Design & Implementation of Cost Effective Wireless Power Transmission Model: GOOD BYE Wires

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Abstract- Power is very important to modern systems. From the smallest sensors, bionic implants, laptops, consumer products to satellites and oil platforms, it is important to be able to deliver power means other than classical wires or transmission lines. Wireless transmission is useful in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, or impossible. An efficient method for wireless power transfer would also enable advances in such diverse areas as embedded computing, mobile computing, sensor networks, and micro robotics. The need to minimize energy consumption is often the main design driver in applications where devices need to operate without tethered. Energy consumption often restricts functionality in such applications. The work depicted in this paper is inspired by potential application of magnetic resonant coupling as a means for WPT from a source coil to a single load. It is observed that without the intermediate coil a LED is lit up to a maximum distance of 70 centimeter and with intermediate coil that lead is lit up to a maximum distance of 91 centimeter with voltage measured 2.2volts. Several experiments regarding this technique need to carry out for a better output and the day is not far when the need for wires will get obsolete.

Index Terms- Wireless Power, transmission, magnetic, resonance, oscillator etc.

I. INTRODUCTION

Power is very important to modern systems. From the smallest sensors, bionic implants, laptops, consumer products to satellites and oil platforms, it is important to be able to deliver power means other than classical wires or transmission lines. Wireless transmission is useful in cases where instantaneous or continuous energy transfer is needed, but interconnecting wires are inconvenient, hazardous, or impossible some times. In the case of biological implants, there must be a battery or energy storage element present that can receive and hold energy. This element takes up valuable space inside a person body. In the case of satellites, UAVs and oil platforms, solar panels, fuel cells, or combustion engines are currently used to supply power [1]. Solar panels take up a great deal of weight and bulk in terms of energy density and must have a tracking system to maximize exposure to the sun. Fuel cells and combustion cells needs fuel and maintenance to be delivered on site. Wireless Power Transmission (WPT) is the efficient transmission of electric power from one point to another trough vacuum or an atmosphere without the use of wire or any other substance. This can be used for applications where either an instantaneous amount or a continuous delivery of energy is needed, but where conventional wires are unaffordable, inconvenient, expensive, hazardous, unwanted or impossible. The power can be transmitted using Inductive coupling for short range, resonant induction for mid range electromagnetic wave power transfer [2]. WPT is a technology that can transport power to locations, which are otherwise not possible or impractical to reach. The objective of this paper is to design and implement a method to transmit wireless electrical power through space. The system will work by using resonant coils to transmit power from an AC line to a resistive load. Investigation of various geometrical and physical form factors evaluated in order to increase coupling between transmitter and receiver. Use of resonant coupling in order to maximize power transfer and analytical derivations of coupled network power transfer calculations is presented.

II. LITERATURE REVIEW

For better comprehension theories related to Magnetic Resonant Coupling, quality factor and optimization techniques for wireless power transfer systems are presented here along with the working principles and constructions of various components. Magnetic coupling is an old and well understood method in the field of wireless power transfer. But as the magnetic field decay very quickly, magnetic field is effective only at a very short distance [3]. By applying resonance with in magnetic coupling, the power transfer at a greater distance can be obtained. For near field wireless power transfer, Magnetic resonant coupling can be the most effective method than any other method available. The block diagram for the whole experiment is shown below. It is consisting of an AC source, rectifier, oscillator, transmitter, secondary sources and load coil. It is observed that the voltage at a distance is better with an intermediate coil than without intermediate coil.

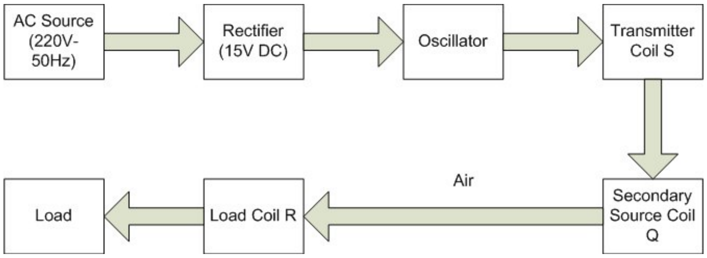

Fig-1: Block diagram of the wireless power transfer system.

