Wireless Power Transfer: Pushing the Boundaries of What is Possible

Main Author: Jay Bapat (ORCID: 0009-0004-5142-7431)

Corresponding Author: Jay Bapat, ORCID: 0009-0004-5142-7431, FCS Innovation Academy,

jay.amit.bapat@gmail.com, (470) 630-6510

|| Background Information ||

Wireless power transfer (also known as WPT, wireless power transmission, wireless energy transfer, or WET) is defined as the transmission of electricity without a physical connection. Often, wireless power transfer is conducted through the means of electromagnetic induction. As stated in Ampère-Maxwell's law and Faraday's Law of Magnetic Induction, an oscillating (changing) electric field creates a magnetic field, and a change in magnetic flux (the density of a magnetic field) induces an alternating current in a nearby conductor (Britannica Faraday's law of induction).

However, before the science behind WPT is introduced, its origin must be understood.

It all began with Scottish scientist James Maxwell and his four equations. Maxwell established the framework for mathematics relating to electromagnetism in the late 1860s. His equations predicted the existence of electromagnetic waves that could travel through space at the speed of light. Maxwell's successor was Hertz, who experimentally proved Maxwell's theories by generating and transmitting radio waves in his laboratory. His groundbreaking work led to the SI unit of frequency being named after him.

In the 1890s, Nikola Tesla began experimenting with wireless power transmission through inductive and capacitive coupling. Tesla began demonstrating wireless power everywhere, lighting lightbulbs from across the room and even developing the first remote-control boat. After that, Tesla became more ambitious, and in 1899, he began experimenting in Colorado Springs. He claimed to have lit two hundred lamps from twenty-five miles away, but detailed data was not published. Arguably one of his most famous inventions was the Tesla coil, which was a large transformer which used magnetic coupling and resonance to produce high-voltage electricity and made artificial sparks. All of Tesla's inventions pushed science forward.

Tesla may have been the most influential scientist in wireless power (Hunt par. 1, 3, 8, 9, and 10).

Now that the origin of WPT is understood, the science of it should be conveyed too. Faraday's law precisely states that a changing magnetic field induces an electromotive force (EMF) in a nearby coil. This can be written as $EMF = -N\left(\frac{d\Phi_B}{dt}\right)$, in which EMF is the electromotive force, N is the number of turns, $d\Phi_B$ is the change in magnetic flux (in Webers), and *dt* is the change in time. This means the number of coils will affect the resulting electromotive force, so more should be used to maximize the EMF.

Magnetic flux is defined as “a measure of magnetic induction represented by lines of force” (Merriam-Webster Online Dictionary). The formula for magnetic flux in a coil with multiple turns is $\Phi_B = n \cdot B \cdot A \cdot \cos(.\ )$. Φ_B is the magnetic flux, *n* is the number of turns in the coil, *B* is the magnetic field strength (in amperes per meter), A is the area of the coil (in square meters), and   is the angle between the magnetic field lines and the normal (perpendicular) to A. This means in this experiment the lines should be as close to parallel as possible because cos(0°) = 1 and cos(90°) = 0.

Furthermore, the Ampère-Maxwell law states that an electric current generates a magnetic field, and a changing electric field also generates a magnetic field. (Ling et. al). This means that the transmitting end in the circuit should use some sort of oscillator (in this case a transistor) to generate AC voltage because DC voltage does not change and therefore will not generate a magnetic field. These two principles show how WPT functions, but more theory on types of WPT is yet to be explained.

There are two main ways to transmit power wirelessly with an electromagnetic field: inductive coupling and resonant inductive coupling. Inductive coupling is the most common of

WPT in which a transmitting coil (TX) generates a magnetic field, and a receiving coil (RX) is surrounded by that magnetic field, which in turn induces current (Bhat 1). This is the rudimentary way most consumer electronics use. This method is effective only over short distances, in most cases. Some systems utilizing Inductive coupling, such as the one used for this experiment, can even transmit electricity over distances even exceeding 30 cm (see data on pg. 10 and following pages). This method is cheap to design and make, contrary to Resonant Inductive coupling.

