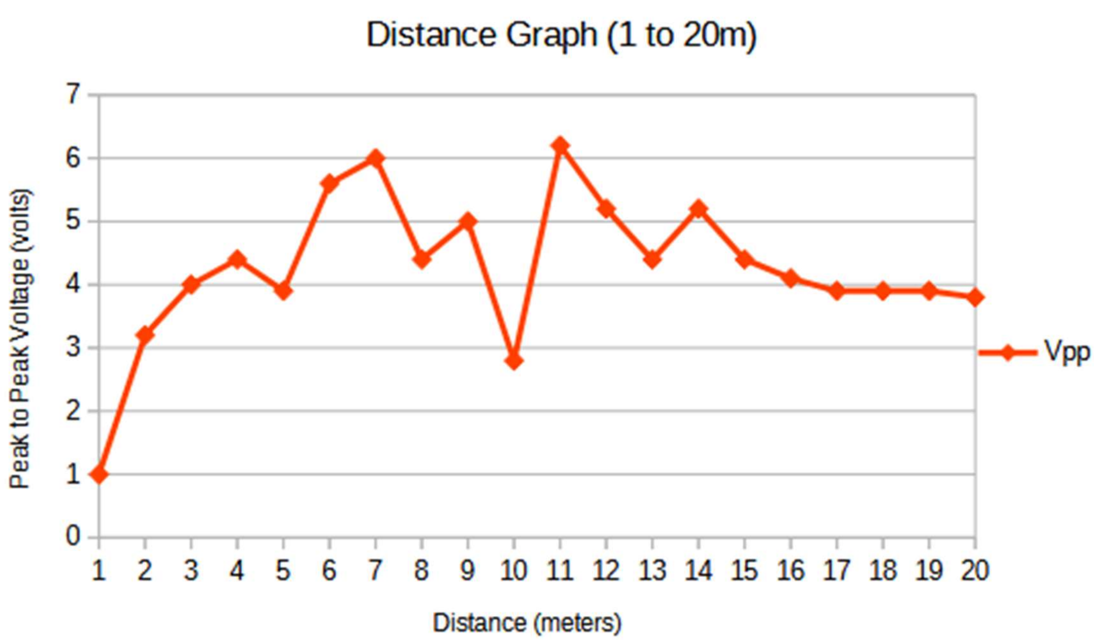

Figure 10. Distance Graph (1 to 20m).

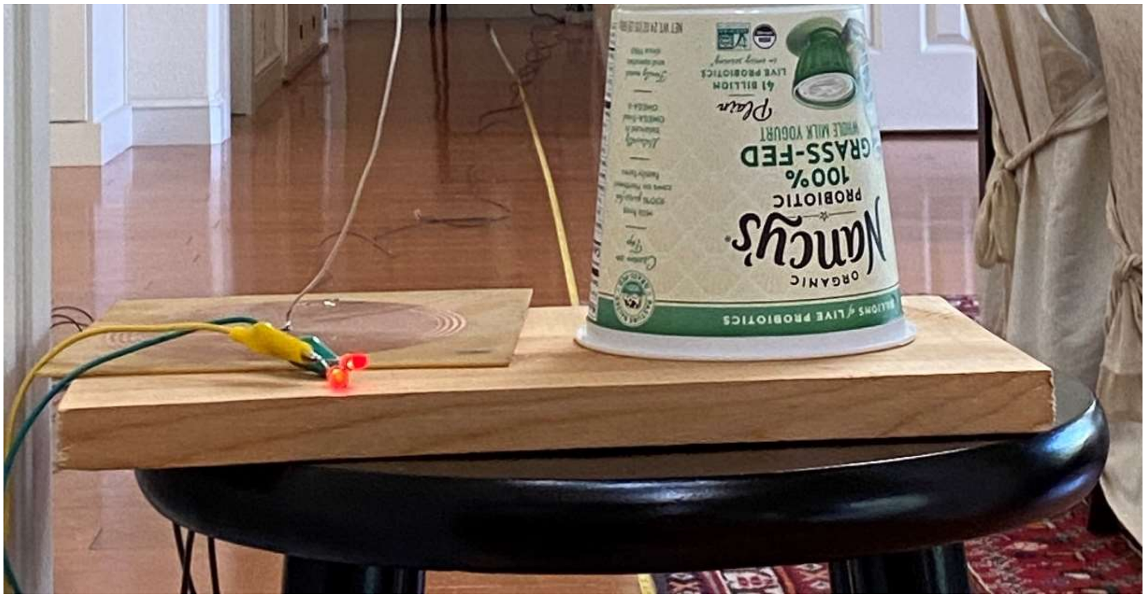

Figure 11. LED load connection at 12 meters.

