Development of a Wireless Power Transfer System using Resonant Inductive Coupling

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***Abstract*— Access to power is a fundamental requirement for the effective functioning of any electrical/electronic circuit. The conduit of transfer of power can be either physical (wires, cables etc.) of non-physical (i.e. wireless). Wireless power transfer is a broad term used to describe any means used to transmit power to electricity dependent systems and devices. In this paper, a wireless power transfer system is developed to provide an alternative to using power cords for electrical/electronic devices. With this technology, challenges like damaged or tangled power cords, sparking hazards and the extensive use of plastic and copper used in cord production are resolved and also the need for batteries in non-mobile devices is eliminated. In this system, electromagnetic energy is transmitted from a power source (transmitter) to an electrical load (receiver) via resonant inductive coupling. The performance achieved is a good indication that power can still be transmitted over a medium range. In addition, possible ways of improving the efficiency of the system are discussed.**

***Index Terms*— printed circuit board, resonant coil, resonant inductive coupling, wireless power transfer**

I. INTRODUCTION

DESPITE the concerted effort to free essential communication devices from wires, portable devices such as mobile phones, laptops, and tablets, that are well equipped with rechargeable batteries still require manual plugging with the wired charging system when the charge is depleted. To fully liberate the portable electronic devices from wires, a cordless power system must be developed [1].

Electric power can be transferred from one point to another without the use of connecting cables through either magnetic inductive coupling [2, 3], electromagnetic radiation [4-8], or resonant inductive coupling [9]. Magnetic inductive coupling employed in transformers limits the range of transmission since the primary coil and the secondary coils are required to be within close proximity due to the axial and angular misalignment between coils. Although wireless power transfer through electromagnetic radiation can potentially cover longer distance, the approach is difficult to implement and dangerous for objects that come in contact with the electromagnetic waves. Furthermore, the Omni-directional properties reduce the efficiency of the system.

However, the tuning of the coils to the same frequency in resonant inductive coupling can improve the range at which power can be transferred efficiently with low complexity and no harmful effect [10]. The power capability of the system can be further improved by the concurrent use of both inductive and resonant couplings to reduce the leakage inductance in the power flow path. Coupled-mode theory (CMT) [9, 11] and reflected load theory (RLT) [12-14] gives the detailed analysis of the operation principles of resonant coupled wireless power transfer.

Wireless power transmission offers a more suitable, greener alternative to conventional plug-in charging because it has the capability to recharge all electricity dependent devices within an average–sized room using a single source of power. This technology becomes relevant in electric vehicles and wireless sensors where it is practically impossible to run cables due to critical environmental conditions. Interestingly, this contactless means of powering electric devices is not only convenient and safe, but also raises their mobility and reliability with low expense as it minimizes the use of plastic and copper for wires [1].

This completely electronic-hardware work covers the design, construction, and testing of the wireless power transfer system. The transmitter and receiver circuits are designed and implemented on printed circuit boards. The paper is arranged as follows: section II reviews historical advancements in the development of wireless power transfer, evaluates previous relevant work, and states the methodology adopted; section III discusses the details of the design process and physical implementation; section IV presents the results of system implementation test; and section V contains a short summary of the work, achievements, and also states the limitations of the work as well as recommendations for future work.

II. LITERATURE REVIEW

A. Brief Historical Background of Wireless Power Transfer

The development of wireless power transfer is traceable to the work done by late Nikola Tesla, who discovered and demonstrated the principles behind this phenomenon. At the turn of the 20th century, he developed a system for transferring large amounts of power across continental distances in a bid to bypass the electrical-wire grid. To achieve this, he planned to use the earth's ionosphere as the transfer medium for electricity. Unfortunately, it proved unfeasible as the theories behind it were based on 19th century ideas [10, 15].