Resonant inductive coupling is rare in consumer electronics; it is still in research phases. Resonant inductive coupling systems typically use variable capacitors to "tune" the two coils to the same resonant frequency, the frequency at which an object resonates with the most amplitude. This creates an LC circuit in which the two coils transmit energy at that specific resonant frequency (Nave par. 1, 5 8, and 9). WPT systems utilizing resonant inductive coupling, when finely tuned, can vastly improve the distances in which power can be transferred, sometimes even doubling or tripling it! This all comes with one major caveat: the difficulty of tuning the two coils. First, the resonant frequency must be calculated based on the specification of the coil, and then that specific capacitance must be used to tune to that resonant frequency. Then comes the tuning. The capacitance must be adjusted with some sort of visual indicator, but most multimeters do not support the high frequency AC voltage of WPT. Finally, bad tuning can lower the efficiency of the system, leading to the decision to use inductive coupling in this experiment.

One common demonstration of WPT uses inductive coupling and simple materials. These demos commonly use thin magnet wire (0.3 mm to 0.6 mm), a 2N2222 NPN Transistor, a 9V battery, and a resistor (10kΩ to 27kΩ). This system can often transfer enough power to light an

LED (however dimly it may be) distances up to 15 cm. These systems are good starting points, but they are too commonly made to be anything unique.

Another demonstration of the capabilities of WPT is Caltech's famous MAPLE, which is a prototype that managed to transmit solar energy from space to earth. MAPLE used microwave wireless power transmission, another way to transmit power wirelessly. Direct current is transformed into microwaves at specific frequencies, which then travel and are rectified back into current. However, this level of distance and efficiency is not attainable in the experiment, but it shows the possible uses of WPT.

Based on background research, the experiment should be conducted using inductive coupling, many turns, large coils, a higher voltage, and placement of coils perpendicular to each other.

|| Absract ||

By testing how far electrical energy can travel wirelessly between two coils, this project aimed to explore the limits of power transfer. The purpose of this experiment was to find the furthest distance power could be transferred using a large wireless power transfer system, estimated to be 40 cm. To test this hypothesis, a transmitting coil with a 9 V battery, a transistor, and two resistors was used. While testing, the system showed consistent results: at 30 cm, dim at 35 cm, and off at 40 cm. The hypothesis was rejected, showing that wireless power transfer works best at shorter ranges. These findings highlight the importance of coil design and alignment. As a result, improving coil size and alignment should be considered to extend transmission distance. Practical applications include charging electric vehicles, charging Active Implantable Medical

Devices (AIMDs), and charging consumer electronics such as smartphones, tablets, and computers.

|| Methodology ||

Coil the magnet wire around the container **twenty-five times** and cut the remaining wire. Then remove the wire and secure it with electrical tape. Label this RX. Repeat, but after coiling thirteen turns, make a 5 cm loop and then continue with the remaining turns. There should be two 25-turn coils of wire now. Label this TX. Cut the top of the loop in the TX. In the RX, secure one leg of the LED to one end of the coil using tape. Repeat for the other leg and the other end of the coil. Do **NOT** solder the LED because it will need to be removed during testing. Before soldering components to the coil, be sure to strip the enamel coating off the ends of the wire, so the components touch the actual metal and not just the coating. Otherwise, electricity will not be transferred. Solder two resistors together. In TX, solder one end of the joined resistors to one end of the coil. Solder the other end of the resistors to the middle leg (base of the transistor. In TX, solder the other end of the coil to the left side of the transistor when flat side is up (the *C* terminal, check data sheets for *C*, *B*, and *E* terminals). Attach one alligator clip to one end of the black hookup wire. Solder the other end of the hookup wire to the right (*E*) terminal of the transistor. Attach an alligator clip to the end of the red hookup wire. Solder the other end to the loop of the TX coil. Connect the black wire to the negative side of the battery and the red wire to the positive side of the battery using the alligator clips. Hold the two coils close together, facing each other. If the LED lights up, proceed to the next steps. If the LED does not light up, make sure the previous steps were followed correctly and troubleshoot. Attach each coil to the stand, making sure they face each other. The WPT system is now ready to be tested. Measure different distances (20 cm, 25 cm, 30 cm, 35 cm, and 40 cm). Check if the LED lights up or not at each distance of separation. Record the data. Repeat four more times. Plug the black probe into the "COM" jack and the red probe into the "VΩmA" jack of the multimeter. Turn the dial to measure AC voltage (usually "V" followed by "~"). Remove the LED and touch each probe to one end of RX. Remeasure the distances (from step 14) and test five times in total. Record data in the table. Repeat steps 14-16, but with the battery disconnected. Make sure to record the data on a separate table. The experimenting stage is now done.