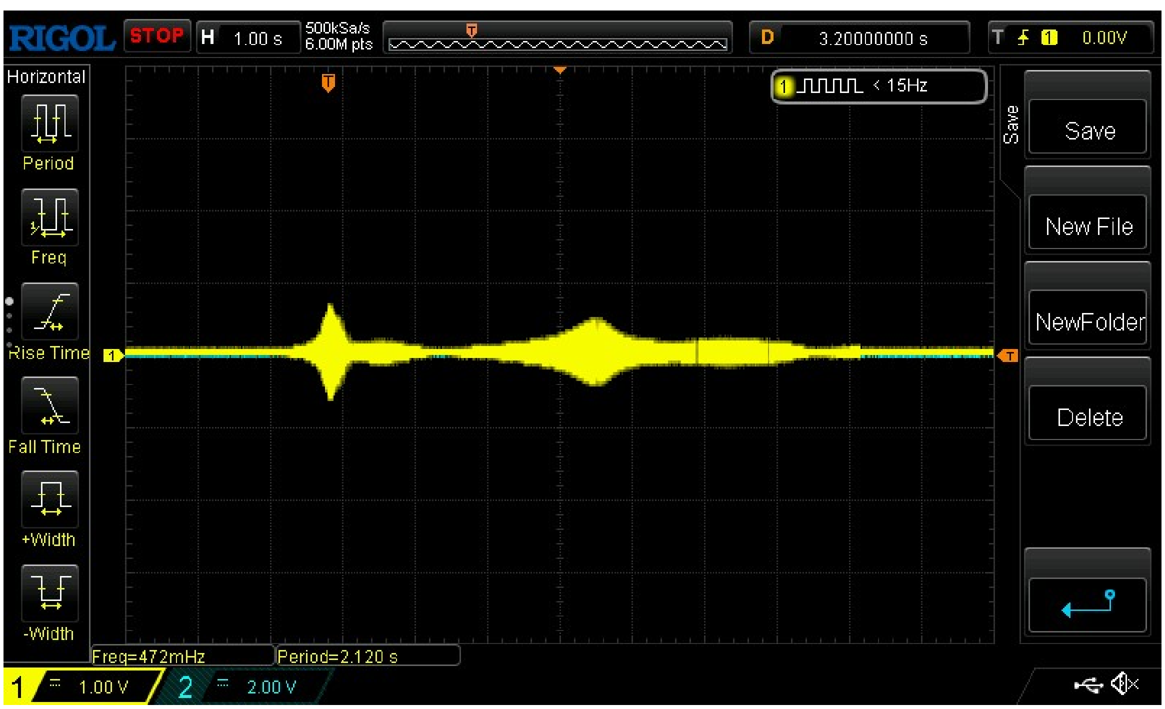

Figure 12. Frequency sweep results with 40cm separation. Horizontal axis is frequency (1KHz – 20MHz, 1.66MHz per division), vertical axis is voltage. Peak voltage of 1.6Vpp at 5.7MHz.

