Characterization Of Resonant Coupled Inductor in A Wireless Power Transfer System

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Abstract: A novel technology known as wireless power transfer based on coupled magnetic resonances allows for the transfer of energy in the non-radiative near-field using coupled magnetic resonances. In this study, a single-loop inductor that serves as the system's receiver and transmitter is designed, simulated, manufactured, and experimentally characterized. To make analyzing the transfer characteristics of a magnetically coupled resonator system easier, a circuit model is proposed. This structure relates the output voltage in the receiving loop to various transfer orientations and distances. Simulated and examined at a predetermined driving frequency. About 580 kHz is the system's driving resonant frequency. According to experimental findings, energy can still be transmitted under most circumstances even when the recipient is shielded. Walls, books, wooden items, organic glass panels, leather, and textiles are examples of non-metallic objects that have no effect on the flow of electrical energy. Energy transfer demonstrates that the square of the difference $\left(\frac{1}{r^2}\right)$ between the transmitting and receiving resonance loops has an inverse relationship with the transfer efficiency. The transfer power and efficiency decrease as the distance between them increases. The near-field idea is portrayed in this.

Keywords - ***Wireless Power Transfer, Coupled Magnetic Resonance, Resonance Frequency, Inductive Coupling.***

I. INTRODUCTION

Nowadays, the manufacturing and improvement of mobile appliances such as mobile phones, laptops and other electronics and communications devices have increased rapidly. Regardless of the portability and mobility to communicate wirelessly these devices require regular charging usually by plugging them into a wall outlet. This intensifies the quest for new techniques in order to provide power wirelessly to these devices to improve their portability and mobility for end users.

Wireless energy transfer or Wireless Power Transfer (WPT) is a process that takes place in a system where electrical energy is transmitted from a power source to an electrical load without interconnecting wires.

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Numerous physiological methods, including a laser, the piezoelectric principle, radio waves, microwaves, inductive coupling, and strong electromagnetic resonance, have been used to transfer energy wirelessly up to this point. Using a magnetic field to transfer large amounts of power eventually leads to discontent and health risks for people. The technique is effective, but it has a drawback because it needs a clear line of sight and has a mechanism that could be harmful to living things. Due to its high-power transfer efficiency and lack of negative effects on human health, wireless energy transfer via the electromagnetic resonance phenomena has thus emerged as a feasible option, at least for short distances. (Karalis et al., 2008)

The technology of WPT, electromagnetic induction and microwave power transfer are famous. However, electromagnetic resonance couplings have only been proposed recently. The technology of this wireless power transfer requires three main elements: large air gaps, high efficiency, and a large amount of power. Electromagnetic resonance coupling is the only technology that deals with these three elements.

The general objective of this study is to characterize resonant coupled inductors for wireless power transfer systems.

Specifically, this study aims to: (1) Design a wireless power transfer system; (2) Create a model of a wireless power transfer system and simulate the system; (3) Determine the effective distance that the model can transmit for a given amount of power for different orientations of the power transmitter; (4) Compare the simulation results with measured values, and (5) Develop a procedure to analyze data to come up with a method for characterizing wireless power transmission systems.

In the development of household devices, engineers and designers today are expected to provide a new level of convenience and flexibility to consumers. A WPT system was investigated to overcome the inconvenience of using a power cable. Wireless transmission is useful in cases where interconnecting wires is inconvenient, hazardous, or impossible. When wireless power transfer is achieved, the portability and mobility of electronic devices will improve because the process of charging devices will be made a lot more convenient as we do not have to plug a cord into a socket. Also, in this case of wireless charging, the danger of being electrocuted due to the wear and tear of an old cord makes the charging safe.

This research project uses resonant inductive coupling to transfer power wirelessly. The research study uses a low power supply to transmit power. The scope of this study is limited to the construction of a simplified WPT system using a resonant coupled inductor system. This study includes the matching sections, derivation of the relationship between the coupling coefficient and distance and the parameters (quality factor, coupling coefficients, mutual inductance, resonance frequency) of the resonators. The researcher uses a 12V, 5W CYD LED bulb as the load to be able to distinguish easily whether the system is operating well or not. This study will not cover other possible methods for improving the efficiency of wireless power.

II. METHODOLOGY

This section outlines the design, approach and techniques followed in the prototyping and testing of the proposed system. Shown in Figure 1 are the procedural steps used in conducting this research study.

As gleaned from the Methodology Flow Chart, data gathering, and analysis cover the required definition of the hardware and software to come out with the appropriate design and the development of the project.