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Regardless of this unsuccessful venture, Tesla was able to make some achievements in the field of wireless power transfer. Some of them include: illuminating light bulbs from across the stage in a demonstration before the American Institute of Electrical Engineers at the 1893 Columbian Exposition in Chicago and another was lighting three incandescent lamps at a distance of about 30 metres. In 1897, he patented the Tesla Coil (also called the high-voltage, resonance transformer) which transfers electrical energy from the primary coil to the secondary coil by resonant induction. His discoveries on resonant inductive coupling are the foundational principles behind modern wireless power technologies such as cell phone charging pads [15]. In 1963, the first microwave power transfer (MPT) system was exhibited at Raytheon [16].

B. *Review of Related Work*

Kurs et al. [17] demonstrated the feasibility and the extent to which resonant electromagnetic induction can be used for efficient energy transfer over considerable distances. The influence of extraneous objects located in-between the transmitter and the receiver was also studied. For efficient wireless power transfer, the authors coupled the transmitter and the receiver with an evanescent, non-radiative near-field as opposed to a radiative far-field because of the stationary (non-lossy) characteristics of the near-field. Fast coupling, an additional requirement for an efficient transmission over a medium range distance (i.e. a distance greater than the characteristic size of the transmitter and receiver by at least a factor of 2 or 3) was achieved using identical, resonant objects that are smaller than the wavelength of the evanescent field. This is because the range of the near-field from the resonators (which act as antennas) depends on its wavelength [18, 19]. The electrical energy transferred over a distance of 2 meters, which was about 8 times the radius of the resonant coils, was used to light up a 60 watt bulb at an efficiency of 40%.

Due to predominant magnetic near-field surrounding the resonators, the influence of extraneous objects on resonant inductive coupling is nearly absent. Therefore, for an object to pose any form of disturbance, it must have significant magnetic properties, else it will interact with the system just as free space. Also, extraneous objects only pose a noticeable disturbance when placed within a distance 10 cm and below from any of the resonator coils. The only disturbance expected to affect the system is a close proximity of large metallic objects [17] [20].

Cannon et al. [21] investigated the potential for the application of magnetic resonant coupling to deliver power to multiple receiving devices from one source device. The system consists of a transmitter made up of an identical pair of a non-resonant source coil inductively coupled with a resonant primary coil, and two receivers each consisting of pair of a resonant secondary coil inductively coupled to an identical non-resonant coil, supplying the load. Both receivers had coils of identical diameters however, they were much smaller than the transmitters. The source and load were inductively coupled to the primary and load to ensure that each resonator has a high Q-factor by isolating the source and receiver impedances. Lumped capacitors were employed in the resonant coils with those of the primary being adjustable to enable the tuning of both resonant circuits to the same frequency due to the difference in inductance.

For a wireless power transmission to multiple receivers to be feasible, each receiver must be made of coils smaller than the transmitter. Therefore, they were kept within the region where the magnetic field from the source coil is relatively uniform. Additionally, the receivers should be spaced far enough apart to ensure that the interaction between any two of them has a negligible impact on their interaction with the source coil. Hence, the normal resonant coupling interaction between source and receiver should suffer minimal impact from the mutual inductance between any two receiver coils.

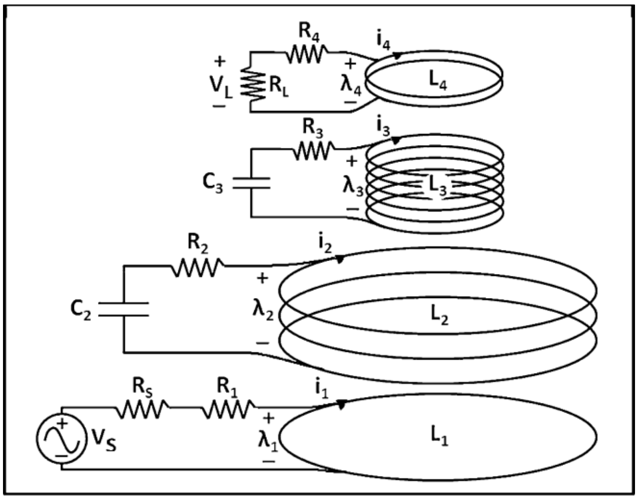


Figure 1: Schematic of a Multiple Receiver System showing only a single receiver.

