Investigation into Wireless Power Transfer in near Field using Induction Technique

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Abstract. Wireless Power Transfer (WPT) enables transfer of electric power from the source to electrical load(s) in the absence of any physical link. This mode of transmission is favourable especially when it is not feasible or convenient to connect wires together. In WPT, the most important parameter is the efficiency, where the energy transmitted by the ‘plant’ is obtained by the receiver, thereby defining the economic importance of such system. This study is aimed at showing how electrical energy can be transferred on a near field basis using induction. In order to achieve this aim, the transmitter converts the DC source from an oscillator, with the high frequency AC, which is linked with the wireless power transmitting coil. The experiment showed how electricity can be transmitted at certain distances from a resonating coil. The project showed that the mutual inductance of two coupled coils resonating at a considerably high frequency is proportional to the power output of the systems. It was observed that inductors wrapped around an iron core placed on the same axis to each other with 56 turns of copper wire resulted in a more efficient power transfer and a higher power output than when inductors placed at different axis to each. An instantaneous increase in voltage was also measured while power was gradually built up in the resonating coil. This project can be applied in the industry for the generation transmission of power without conducting cables.

Keywords: inductive coupling; iron core; receiver coil; transmitter coil; Wireless power transmission

1. Introduction

Wireless Power Transfer (WPT) is transferring electrical energy without the use of conducting cables or wires. WPT technology was demonstrated in 1890 by Nikola Tesla where he lighted up two 50 W incandescent lamps 42 km from the transmission station [1, 2]. According to [2] a 60 W light bulb was powered with the same technology for a distance above 2.0 m using electromagnetically coupled resonance system. Wireless transmission is used in cases where using connecting wires are inconvenient or hazardous. WPT removes the risks of electric shock and fire incident that can be caused in power cords [3]. It is a clean source of energy that helps to overcome the challenge of power losses and minimize cost of generation and transmission as in the case of power transmission through cables [4]. WPT technology has been made possible due to technological advancement and improved implementations of transfer techniques [3]. It is used in powering cell phones, laptops, blenders, mixers, smart watches, electric cars, aerial vehicles, and several other devices ([3, 5].

WPT are based on three principles as electromagnetic radiation (EMR), electric coupling and magnetic coupling [6]. EMR is radiative and applies to far-field WPT unlike electric and magnetic coupling that are applied in near-field WPT and non-radiative [6]. However, electric coupling uses capacitors for transmission and electric field are more harmful to living things compared to magnetic field [6]. Based
on the risk limitation of electric coupling, magnetic coupling is often times the preferred choice of WPT [6]. Magnetic coupling is grouped into inductive power transfer (IPT) and coupled magnetic resonance system (CMRS), with CMRS having a larger quality factor [6, 7]. Also, CMRS is known to be more efficient, provides greater range and direction and have negligible radiation loss as compared to inductive coupling [4].

2. Materials and Method
Based on this study, the principle of inductive coupling guides the wireless mobile charging. With the concept of inductive coupling, the overall functioning of wireless charger circuit requires a transmitter and receiver section. The transmitter coil in the transmitter section would convert the DC power from an oscillator which is built into the transmitter circuit with a high frequency AC power signal. This high frequency AC, is linked with the wireless power transmitting coil, which would in turn create an alternating magnetic field in the coil as a result of induction for the transmission of the electric energy. The energy is received in receiver section as an induced alternating voltage in its coil and a rectifier converts the voltage to DC. Finally this voltage would feed the load after passing through a voltage controller as shown in Figure 1. The wireless charging circuit has mainly two sections: the transmitter and receiver. The transmitter section comprises a DC power source, oscillator circuit and a transmitter coil [2]. A constant DC voltage is provided by a DC power source, and this DC signal is the input to the oscillator circuit [8]. Due to the high frequency, the transmitter coil starts oscillating, and generates a magnetic field. However, the receiver section is made up of rectifier circuit, receiver coil as well as voltage regulator Integrated Circuit (IC). A power supply is required to power the oscillator. In order to achieve this, a 30 V DC source was constructed using Figure 2.