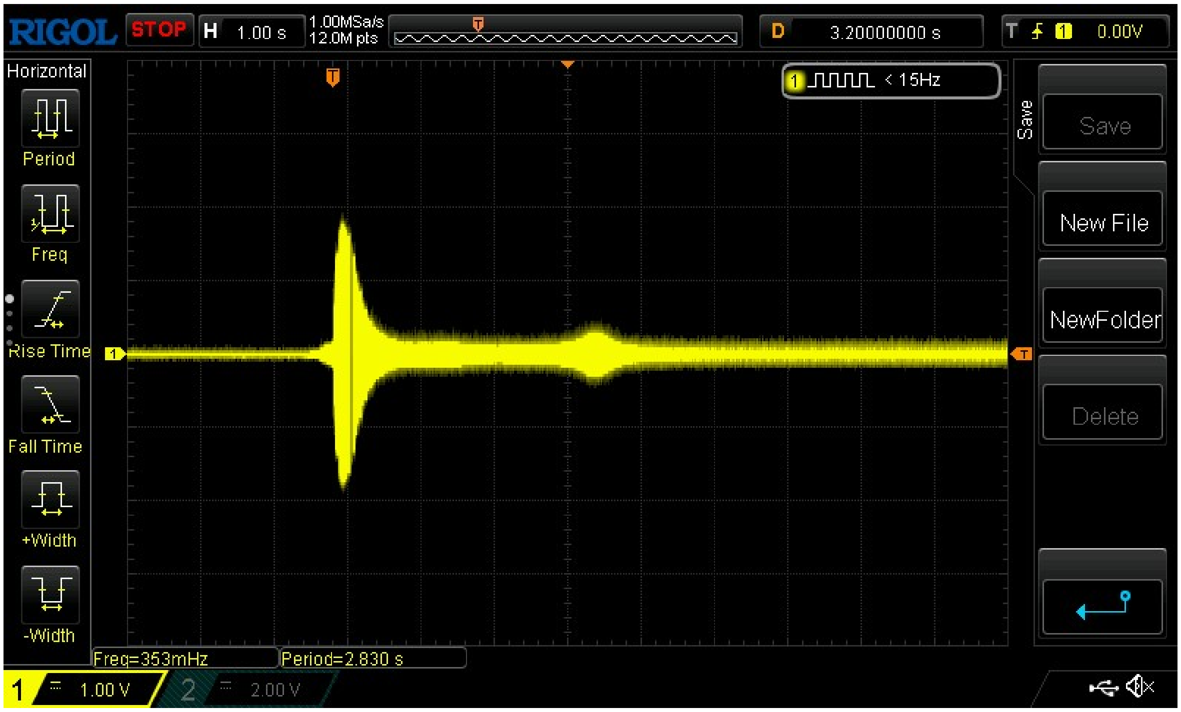

Figure 13. Frequency sweep results with 20m separation. Horizontal axis is frequency (1KHz – 20MHz, 1.66MHz per division), vertical axis is voltage. Peak voltage of 3.8Vpp at 5.7MHz