When strongly coupled interactions occur between any two receivers, the single-transfer function resonant peak splits into two distinct peaks. As a result, the resonant circuits have to be tuned to one of these new frequencies before power can be transferred to them [21]. Thus, the second condition for a multiple receiver wireless power transmission becomes necessary.

Kim et al. [22] analysed the effect of an intermediate coil on the power efficiency of a resonant wireless power transmission between a transmitter coil and a receiver coil. Identical helical coils were employed as the transmitter and receiver resonant coils while a spiral coil serves as the intermediate coil to ensure that the volume of the intermediate coil is lesser than that of the transmitter and receiver coils. Adjustable, high Q-factor capacitors were used for the resonant coils of the transmitter to allow for adjusting of their resonant frequency and to reduce power loss during transfer. In this case, the source and the load are both inductively coupled to the transmitter and the receiver coils respectively.

Findings revealed that the efficiency of the power transfer improved greatly with an intermediate coil than without both a perpendicular and a coaxial orientation. From the results obtained, maximum efficiency can be achieved when the intermediate coil is in the centre between the transmitter and the receiver coils. Also, a coaxial orientation of the intermediate coil yield better results in terms of efficiency than a perpendicular orientation [22].

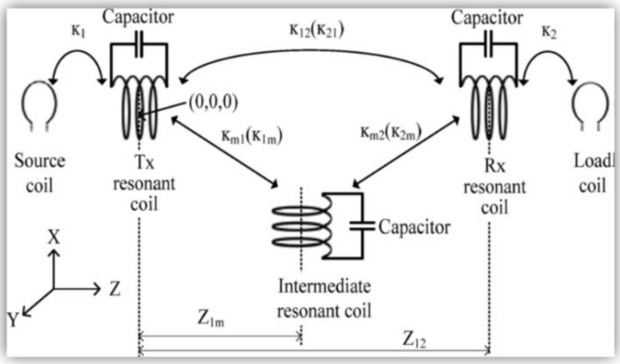


Figure 2: Schematic of a Resonant Wireless Power Transfer System with intermediate coil.

In this work, we developed a resonant wireless power transfer system with the transmitter and receiver coils directly connected to both the source and the load respectively. The transmitter and the receiver both consist of resonant coils of one turn each without any intermediate coil. More so, same resonant frequency is achieved by using identical resonant coils of same diameter and the same material.

III. System Design Methodology

The wireless power system consists of two modules: the transmitter module and the receiver module. The transmitter module, which consists of a direct current (d.c) power supply connected to an oscillator circuit and a transmitting coil, generates oscillating magnetic field for power transfer. In operation, the oscillator circuit converts the d.c output of the power supply into a high frequency alternating current (a.c) current while the transmitting coil produces an oscillating magnetic field from the a.c current.