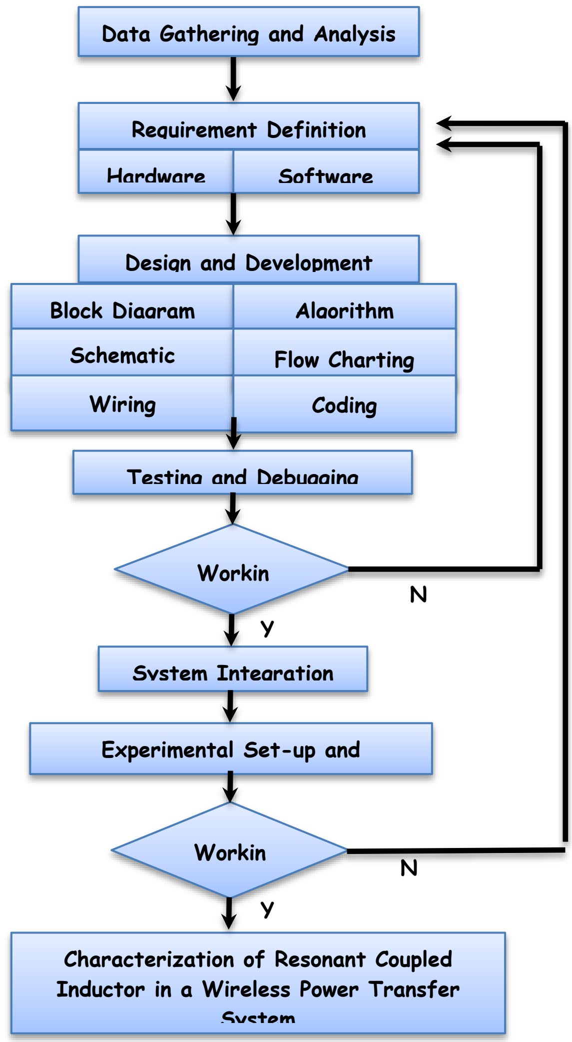

Fig. 1. Methodology Flow Chart

The design refers to the actual planning for the hardware and software of the system. It includes the determination of the conceptual framework and materials used for the hardware implementation. It also refers to the determination of the algorithm, program flow and the type of software used for the software implementation.

After the project was assembled, testing and debugging followed. Al the necessary adjustment is already done. Also, the hardware and the software were integrated for testing.

Experiments were done considering the variables of the study which are the distances between the transmitting and receiving coils, resonant frequency, voltage gain and the efficiency of the system.

Characterization of the parameter of Resonant Coupled Inductor in a Wireless Power Transfer System was based on the results of the experiment which are discussed in the following sections of this paper.

2.1 System Block Diagram

Figure 2 shows the block diagram of the system. The system is composed of four main sections: the power amplifier; the transmitting loops; the receiving loops and the voltage rectifier, these systems are being design to modify the objectives.

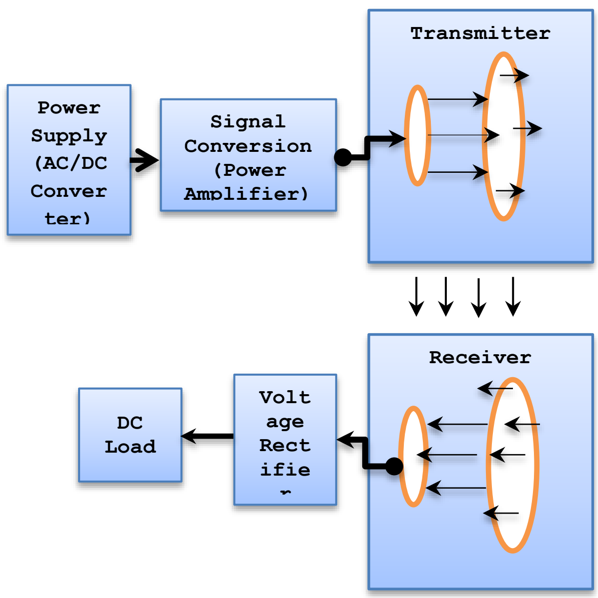

Fig. 2. The Block Diagram of the System

2.2 Circuit Model and Transfer System

The magnetically coupled resonator system can be represented in terms of lumped circuit elements L, C, and R. Figure 3 shows a circuit diagram that can be used for hand analysis or for SPICE simulations.