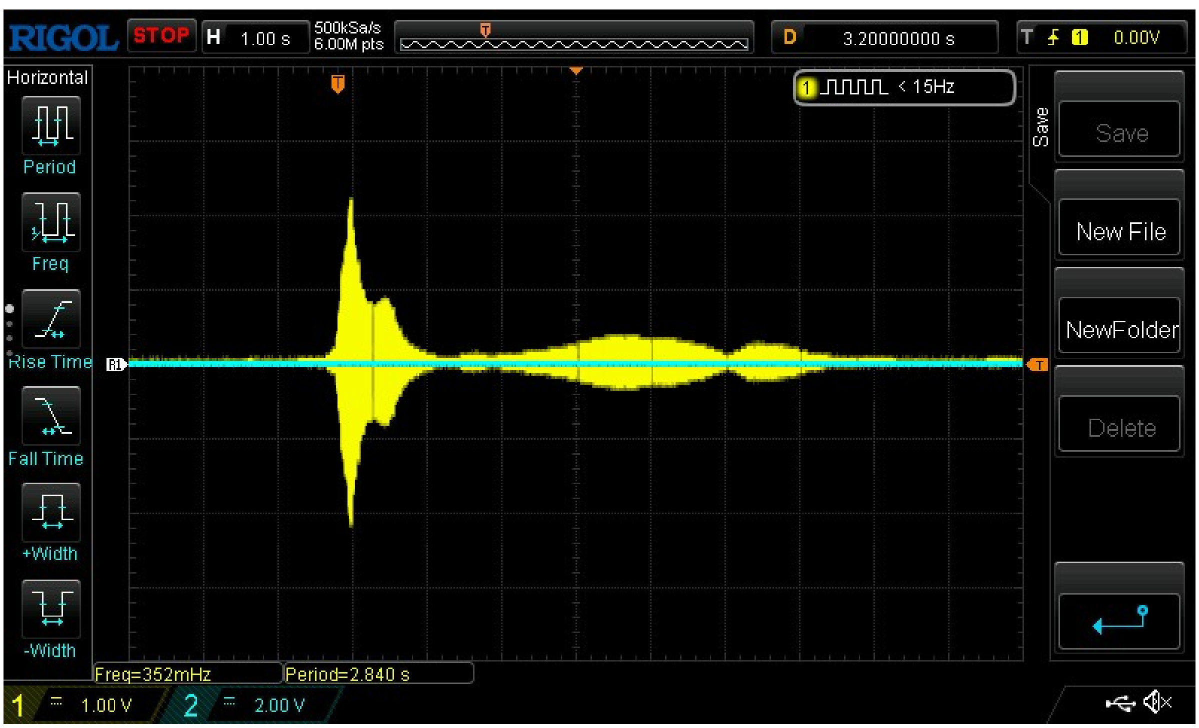

Figure 14. Frequency sweep results with 4m separation. Horizontal axis is frequency (1KHz – 20MHz, 1.66MHz per division), vertical axis is voltage. Peak voltage of 4.4Vpp at 5.7MHz, blue waveform represents 0Vpp.

Across the full set of distances, the system exhibited three regions of transmission: short range (0-1 meters), mid-range (1-15 meters) and long range (15+ meters). For short range, the scaled WPT system received voltage amplitude decreases at 1/D^1.57 distance relationship, as can be observed from Figure 9, with a coefficient of determination of 0.734. However, upon entering mid-range, the voltage amplitude begins to rapidly increase and then fluctuate, as seen in Figure 10. At long range the voltage amplitude no longer fluctuates and stabilizes to a 4 Volt peak-to-peak signal. Further increases in distance resulted in little to no change, with a trend towards a very slight linear decrease in signal voltage amplitude with distance. The position of the coils relative to the terminals did not have any noticeable effect on the voltage amplitude.

The resonant frequency at which the voltage is at its peak, as can be observed in Figures 12, 13, and 14, appears to consistently be 5.7MHz, regardless of distance. This value was verified at 12m and 20m by connecting LEDs at the receiving end and observing the brightness. This can be observed in Figure 11. There also appears to be a second resonant peak at about 11.5MHz, which is exactly double the resonant frequency. This second peak was most noticeable in the lower distance ranges and at 4m when the signal is in flux, observable in Figures 12 and 14.

Power Tests

Objective:
Determine the power transfer efficiency of the system.

Procedure:
The signal generator was set to generate a 10Vpp sine wave signal at 5.7MHz. This signal was connected to the transmitter of the WPT system. A 55.3Ω resistor was connected to the receiver of the scaled WPT system, which was in turn placed 4 meters apart from the transmitter. The oscilloscope was first used to measure two waveforms: the waveform directly from the signal generator and the waveform as it connects to the transmitter. These waveforms were compared to calculate the phase difference. The input current was then calculated, and the result was used to determine the real input power into the WPT system. The oscilloscope was then used to measure the waveform across the load resistor. This waveform was then used to calculate the output current and power. The two powers were compared to determine power transfer efficiency.

Equations and Definitions:
The source resistance R_S was measured to be 58.3Ω using a DMM, which represents both the 50Ω of the signal generator and the resistance of the BNC coaxial cables used to connect the signal generator the scaled WPT system. The load resistor R_L was chosen to be 55.3Ω due to a combination of available resources and the Maximum Power Transfer Theorem (MPTT) [17]. The Maximum Power Transfer Theorem states that the maximum power transfer occurs when $R_L = R_S$. Assuming a 14.14Vpp input, as an example, the output power can be calculated to be 107.2mW if $R_L = R_S = 58.3\Omega$. If $R_L = 55.3\Omega$, then the output power would be 107.1mW. This is a 0.09% deviation from maximum, which is small enough to be considered negligible for this test.