A. Magnetic Resonant Coupling

Inductive or Magnetic coupling works on the principle of electromagnetism. Transferring energy between wires through magnetic fields is inductive coupling. If a portion of the magnetic flux established by one circuit interlinks with the second circuit, then two circuits are coupled magnetically and the energy may be transferred from one circuit to the another circuit [2]. This energy transfer is performed by the transfer of the magnetic field which is common to the both circuits.

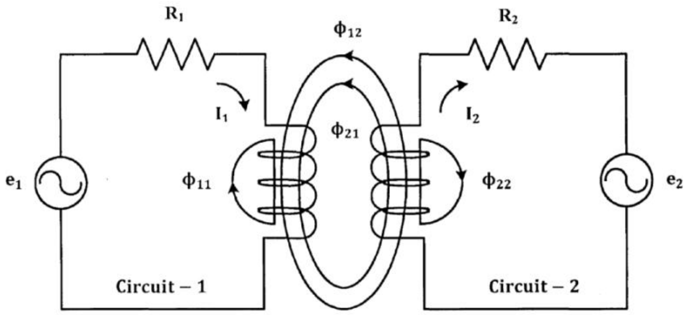

Fig-2: Magnetic coupling with four component fluxes.

Magnetic coupling between two individual circuits are shown in Figure 2. For the purpose of analysis it is assumed the total flux which is established by i_1 (circuit-1 current) is divided into two components. One component of is that part which links with circuit-1 but not with circuit-2. The second component of is which links with both circuit-2 and circuit-1. In this similar way the flux established by i_2 (circuit-2 current), namely 2 has also two components. One component of 2 is 22 which links only circuit-2 but not with circuit-1. Again another component of 2 is 21 which links both circuit-2 and circuit-1.

$$\phi_1=\phi_{11}+\phi_{12}$$

$$\phi_2=\phi_{22}+\phi_{21}$$

Here 12 is a fractional part of ϕ_1, which links with the turns of circuit-2. So ϕ_{12} is called the mutual flux produced by circuit-1. In the same way the fractional part of ϕ_2 is ϕ_{21} which links with the turns of circuit-2. So ϕ_{21} is called the mutual flux produced by circuit-2. This is the phenomenon how the magnetic coupling takes place between two individual circuits. This effect can be magnified or amplified through coiling the wire. Power transfer efficiency of magnetic coupling can be increased by increasing the number of turns in the coil, the strength of the current, the area of cross-section of the coil and the strength of the radial magnetic field.

B. Resonant frequency

Resonance is a phenomenon that causes an object to vibrate when energy of a certain frequency is applied. In physics, resonance is the tendency of a system (usually a linear system) to oscillate with larger amplitude at some frequencies than at others. These are known as the system's resonant frequencies. In these particular frequencies, small periodic driving forces even can produce oscillations having large amplitude.

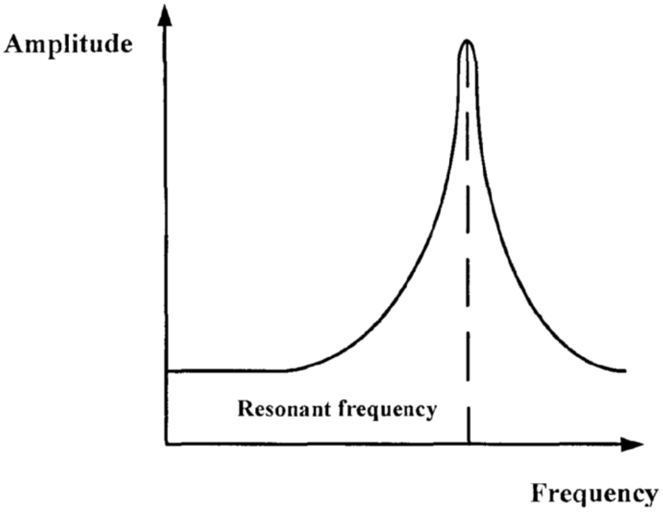

Fig-3: Resonant frequency.

C. Magnetic Resonant Coupling

Magnetic Resonant coupling uses the same principles as inductive coupling, but it uses resonance to increase the range at which the energy transfer can efficiently take place. Resonance can be two types: (a) series resonance & (b) parallel resonance. In these both types of resonance the principle which is to get maximum energy transfer is same but the methods are quite different.