The schematic diagram in figure 3.7 consists of four resonant circuits, linked magnetically by coupling coefficients $\boldsymbol{k_{12}}, \boldsymbol{k_{23}}$, and $\boldsymbol{k_{34}}$. Starting from the left, the power loop is excited by a source with finite output impedance, $\boldsymbol{R_S}$. Modeling a straightforward one-turn power loop as an inductor L_1 with a parasitic resistance R_1 is possible. To make the power loop resonate at the desired frequency, capacitor C_1 is applied. The parasitic resistance R_2 and one-turn air core inductor L_2 make up the transmitter (T_x) loop as well. The geometry of the Tx loop determines its self-capacitance which is represented as $\boldsymbol{C_2}$. Inductors $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ are connected with coupling coefficient $\boldsymbol{k_{12}}$; the receive side is defined similarly. Finally, the transmitter and receiver loops are linked by coupling coefficient, $\boldsymbol{k_{23}}$. A typical implementation of the system would have the drive loop and Tx coil built into a single device such that $\boldsymbol{k_{12}}$ would be fixed. Similarly, $\boldsymbol{k_{34}}$ would also be fixed. Thus $\boldsymbol{k_{23}}$ is the remaining uncontrolled value which varies as a function of the distances between the transmitter and the receiver.

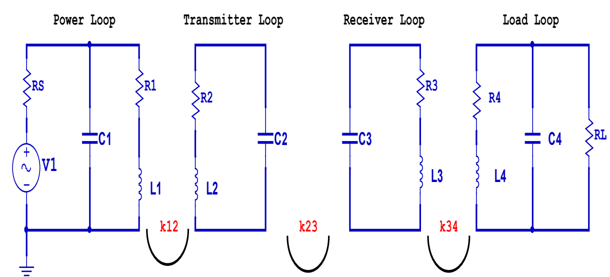

Fig. 3. Equivalent Circuit Model of the Wireless Power Transfer System.

Each of the four antenna elements are modelled as parallel resonators, which are linked by mutual inductances and coupling coefficients.

Analyzing the transfer properties of a magnetically linked resonator system can be done easily using the circuit model as a reference. To keep the analysis simple, the cross-coupling terms k_{12} and k_{34} are ignored. The circuit model provides a straightforward means of systematically analyzing the system's properties. A relationship between the current flowing through each coil and the voltage applied to the power coil can be captured by applying the Kirchhoff's Voltage Law (KVL) of circuit theory to this system, with the currents in each resonant circuit selected as shown in Figure 3. The coupling coefficient is defined in equation 2.

$$\begin{bmatrix} V_s \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} & 0 & 0 \\ j\omega M_{12} & Z_2 & -j\omega M_{23} & 0 \\ 0 & -j\omega M_{23} & Z_3 & j\omega M_{34} \\ 0 & 0 & j\omega M_{34} & Z_4 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} \quad (1)$$

$$k_{xy} = \frac{M_{xy}}{\sqrt{L_x L_y}}, \ 0 \le k_{xy} \le 1 \quad (2)$$

$\mathbf{M_{xy}}$ denotes the mutual inductance between coils "x" and "y," and $\mathbf{Z_1}$, $\mathbf{Z_2}$, $\mathbf{Z_3}$, and $\mathbf{Z_4}$ denote the loop impedances of the four coils. These impedances are denoted as follows.

$$Z_1 = R_s + \frac{R_1 + j\omega L_1}{\omega^2 L_1 - j\omega C_1 R_1 + 1} \quad (3)$$

$$Z_2 = R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \quad (4)$$

$$Z_3 = R_3 + j\left(\omega L_3 - \frac{1}{\omega C_3}\right) \quad (5)$$

$$Z_4 = R_L + \frac{R_4 + j\omega L_4}{\omega^2 L_4 - j\omega C_4 R_4 + 1} \quad (6)$$

The current in the load coil resonant circuit is calculated from matrix 1 using the substitution method as

$$i_4 = -\frac{j\omega^3 M_{12} M_{23} M_{34} V_S}{Z_1 Z_2 Z_3 Z_4 + \omega^2 {M_{12}}^2 Z_3 Z_4 + \omega^2 {M_{23}}^2 Z_1 Z_4 + \omega^2 {M_{34}}^2 Z_1 Z_2 + \omega^4 {M_{12}}^2 {M_{34}}^2} \quad (7)$$

As can be seen, the voltage across the load is equal to $\mathbf{V_L = -i_4 R_L}$, and the source and load voltages have a voltage-to-voltage relationship denoted by the symbol $\mathbf{V_L/V_s}$.