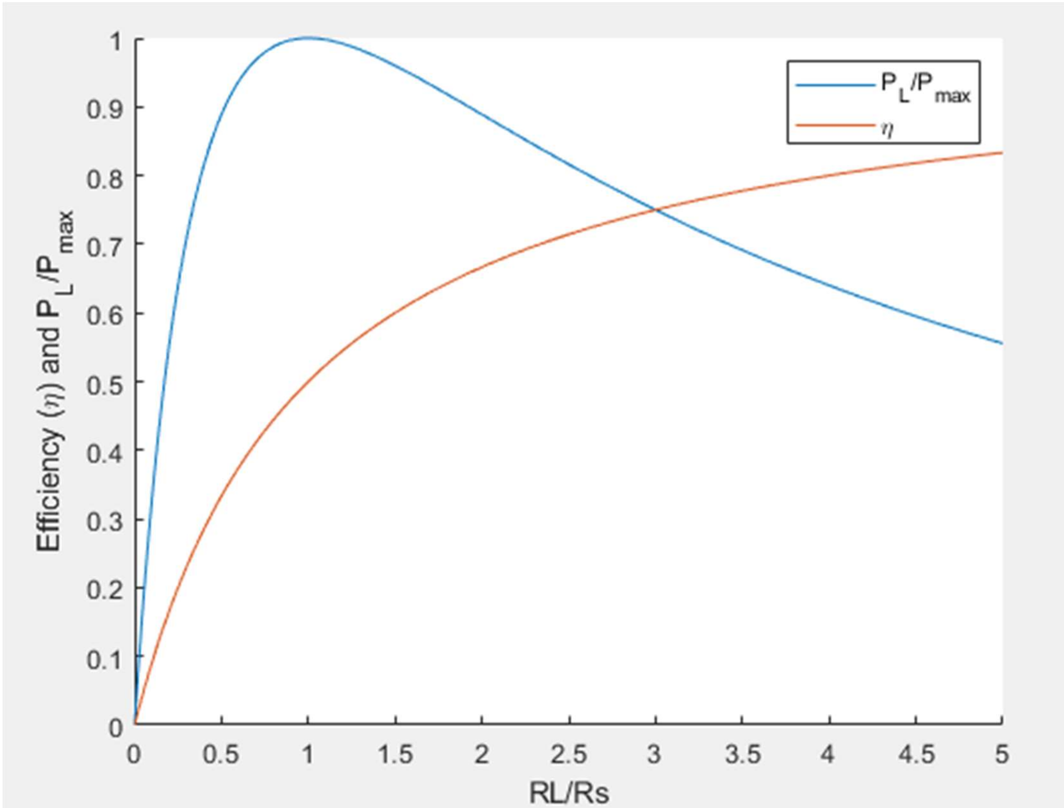

Figure 15. MPTT graph showing the effects of load and source resistance on maximum power transfer (blue line) and power transfer efficiency (orange line).

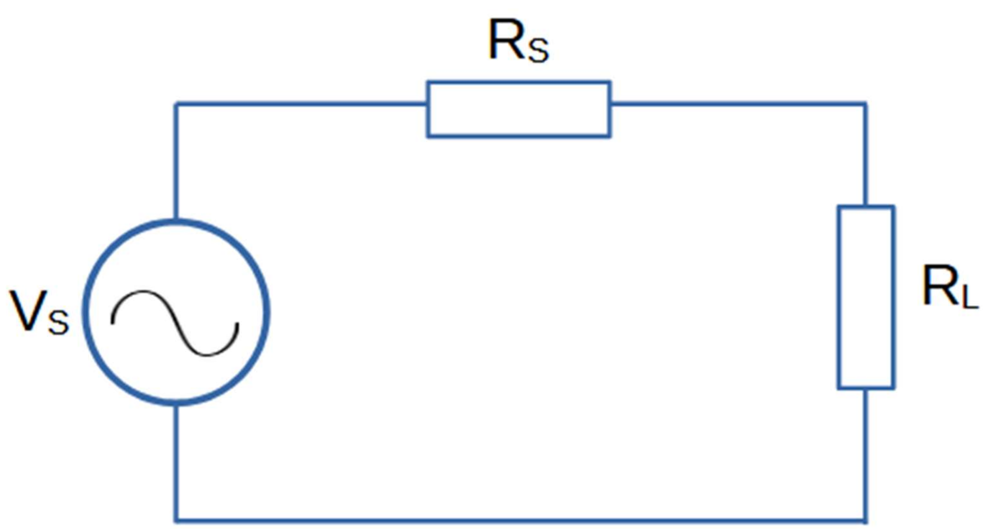

Figure 16. Basic voltage divider diagram that MPTT is based on.