![Figure 1: Block diagram of WPT mobile charging circuit using inductive coupling [8]](image-url)
Figure 2: Circuit Diagram of 30 V DC Power Supply [9, 10]

2.1 The Transmitter Section
When power is transferred to the circuit, the DC current flows through both sides of the coils and enters the drain terminals of the Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). At the same time that this is happening, voltage that has been passed to the gate of the transistors enables the first transistor to turn ON (as it’s usually does). On this, the first MOSFET’s drain voltage will run through ground, at the same time, the second MOSFET will conduct less and its drain voltage will rise to a peak gradually before it starts to fall. The frequency at which the transmitter oscillates is determined by Eq. (1).

\[ f = \frac{1}{2\pi\sqrt{LC}} \]  

A heat sink is attached to each of the MOSFETs to prevent overheating and keep them cool. In order to achieve a high current on transmitting coil, a Royer oscillator circuit is used in this study as revealed in Figure 3. A copper wire of 1.15 mm is used to construct a transmitter coil of length 5.6 m, with diameter 13 cm. In addition, the wire used has a thin layer of insulation coatings so as to prevent current from passing through the turns in the coil.

Figure 3: Transmitter section circuit [8]

2.2 The Receiver Section
The receiver (as revealed in Figure 4) is made up of three sections: the receiver coil; the voltage regulator IC; and the rectifier circuit. The transmitter coil allows the flow of electric current through a magnetic field. The magnetic field in the transmitter coil extends to this receiver coil, it is placed
within a specific distance from this transmitter coil, and AC voltage is induced, which generates a flow of current in the receiver coil of the wireless charger. The rectifier circuit in the receiver section converts the AC voltage to DC. The voltage regulator IC in the circuit provides a constant limited regulated output voltage to the load for charging the low power devices. The voltage regulator is employed to give a regulated 5V as its output.

Figure 4: Receiver section circuit

2.3 Resonance
It involves oscillation of energy between two nodes for example a pendulum wherein the energy is changing between potential and kinetic forms. In a resonant system, it could sometimes occur that the system is only weakly excited in spite of a large amount of energy stored up. This happens when the energy injected into the system is greater than the amount of energy that leaves the system. The characteristics of a resonator can be described by the resonant frequency $\omega_0$ and intrinsic loss rate $\Gamma$. The relationship of both parameters is expressed in Eq. (2), it is a measure of how well the system stores energy. Quality factor ($Q$) can also be defined as the ratio of the inductance to the resistance of the coil as expressed in Eq. (3):

$$Q = \frac{\omega_0}{2\Gamma} \quad (2)$$

$$Q = \frac{\omega L}{R} \quad (3)$$

Self-inductance, $L$ is calculated using Eq. (4).

$$L = \frac{N^2(D_o - N(\omega + p))^2}{16D_o^2 + 28N(\omega + p)} \quad (4)$$

where $N$ is number of turns for transmitter coil, $D_o$ is outer diameter, $\omega$ is wire diameter and $p$ is spacing between turns (which in this case is 0). $N = 14$, $D = 13.5\text{cm}$, $\omega = 1.15\text{mm}$, $p = 0$

By substituting all these values into Eq. (4), $L$ for transmitter coil is obtained as 0.295 $\mu\text{H}$. The operating frequency for the system using Eq. (1) is given by 3.55 MHz. $\omega_0$ is the Royer oscillator circuit used enables transfer between transmitter TX and receiver RX. This is obtained as 22.3 MHz based on Eq. (5). Also, $Q$ is estimated as $3.87 \times 10^8$ using Eq. (3).

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (5)$$
For the second coil, parameters N, D, ω and p are given as 14, 9 cm, 1.15 mm and 0 respectively. Therefore, L1 for TX2 is estimated as 2.20 μH. Values of f, ω and Q are 1.3 MHz, 8.1 MHz and 10.48 × 10^8 respectively. For a receiver coil RX of the same parameters as the second transmitter coil TX2, the same values were used for N, D, ω and p respectively. The values obtained for L2, f, ω and Q are 0.295 μH, 1.3 MHz, 8.1 MHz and 10.48 × 10^8 respectively. The mutual inductance M for the coupled coil is the same value as one of the inductances of the coupled coils, which is given by Eq. (6).

\[ M = \sqrt{L_1L_2} = L \] (6)

Therefore, the mutual inductance using coils TX2 and RX is 2.2 μH.