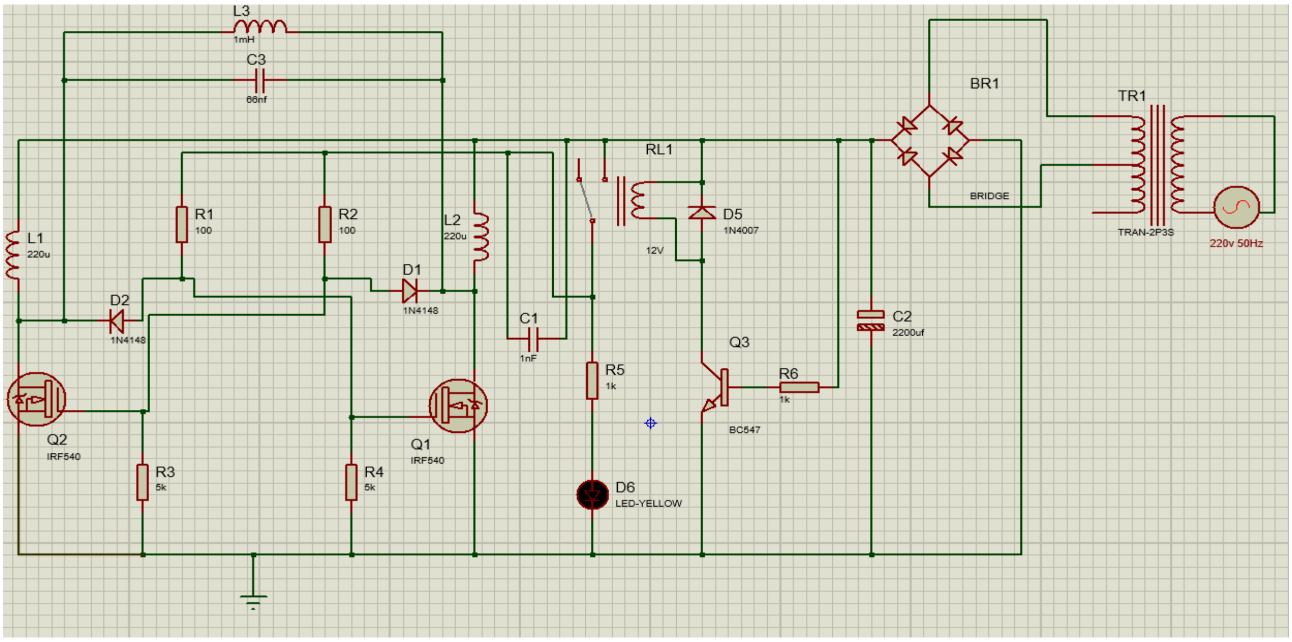


Figure 3: Complete Transmitter Circuit

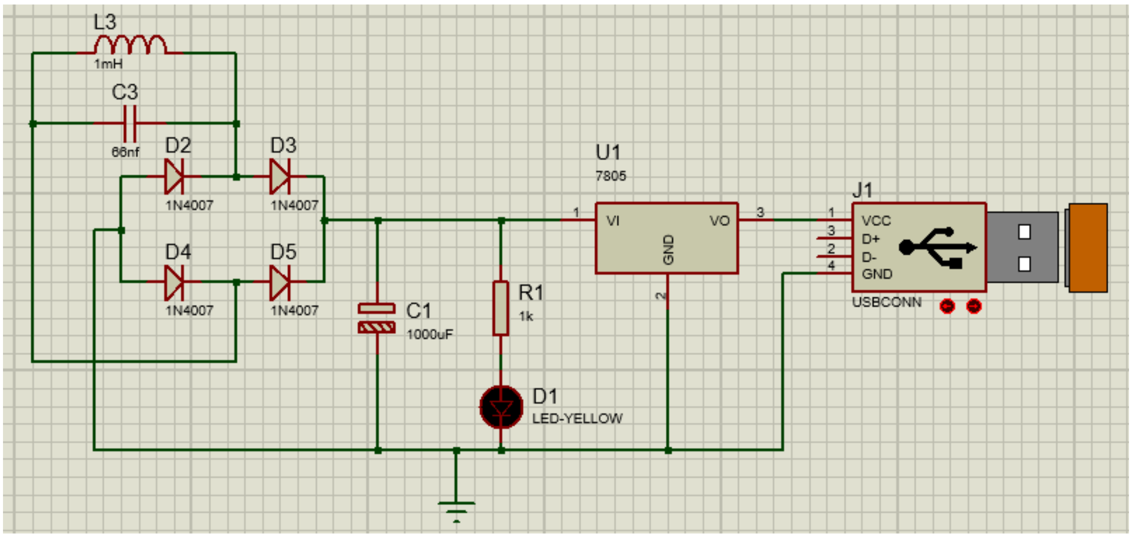


Figure 4: Complete Receiver Circuit

Table 1: Transmitter Module Components

COMPONENT NAME	COMPONENT VALUE
Transformer	240/24V centre-tapped
Non-polarized capacitor, C2	66nF
Non-polarized capacitor, C1	0.1µF
Electrolytic capacitor	4700µF, 35V
BJT Transistor	BC547
Relay	12V coil SPDT
LED	Green
Ferrite core inductor: L1, L2	220µH
Resistors: R1, R2	100Ω
Resistor: R3, R4	5kΩ
Resistors: R5, R6	1kΩ
Diodes: D1, D2	1N4148
MOSFETS: Q1,Q2	IRF540
Transmitter Coil, L1	0.1026µH
Diode, D5	1N4007