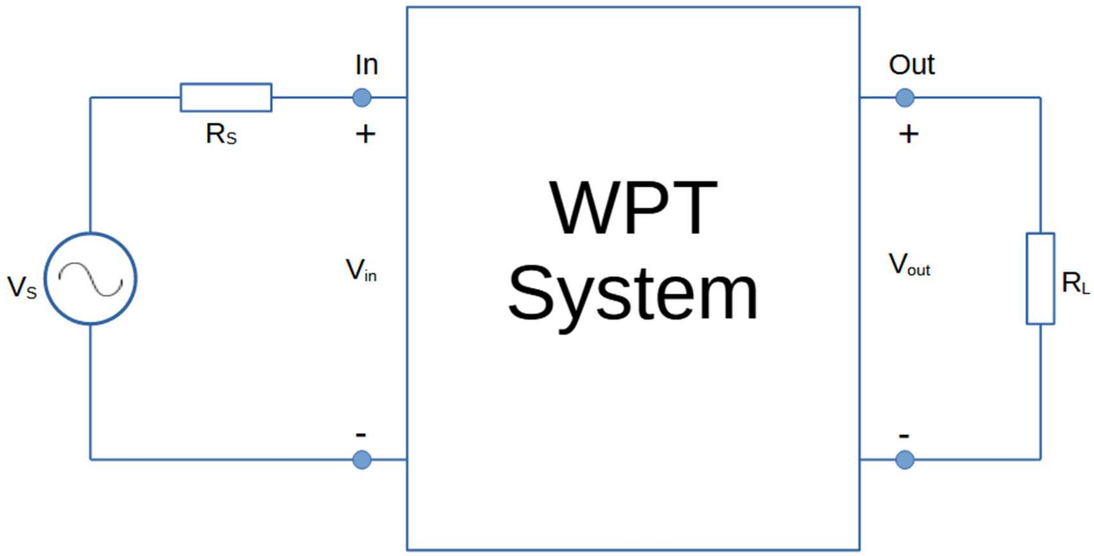

Figure 17. Equivalent circuit of WPT system with marked input and output terminals.

In order to calculate the input power P_{in}, the input voltage V_S and the input current were measured, with V_S being converted from peak-to-peak to RMS to get the average AC value. The real input power was then calculated using Ohms law [18] and the measured phase difference θ:

$$P_{in} = Re\{VI^*\} = Re\left\{V_{in} * \left(\frac{V_S - V_{in}\cos(-\theta)}{R_S} - \frac{jV_{in}\sin(-\theta)}{R_S}\right)\right\} = V_{in} * \frac{V_S - V_{in} * \cos(-\theta)}{R_S} \quad (5)$$

In order to measure the output power P_{out}, the voltage across V_{out} was measured and converted to RMS. This was used to calculate the output current and then the output power using Ohms Law.

$$P_{out} = I^2R = \left(\frac{V_{out}}{R_L}\right)^2 * R_L \quad (6)$$

In order to determine the power transfer efficiency η, the output power P_{out} is divided by the real input power P_{in}:

$$\eta = \frac{P_{out}}{P_{in}} \quad (7)$$

Results:

Figure 18. Voltage waveform measured at input (10Vpp input). Blue waveform is when the signal is not connected to WPT system, yellow waveform is when the signal is connected to WPT system. Horizontal axis is time, vertical axis is voltage.