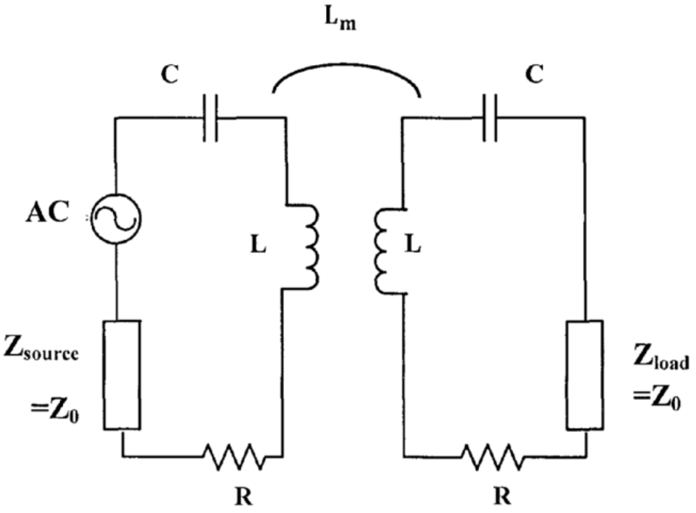

Fig-4: Equivalent Circuit of Magnetic Resonant Coupling.

Figure 4 shows how the resonance occurs. Here the circuit-1 is called primary circuit and the circuit-2 is called secondary circuit. The energy transfer will occur between these two circuits. The resonant conditions in such circuit either in the primary circuit, when the primary current is in phase with the input voltage, or in the secondary circuit, when the secondary circuit current is in phase with the secondary induced voltage. The former resonance is called primary particular resonance and the latter is a secondary particular resonance [4]. The full resonance occurs when both the primary and the secondary circuits are in the resonant condition. Resonant transfer works by making a coil ring with an oscillating current [6]. This generates an oscillating magnetic field. Because the coil is highly resonant and any amount of energy placed in the coil dies away relatively slowly over time periods. However, if a second coil is brought near to it, the coil can pick up most of the energy before it is lost. The resonant frequency can be calculated from the equivalent circuit. To satisfy the resonance condition, the reactance of Figure 4 must be zero, as in equation (1). The condition in equation (1) can be satisfied by two resonant frequencies as calculated in equation (2) and (3). The coupling coefficient can be calculated from equation (2) and (3) to become equation (4). It represents the strength of the magnetic coupling between the antennas, which is closely related to factors such as the air gap between the antennas and the obstacles between them.

$$\frac{1}{\omega L_m} + \frac{2}{\omega(L-L_m)-\frac{1}{\omega C}} = 0 \qquad \ldots\ldots(1)$$

$$\omega_m = \frac{\omega_0}{\sqrt{(1+K)}} = \frac{1}{\sqrt{(L+L_m)C}} \qquad \ldots\ldots(2)$$

$$\omega_e = \frac{\omega_0}{\sqrt{(1+K)}} = \frac{1}{\sqrt{(L-L_m)C}} \qquad \ldots\ldots(3)$$

$$K = \frac{L_m}{L} = \frac{\omega_e^2-\omega_m^2}{\omega_e^2+\omega_m^2} \qquad \ldots\ldots(4)$$

D. Quality Factor

In physics and engineering the Quality factor (Q-factor) is a dimensionless parameter that describes the characteristics of an oscillator or resonator, or equivalently, characterizes a resonator's bandwidth relative to its center frequency [1]. Higher Q indicates the stored energy of the oscillator is relative of a lower rate of energy loss and the oscillations die out more slowly. So it can be stated that, Oscillators with high quality factors have low damping so that they pendulum ring longer, in case of a pendulum example.

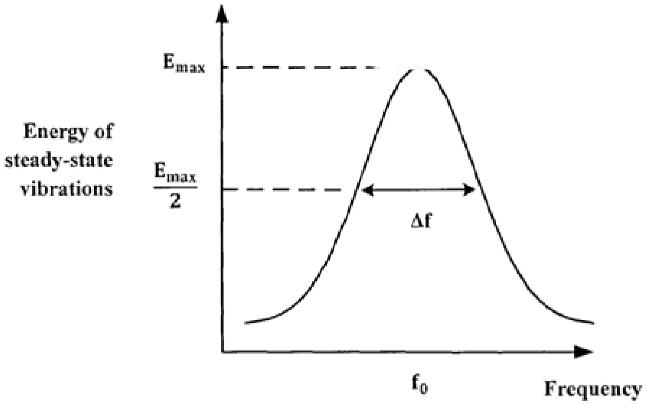

Fig-5: Bandwidth versus frequency.