Mutual inductance using coils TX1 and RX is calculated using Eq. (7).

\[ M = \frac{\mu_0\mu_1N_1N_2A}{l} \] (7)

where \( \mu_0 \) is permeability of free space, which is given by \( 4\pi \times 10^{-7} \); \( \mu_r \) is relative permeability of copper which is approximately unity (i.e. 1); \( N_1 \) and \( N_2 \) is the number of turns which is 14; A is the area, which is given by \( \pi r^2 \); and l is the length of wire in meters i.e. 6 m. Therefore, M is obtained as 2.1 mH. The inductance of the coils L1 (2.1 mH) and L2 (5.9 μH) is obtained by Eq. (8).

\[ L = \mu \frac{N^2}{l} (1.26 \times 10^{-6}) \] (8)

The mutual inductance of 8.98 kH was obtained based on Eq. (9).

\[ M = \frac{K}{\sqrt{L_1L_2}} \] (9)

where k is the coupling coefficient which is assumed to be 1

3. Results and Discussion

Royer oscillator circuit was used with the calculated parameters in this study. The most important component of the transmitter circuit is the transmitting coil TX, because it is what transfers the energy from the oscillator circuit to the receiver circuit. While constructing the receiver circuit, hand-made wounded receiver coil RX using the same parameters as the smaller transmitter coil so as to obtain the same result as of the smaller transmitter coil TX2 was used. This was done because theoretically, resonant systems are expected. TX and RX coils of the same or very close self-inductances were obtained. The mutual inductance M for the coupled coil is the same value as the individual self-inductance because inductance is equal for both coils used, although M is larger when both coils are of different size and placed together than when they are of equal size. Mutual inductance is primarily a function of their orientation and position (distance) relative to each other. A high mutual inductance increases the chances of 100% transfer of energy from L1 to L2 (TX to RX). The coupling factor is higher when both circuits resonate at the same frequency and have equal inductance. This usually occurs when both coils are of the same size and parameters especially size and number of turns.

At the input of the transmitting circuit, voltage of 5 V is measured. This was due to the fact that 30 V was needed to power the oscillator circuit; instead, a 5 V was only supplied to the circuit. To step up the voltage to the required amount, a DC-DC boost converter was used, which stepped up a 7 V to 110 V. This was used to power the oscillator circuit. The voltage-in was received at the transmitter coil but no oscillation occurred in the coil or in resonance with the receiver coil. TX and RX coils wound to oscillate in resonance with each other in this power transmitting circuit are assumed to do that through an air core, this is because the air serves as a conduction medium for the transfer that should occur between both coils over certain distance. While making the coils, it was ensured that both coils had
equal number of turns so that they would have almost equal resonant frequencies. Initially, energy is transmitted from transmitter TX to receiver RX through an air core. Difficulty is encountered when trying to transmit the electric energy by induction through the air core as the current reached the transmitter coil but did not transfer to the receiver coil even though the coil was heating up. The Tesla coil was used in place of air core and the Tesla core was handmade by winding the coils around an iron core. The relative permeability of the iron core is 100. The inductance of the coils $L_1$ (2.1 mH) and $L_2$ (5.9 µH) as obtained from Eq. (8). The mutual inductance of 8.98 kH was obtained based on Eq. (9). This is very reasonable since both coils are wound around each other and there is no separation between both coils. Therefore the mutual inductance is very high because mutual inductance is highly dependent on the coupling of both coils. The $M$ for air core and iron core are 2.1 mH and 8.98 kH respectively. By comparing both inductances, a great difference is observed. In a much larger system similar to this, using the same theory of induction, the lamp could be moved anywhere and still be lit. Resonant circuits are usually used to enhance inductive power transmission. Quality factor obtained using iron core is $18.33 \times 10^{11}$. The system’s quality factor is an average of the quality factor of the transmitter and receiver coils. By comparing the quality factor of both systems, it is observed that the $Q$ of the iron core is more efficient than that of the air core. Placing the LED at very close range (distance) to the primary coil (56 turns), which is wrapped around by a secondary coil of 3 turns in close proximity to the coils in induction with each other, the LED is lit up as revealed in Figure 5.