An analogy to a two-port network would be the system model. S - parameter is a suitable candidate for analyzing a figure of merit of this type of system. S_{21} refers to a vector that measures the proportion of signals that exit output ports to signals that enter input ports. The critical element determining the effectiveness of power transfer is a power gain, which is determined by the parameter $|\mathbf{S_{21}}|^2$, the squared magnitude of $\mathbf{S_{21}}$. $\mathbf{S_{21}}$'s parameter is calculated by (Sample et al., 2011, as cited in Fletcher & Rossing, 1998; Mongia, 2007) (Sample et al., 2011, as cited in Fletcher & Rossing, 1998; Mongia, 2007)

$$S_{21} = 2\frac{V_L}{V_S}\left(\frac{R_S}{R_L}\right)^{1/2} \quad (8)$$

III. EXPERIMENTAL RESULTS AND VALIDATION

According to the structure proposed before, the experimental device has been made and study of energy transfer shows a broad application prospect for this technology in the future. Fig.4. depicts the structure of the inductive coupling between the source, the transmitting resonator, the receiving resonator, and the load. The source is represented by the first loop on the left (last loop on the right). The experimental configuration utilized to verify the theoretical model. The transmitter on the left consists of a small drive loop centered within a bigger loop resonator with 0.7 cm apart. The drive loop is 30 cm in diameter, with a parallel connected capacitor used to tune the system to 593.383 kHz. The large transmit loop has an outer diameter of 40 cm. The resonant frequency of 593.383 kHz was determined experimentally. The receiver is constructed similarly with the same distance as the transmitter. All elements are made of 13 mm diameter copper tube, supported by Plexiglas armatures. One of the significant challenges when comparing the theoretical model to measured data is the accurate estimation of the lumped circuit parameters L, C and R of the physical system. To accomplish this task, we used standard RF and microwave measurement techniques developed to extract parameters such as resonant frequency, coupling coefficient, and unloaded Q factor from resonant structures.

The advantage of this technology is energy transfer can go through various objects. Different kinds of obstacles were placed between the transmitting and receiving loops respectively to test the ability of going through objects. Experimental results show that energy can still be transferred even the receiver is sheltered in most conditions. Non-metallic objects such as walls, books, wooden products, organic glass panels, leather, and textiles have no impact on power transfer.

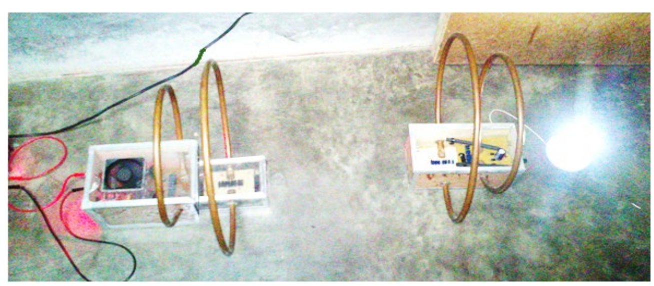

Fig.4. The Energy Transfer Experimental Device

The impact of metallic objects on the system depends on different characteristics of metal conductor. It would have slight impact if the object with size less than the diameter of coil as discussed earlier, or which cannot generate a larger eddy current (Zhu et al., 2008). If the metallic objects which can generate larger eddy current or form a close loop is close to this system, the impact will be greater even block energy transfer.

3.1 System Efficiency

The power received in the receiver coil divided by the power emitted from the transmitter coil is used to calculate the power transfer efficiency, which describes the direct energy transfer between the transmitter and receiver coils as stated in equation 8. The graph below demonstrate that efficiency increases with decreasing distance. Because of the lower efficiency, there should be more space between the transmitting and receiving coils. The graph also shows that the distance between the two coils has a limit. The graph's intersection with the efficiency zero line occurred at this point.

The statistic multiple R suggests that efficiency is highly related to the distance between the coils. Moreover, the R-square (R^2) suggests that 71.15 percent of the variance in the efficiency tested can be explained by the distance of the two coils during the experiment.

Moreover, the analysis of variance yielded an F=24.66 which is significant even beyond the 0.01 level. Actually, the significance level is 0.000564872. This result could be interpreted to mean that there is enough evidence to show that distance between the coils determines higher efficiency of the prototype. This result finds support from the studies of (Sample et al., 2009), (Kurs et al., 2007), (Park and Kim, 2012) and (Yoon and Ling, 2012).