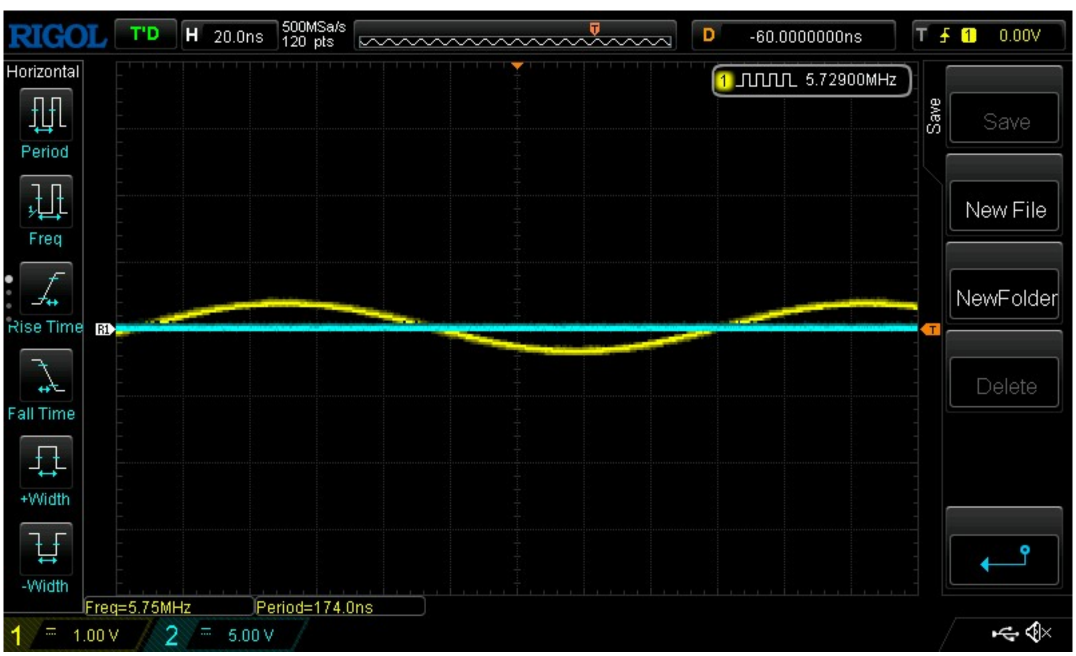

Figure 19. Voltage waveform (yellow waveform) measured across load resistor connected to receiver of WPT system (10Vpp input). Horizontal axis is time, vertical axis is voltage, blue waveform represents 0Vpp.

TABLE 1

POWER TEST RESULTS

Test Voltage (Vpp)	Input Voltage (Vpp)	Phase Difference (θ, degrees)	Input Current (mA, rms)	Input Impedance (Ω)	Input Power (mW)	Output Voltage (Vpp)	Output Current (mA, rms)	Output Power (mW)	Power Transfer Efficiency (%)
10	8.96	-8.64	10.7	191.44-j225.7	21.933	0.8	5.115	1.447	6.597
12	11.4	3.70286	5.852	445.23+j525.49	15.247	0.96	6.138	2.083	13.662
14	13.7	2.88	4.597	441.14+j956.98	9.32	1.1	7.033	2.735	29.346
16	15.6	2.46857	4.788	604.82+i980.48	13.863	1.22	7.8	3.364	24.266
18	17.2	4.93714	10.394	294.9+j505.33	31.856	1.38	8.823	4.305	13.514
20	19	4.52571	11.13	348.2+j492.83	43.151	1.52	9.718	5.222	12.102

The average power transfer efficiency of all the tests was calculated to be 16.6%. This efficiency is low; a 60.31mW input is necessary just to transfer 10mW.

The fluctuations in measured phase difference, input impedance, and efficiency were not expected. This WPT is a linear system, and the source and load resistances did not change between tests. As such, phase difference and efficiency should have remained constant values. The most probable cause of these fluctuations is due to measurement difficulties. Accurately measuring the phase difference at such a high frequency requires a high degree of precision, as it is necessary to be able to measure picosecond differences in a signal with a period of 172 nanoseconds. The oscilloscope used lacked this precision. More accurate measurements could have been procured through the use of higher precision tools such as a vector network analyzer, but such equipment was not available during the timeframe of these tests.

Analysis and Discussion

There are several notable observations to be made based on the results of the performed experiments.

Distance Tests

To summarize the observations in the distance tests:

i. In the initial distance tests, at short range, the received signal voltage amplitude appeared to adhere to a 1/D^1.57 relationship.
ii. Between 1 and 3 meters the received signal voltage amplitude increased rapidly to the point that enough power was being received to light LEDs brightly.
iii. For mid-range, the received resonant signal voltage was consistent, but varied in amplitude.
iv. Surprisingly, at long range, the received resonant signal strength remained consistent, and tapered in a linear manner, but even out to 20 meters from the transmitter the power received at resonance was more than enough to light multiple LEDs brightly.
v. Most measurements had a clear line of sight between the transmitter and the receiver, but the long-range measurements passed through a building wall, which housed a large oven and power cables. Surprisingly, those measurements appeared unaffected by those obstacles.