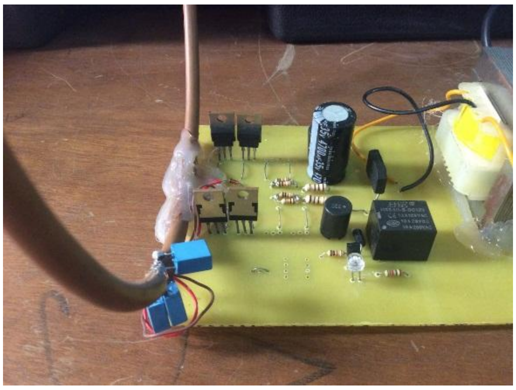


Figure 5: The Transmitter Module

The receiver module of the wireless power transfer system is untethered to a wall outlet, picking up all of its power from the magnetic field generated by the transmitter module. It consists of a receiving coil, a rectifier circuit, a voltage regulator to give a constant output voltage and a universal serial board connector (USB) connector.

Table 2 outlines the components used in the receiver module and their values or codes.

Table 2: Receiver Module Components

COMPONENT NAME	COMPONENT CODE/VALUE
Receiver coil, L3	0.1026µH
Non-polarized capacitor	66nF
Diodes: D2, D3, D4, D5	1N4007
Electrolytic Capacitor,	1000µF
Resistor, R1	1kΩ
Voltage Regulator	7805
U.S.B cable	3.5 mm jack

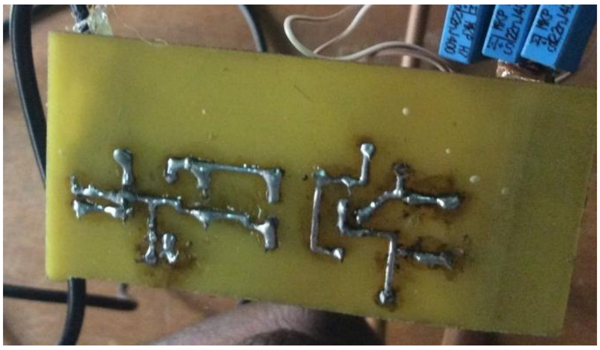
Figure 6: The Receiver Module

IV. SYSTEM IMPLEMENTATION AND PERFORMANCE ANALYSIS

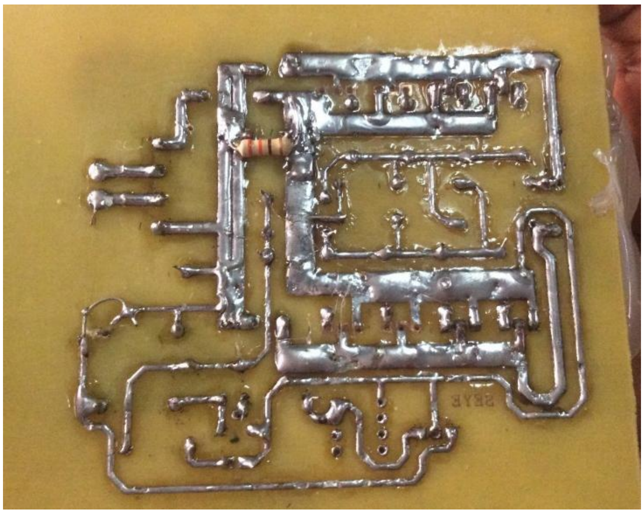
A. *Printed Circuit Board (PCB) Design and Development*

First, the circuit board was designed with the PCB development package in *Proteus* software, making sure that necessary connections for all the components were adequately laid out and drawn with different sizes for the connections based on the amount of current required.