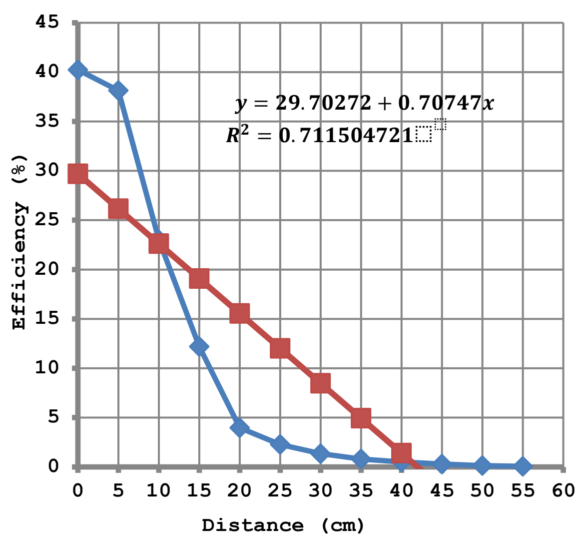

Fig. 5. Relationship between the Transfer Distance and System Efficiency

3.2 Voltage Patterns as a Function of Angular Displacements

The radiation patterns for the producing coil are displayed on the graph in figure 6 below. From this experiment, it can be shown that the energy generated by the producing coil spreads at a 90° angle in front of the coil and at a 90° angle behind the coil. This finding is intriguing since the following experiment will be planned to send the largest amount of forward energy while also taking the rear into consideration for future tests. Additionally, the highest radiation levels are at 345° and 165°, or directly in front and behind the generating coil, respectively (due to the configuration and experiment conditions, the receiving coil had a displacement to the x-axis of around 15°). Given that energy depends on the directivity of the coil, the fact that the pattern is bidirectional has a significant impact on the gain calculation of the system. Thus, the radiation pattern's shape will have an impact on efficiency.

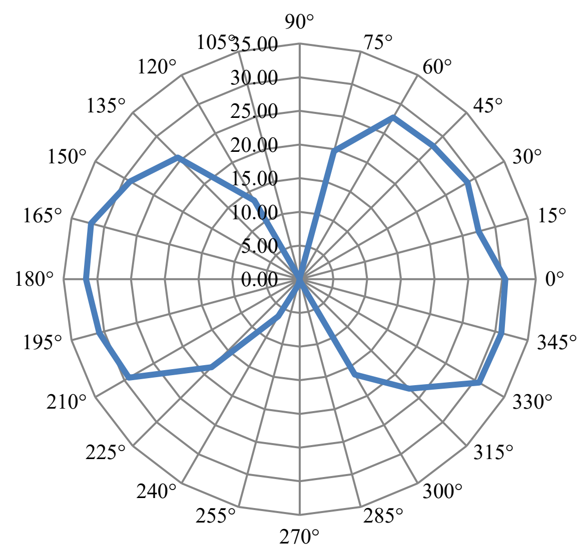

Fig. 6. Voltage Pattern in Different Orientation

IV. CONCLUSION

Wireless energy transfer is completely having potential to be improved and magnetic resonance coupling is most feasible method in wireless energy transfer. Otherwise, this paper also proved that the electrical energy transmission will transpire the most efficient in the resonance frequency. The application was used to prove this by using cell phone, dc motor, led and bulb. In addition, it can conclude that the maximum output voltage at receiver of the resonant wireless energy transfer depends on the size of coil and the input voltage. The transfer energy could be done effectively by increasing the input voltage. The size and frequency of the device also should be taken into account since the resonance wireless energy transfer device works in the medium or high frequency range of electromagnetic field. The higher the frequency, the closer is the common coil and capacitor to the resonant condition.

This work establishes the foundation for creative wireless power technology and presents potential for the commercial application of cutting-edge electromagnetic resonance based on WPT systems. It has been demonstrated that energy transfer using magnetic coupling resonance technology is entirely practical based on the experimental findings and analysis. To obtain the initial and deterministic design parameters of the WPT system comprising resonators and their coupling elements and achieve a pass band at the frequency of interest, straightforward and widely used processes based on electrical circuit theory are applied to the analyses throughout this paper. Additionally, Multisim has been used to simulate circuits.

The Power Transfer Efficiency significantly declines as a function of distance outside the coupled mode zone. This demonstrates the hypothesis since the coupled mode resonance phenomena vanishes as the distance between the two antennas grows, and the antennas in the near field operate like conventional transmitting and receiving antennas. It was verified that the distance between the coils center play an important role on the efficiency of the power transfer, decreasing as the center are moved away and reaching its maximum at 0 cm. Besides, the relative angles between planes of each coil also affect the efficiency, establishing in experiment that the planes should be placed in parallel fashion over the same axis. This theoretical model is validated against measured data and shows an excellent average coefficient of determination R^2 of 0.937118 that signifies 93.7118 percent of the variation in the distance can be explained through the linear regression relation.

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