|| Recorded Data ||

Trial 1

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.4	Yes
25	2.5	Yes
30	1.4	Yes
35	0.9	Yes (dim)
40	0.2	No

Trial 2

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.5	Yes
25	2.4	Yes
30	1.2	Yes

35	0.7	Yes (dim)
40	0.1	No

Trial 3

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.4	Yes
25	2.5	Yes
30	1.3	Yes
35	0.8	Yes (dim)
40	0.2	No

Trial 4

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.5	Yes
25	2.4	Yes
30	1.2	Yes
35	0. 8	No
40	0.1	No

Trial 5

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.4	Yes
25	2.4	Yes
30	1.3	Yes
35	0.9	Yes (dim)
40	0.1	No

Average Data

Distance Between TX and RX (in cm)	Voltage Transmitted (in volts)	LED Turns On (Yes/No)?
20	3.46	Yes
25	2.44	Yes
30	1.28	Yes
35	0.82	Yes (dim)
40	0.14	No

|| Results ||

Graphs:

Regression Based on Average Points

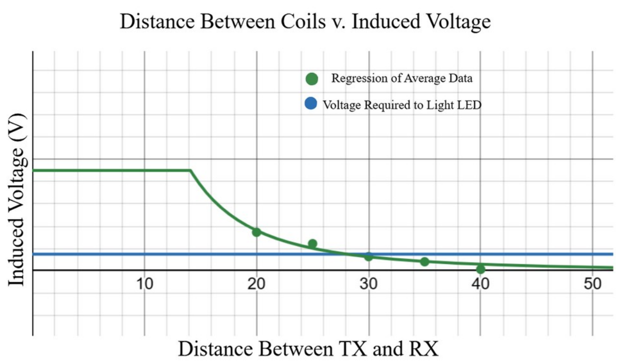

Fig. 1, regression line of average data points. Data shows induced voltage gradually decreasing until eventually going under the LED's forward voltage. When this happens, the LED will not light up.

Estimation Based on Faraday's Law

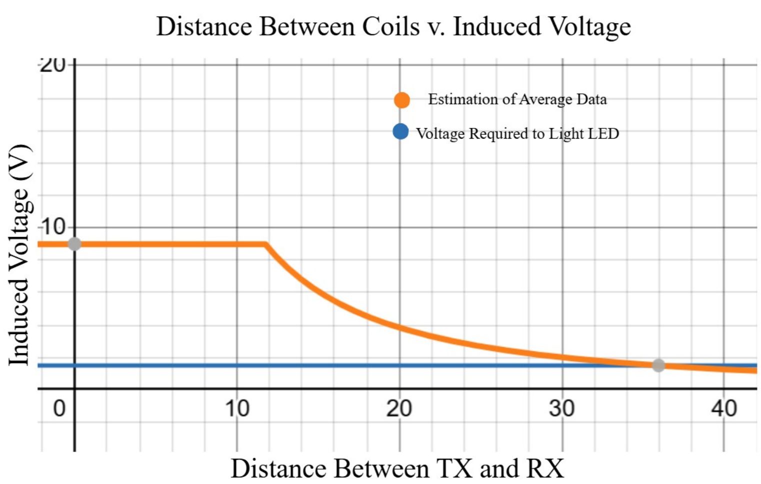

Fig. 2, estimation of induced voltage based on Faraday's law. The graph shows how a perfectly aligned system would transmit power. This estimation assumes perfect alignment and minimal resistance. Compared to the regression model, this graph intersects the blue line at ~35 cm rather than ~30 cm.

||Data Analysis and Discussion||

This experiment measured the voltage transmitted wirelessly as the distance between two coils increased. Various distances were measured out (20 cm – 40 cm with distance increasing 5 cm each time), and the LED would either light up, faintly glow, or not glow at all. The results were also measured with a multimeter, showing the voltage in the receiving coil.