![Figure 5: Power Transfer from Coil to LED by Induction](image)

Comparison between the air and iron core circuits reveal that the axial positions of the coils played out different roles in both circuits. In the former, the relatively small receiver coil was not placed in the same axis as the large transmitter. When placed in the same axis, the amount of field lines passing through the transmitter and receiver increases, hereby increasing the transmission capability. By using an induction with an iron core, the aim of this study is achieved because it is now shown that electrical energy can be transferred on a near field basis using induction. This is observed in the plot of voltage against time, as revealed in Figure 6. The voltage increases with time. As voltage rises, temperature also rises. Skin effect was observed with the Tesla coil made from 17AWG copper wire unit) canceling the resistance experienced by the current that could lead to loss. Hence, energy is transmitted to the LED placed in close range to it. For the circuit with air core, there were equal number of turns and so there was no difference in voltages measured at the input of the oscillator circuit and at its output. This was maintained until the voltage was manually stepped up, which resulted to equal increase in input and output of the oscillator. In the second circuit,
number of primary turns was greater than number of secondary turns, and where V (in) was 7.5 volts, the output voltage increased significantly. Another observation was the fluctuation in power efficiency as distance increased. As the resonating coils were separated from each other over different distances, the power received in the load reduced exponentially. When the LED was separated by a farther distance from the coils around the iron core, it went off. Figure 7 shows the relationship between distance and power transfer’s efficiency. The result is in accordance with results obtained by [2] in which they achieved efficient power transfer of about 60 watts with 40% efficiency, but only over distances in excess of 2 m.

Figure 6: Variation of voltage with time

Figure 7: Relationship of system efficiency and separation distance
4. Conclusion

In this work, wireless transmission on a near field using induction technique has been designed, constructed and tested. Functional oscillator circuit was constructed and power was transferred wirelessly to an array of LEDs by inductive coupling using the Tesla coil. It was observed that wireless power transfer by inductive coupling is most efficient on a near field basis. This is also coupled with the fact that heat loss during oscillation in such a system is inevitable and this is a disadvantage of wireless transfer by inductive coupling. Therefore, the major hindrance to a near field wireless power transmission would be the distance between the transmitter (TX) and the receiver (RX). Receivers must be at close range with transmitters. The study hereby recommended that research should be carried out on how both TX and RX systems can be better tuned to result in a higher quality factor for wireless transfer systems. The use of power amplifiers is needed for wireless power transfer systems in order to achieve higher efficiency, increase stability in the amount of power transmitted as output.

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References

[1] Curty, J.P., Declercq, M., Dehollain, C., Joehl, N. (2007). Wireless power transmission, In: Design and optimization of passive UHF RFID systems. Springer US, Boston USA.
[2] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J.D., Fischer, P., Soljacic, M. (2007). Wireless power transfer via strongly coupled magnetic resonances. Science Express, 317 (5834): 83-86.
[3] Rajeev, M.R. (2014). Cut the cord: Wireless power transfer, its applications, and its limits. https://www.cse.wustl.edu/~jain/cse574-14/ftp/power.pdf (accessed: 21-01-19).
[4] Shidujaman, M., Samani, H., Arif, M. (2014). Wireless power transmission trends, 3rd International Conference on Informatics, Electronics and Vision, IEEE, 978-1-4799-5180.
[5] Jawad, A.M., Nordin, R., Gharghan, S.K., Jawad, H.M., Ismail, M. (2017). Opportunities and challenges for near-field wireless power transfer: A review. Energies, 10 (1022): 1-28.
[6] Sun, L., Ma, D., Tang, H. (2018). A review of recent trends in wireless power transfer technology and its applications in electric vehicle wireless charging. Renewable and Sustainable Energy Reviews, 91: 490-503.
[7] Choi, B., Lee, E., Huh, J., Rim, C.T. (2015). Lumped impedance transformers for compact and robust coupled magnetic resonance systems. IEEE Trans Power Electron, 30 (11): 6046-6056.
[8] Wireless Power Transmission Mobile Charger Circuit Using Inductive Coupling www.mepits.com/project/171/
[9] Nwoye C. D., Usikalu M. R., Babarimisa I. O, Achuka J. A and Ayara W. A. (2017) Construction of An Automatic Power Switch using Infrared Motion Sensor, Journal of Informatics and Mathematical Sciences, 9(2): 331–337
[10] Ayara W. A, Omotosho T. V, Usikalu M. R, Singh M. S and Suparta W. (2017) Development of a solar charged laboratory bench power supply, Journal of Physics: Conference Series, 852(1): 012044