For practical development of the PCB, the heat transfer method was employed. First, the circuit board layout was printed using a laser printer on glossy paper used for magazines. Afterwards, a laminating machine was used to transfer the ink-printed layout from the paper to a copper board with its oxidation layer scrapped off. This leaves a layer of ink on the board. Next, the board is immersed into an etching chemical to remove the exposed parts of copper from the board. The etching leaves only the circuit layout on the board, covered with ink, which was removed with a solution of acetone or methylated spirit. Finally the components of the system are soldered onto the board then its entire layout is covered with soldering lead.



(a)



(b)

Figure 7 (a) and (b): Printed Circuit Boards of the Wireless Power Transfer System with layouts covered with soldering lead.

B. *System Performance Analysis*

For transmitter performance guarantee, voltage values are measured at different stages of the transmitter circuit to obtain the exact values of the voltages at every stage. These values are needed because they may vary from theoretical values. The result of this test is given in Table 3.

Table 3: Output Voltage Measurement Result of the Transmitter Module

Parameter	**Voltage Type (AC/DC)**	**Theoretical Value (V)**	**Actual Value (V)**
Transformer Output	AC	12	12
Rectifier Output	DC	12	11.72
Oscillator output	AC	12	10

Also, transmission range was estimated by varying the distance between the transmitter and the receiver; and by measuring the induced voltage at the receiver at regular successive intervals. Readings were obtained until no voltage is induced at the receiver, beyond which the range of transmission can correctly be concluded to have been exceeded. A metre rule was used to monitor the distance between the transmitter and the receiver while a voltmeter was used for voltage measurements. The test result is shown in Table 4.

Table 4: Transmission Range Analysis

Distance (cm)	**Induced AC Voltage (V)**
0	9.7
5	8.1
10	7.6
15	6.9
20	5.6
25	4.9
30	3.2

Furthermore, power transfer efficiency of the system was calculated by finding the ratio of the output voltage of the transmitter to the induced voltage at the receiver end. This was done for each successive distance using the formula:

$$\eta = \frac{Receiver\ \ induced\ \ voltage\ \ at\ x(cm)}{Transmitter\ \ output\ \ voltage} \times 100\% \qquad (1)$$

The result of the transfer efficiency test is given in Table 5.

Table 5: Transfer Efficiency Test Result

Distance (cm)	**Transfer Efficiency (%)**
0	97
5	81
10	76
15	69
20	56
25	49
30	32

V. LIMITATIONS OF WORK

A. Large The size of the copper rings that are part of the LC circuit, which resonate is simply too robust for it to be part of any wireless energy package
B. The range, which is the distance the wireless power system can transmit power over is not up to a meter, in more complex wireless power systems the distance is just a few meters. This is a major hurdle for wireless power networks.
C. The wireless power system's efficiency ranges between 45% and 85%, which is lower than the conventional method of power transmission, which the wireless power system seek to replace.

VI. CONCLUSION AND RECOMMENDATIONS

Delivery of electric power wirelessly to device using resonant inductive coupling promises greater level of convenience to users of portable devices, and eliminates the environmental threat posed by bad cord and cable disposal. With proven concept of wireless power transfer backed up by well-known principles of physics which assents to its feasibility, the system which comprise of a transmitting device tethered to a wall outlet and a receiving device was successfully implemented through circuit simulations and Printed Circuit Board (PCB) production.

Future work should aim at increasing the amount of power that can be transferred. A power amplifier can be employed to increase the output voltage, but this requires a trade-off between the need for high power and preventing the circuit temperature from exceeding safe level. On the other hand, the coil size and the number of turns of wire that make up the coil can be changed to increase power output. After an ideal power output is reached, it will be interesting to explore the effect of different coil orientations and the presence of extraneous objects on power transfer.

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