The distance tests demonstrate that this WPT system design is capable of transmitting power over a significant range. This scaled WPT system was capable of transmitting power over several meters compared to only a fraction of a meter like in typical WPT systems such as resonant inductive coupling systems [10].

Power Tests

To summarize the observations in the power tests:

i. The average power transfer efficiency was only 16.6%.
ii. Phase difference and power transfer efficiency fluctuates as input power increases, most likely due to measurement inaccuracies.

The power tests demonstrate that this WPT system design can transmit some significant power, but its power transfer efficiency is low, to the point that its viability as a usable form of power transmission is questionable. While it can provide power over distance, and is in this regard a functional system, the amount of power transmitted compared to the amount of power inserted is simply too low to be practical, save for low power systems where efficiency is not a concern. The exact cause of the inefficiency of the WPT system is unknown, as the exact amount of power transferred through the WPT system cannot be determined with available equipment and information. More precise testing would need to be conducted before a reasonable explanation can be proposed.

This scaled WPT system displayed many anomalous properties, particularly with regards to the fluctuating voltages in the distance tests. There is no explanation for these observations at this time, as the exact mechanism of transmission of electrical energy that this system utilizes is still mostly unknown. Tesla's patent makes multiple claims, such as it being a form of "true conduction" [19] and "utilizing rarified gases" [8]. However, these claims are vague and are contingent on a high voltage, high power, low frequency system, which is different from this thesis' low voltage, low power, high frequency system. As such, verifying these claims and determining the mechanism of transmission is beyond the scope and capabilities of this thesis and this prototyped WPT system, and would require a new WPT system that matches Tesla's design specifications directly. Further research is warranted in this regard.

Conclusion

This thesis explored a low power, scaled variation of Nikola Tesla's "System of Transmission of Electrical Energy" (Patent No 645576). The primary objective was to determine if this WPT system design is viable. In this regard, the thesis was able to demonstrate that this WPT system design is not viable in its current state. The prototype was successfully constructed, and the system is shown to be capable of power transmission over a significant distance. However, the power transfer efficiency of the system was found to be too low to be viable for most practical applications.

There is a significant push in modern research to advance our current understanding of WPT systems and incorporate them into other systems. In its current state, this WPT system is not a viable alternative to more traditional resonant inductive coupling WPT systems for short range (under 2 meters) applications, which are capable of about 40% power transfer efficiency at a range of 2 meters [20]. However, there is some future potential. If the mechanism of electrical transmission can be conclusively discovered and tested, then it should be possible to develop supporting systems to increase transmission range and power transfer efficiency and potentially make this technology more viable. Several potential avenues of research are listed in the Future Work section.

Future Work

The conducted experiments represent a first step in the exploration of the potential of this WPT system design. There are several avenues of research that can and should be pursued to further understand the nature and use of this technology, and further evolve its viability.

Physics Exploration:
The exact mechanism that this WPT system uses to transmit electrical energy is unknown. Discovering the physics of the WPT system with advanced equipment can provide insight on how and why the WPT system works the way it does. This insight may provide an explanation for the more anomalous results observed during these experiments, such as the mid-range voltage fluctuations, and may also allow for the development of supporting systems to combat the system's inefficiency.

Different Designs:
Given more time, further designs could be tested. What relationship, if any, is there between the number of turns of the inner coil and the number of turns of the outer coil? How does the shape of the coil affect the EM properties of the WPT system (what if one or both coils are square, or hexagonal, instead of circular)? Can the resonant frequency be adjusted by changing the connection point to the A and A' coils? Does the geometry of D and D' have any effect on transmission?

Network Tests:
These experiments focusing on the WPT system were limited to only two terminals due to equipment constraints. Given more time and equipment, this system can be expanded. What if there are more than two terminals? What if there are coils with different resonant frequencies in close proximity to each other? What if multiple terminals act as transmitters, or receivers? Can a system be designed to automatically change which terminal is transmitting or receiving?

Industrial Modeling:
Tesla's ultimate objective when creating this WPT system was to implement it on a national scale. Once more research is conducted on this WPT system, particularly in regard to the mechanism of transmission, it should be possible to create a theoretical framework for integrating this technology on a larger scale.

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