Results Summary: The average voltage for 20 cm was 3.46 V induced. The LED glowed brightly and was visible in full light. At 25 cm, the average voltage induced was 2.44 V, with the LED glowing well, but not as bright as at 20 cm. Even further, at 30 cm the LED started to dim more than earlier; the induced voltage was 1.28 V on average .When the distance between the two coils was 35 cm, the LED was barely glowing, and the average voltage induced was only 0.82 V. Even though the results often noted the LED was faintly glowing, the light emitted was so little that it could be mistaken for the LED reflecting light instead of giving it off. At 40 cm, the LED was never glowing. The average voltage in the receiving coil was a miniscule 0.14 V, and the LED showed no signs of light.

Trend Analysis: There is a clear negative trend in the graphs; as the distance between the coils increases, the voltage transmitted decreases. Although it could be mistaken for an exponential equation, the regression line graphed is a power function. The further apart the coils are, the faster the voltage drops. The regression graph shows how there may have been slight errors in either the measurement of the induced voltage or the detection of the emission of light by the LED. Even when the voltage was below the LED's forward voltage, sometimes the LED still lit up. Also, there is a slight difference between the regression line and the estimation line. Although both start with a plateau of 9.0 V (which is because the battery was only 9.0 V), the estimation line drops in voltage slower than the regression line. This is because of the slight errors such as misalignment and increased resistance that happen in real life. Because the line is just an estimation, it does not account for these slight variations.

To summarize, the data in this experiment showed how the voltage dropped as the distance increased. At closer distances, the LED glowed brighter than when it was far away. The estimation provided a rough example of how far power could be transferred if alignment were perfect, and resistance was minimized. Even though the system did not transfer power from 40 cm away, it successfully did so from 35 cm away.

|| Conclusion ||

Based on the data and reasoning above, the proposed hypothesis that stated "an optimized wireless power transfer system using inductive coupling can transfer power enough to light a 1.5 Vf Led" is rejected. Testing revealed that the furthest the optimized system could transfer power was 35 cm, and even then, the LED glowed very dimly. Furthermore, when the voltage was measured at 40 cm, the voltage was less than 1 V every time.

Based on the predicted outcomes, it was expected that the WPT system would be able to light an LED from 35 cm away, and it would be able to transfer power from 40 cm, too. However, because of errors in alignment, an increase in resistance due to soldering and the length of the coils, and less than expected voltage in the battery, the power transfer system could not achieve the task at hand. These errors might have only slightly decreased efficiency at short ranges, but as the range increases, efficiency is key. Without the errors, it may have been possible to transfer more power wirelessly.

The background research was crucial in this experiment as knowledge of electrical components and concepts was needed to build and test the transfer system. For example, if it was not known that a changing electric field is required to generate a magnetic field, one might have used DC voltage without converting it to AC voltage. This would have led to the LED only flashing briefly or the system not working at all. Also, background research in types of WPT led to the decision about using resonant inductive coupling and knowledge about coil alignment. Overall, background research was critical to the success of this experiment.

This experiment could be changed to transmit over longer distances by adding more coils or increasing the battery voltage. Different forms of WPT such as resonant inductive coupling or radio frequency WPT could also be used to optimize efficiency over longer distances. Long distance WPT could be beneficial for everyone. Ideas include electric vehicle charging on the road, wireless phone charging from across the room, and even wirelessly charging pacemakers for people with heart conditions. Wireless power may just be the future of technology, so it is important to develop it and optimize it for later applications.

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