The above graph is the representation of the bandwidth, Δf, of a damped oscillator energy versus frequency. The higher the Q, the narrower and 'sharper' the peak is $\frac{\mathrm{fo}}{\Delta \mathrm{f}}$. Sinusoidal signal driven resonators having higher Q factors resonate with greater amplitudes (at the resonant frequency) but have a smaller range of frequencies around that frequency for which they resonate; the range of frequencies for which the oscillator resonates is called the bandwidth. Thus, a high Q tuned circuit in a radio receiver would be more difficult to tune, but would have more selectivity [5].

In an ideal series RLC circuit and in a tuned radio frequency receiver (TRF) the Q factor can be written as:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Where, R, L and C are respectively the resistance, inductance and capacitance of the tuned circuit. For a parallel RLC circuit, the Q factor is the inverse of the series case.

$$Q = R\sqrt{\frac{C}{L}}$$

For a circuit where R, L and C are all in parallel, the lower the parallel resistance, the more effects it will have in damping the circuit and thus the lower the Q [9]. In this case the X and R are interchanged.

E. Basic Theory of Impedance Matching

Impedance Matching is a technique commonly used in power transfer systems and communication systems to improve the efficiency of the system. It usually involves inserting a matching network (such as an LC circuit) to minimize the power reflection ratio to the power source of the system. In Figure-6, the power transferred to the load is written as equation (5) when the impedance of the power source is defined as Z_{source} and that of the load is defined as Z_{load}. The power transferred to the load reaches its maximum when $Z_{source}=Z^*_{load}$, as in equation (6). Therefore, the circuit is considered matched and the maximum efficiency achieved when the impedance of the load from the source's point of view matches Z_{source}, and vice versa.

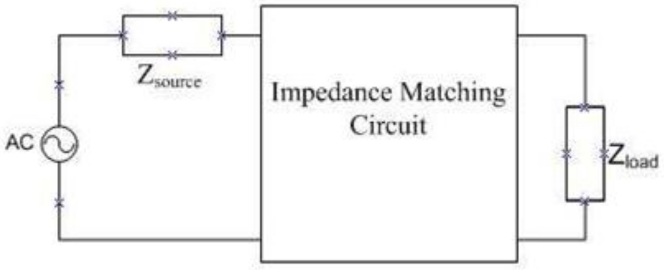

Fig-6: Theory of impedance matching.

$$P = I^2 Z = \frac{V^2}{Z_{Source}}\left(\frac{1}{\frac{Z_{Source}}{Z_{Load}}+2+\frac{Z_{Load}}{Z_{Source}}}\right) \quad ……(5)$$

$$P_{max} = \frac{V^2}{4Z_{Source}} \quad ……(6)$$

The Impedance matching circuit can be considered as a two-port network that can be described with equation (7). The matching conditions are satisfied when the parameters satisfy equation (8) & (9).

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}\begin{pmatrix} V_2 \\ I_2 \end{pmatrix} \quad ……(7)$$

$$Z_{Source} = \sqrt{\frac{AB}{CD}} \quad ……(8)$$

$$Z_{Load} = \sqrt{\frac{DB}{CA}} \quad ……(9)$$

III. CIRCUIT DESIGN

Our experimental realization of the scheme consists of three coils that are tuned at the same frequency. An oscillating circuit is connected with a source coil S. Coil S is coupled resonant inductively to an intermediate coil Q; which is in turn coupled resonant inductively to a load carrying coil R. The coils are made of an electrically conducting copper pipe of cross-sectional radius a wound into a helix of single turn, radius r.

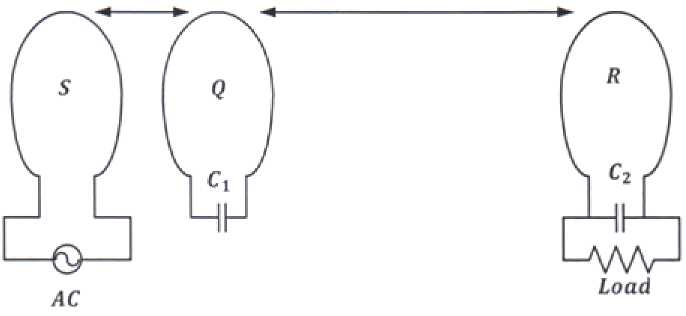

Fig-7: Theoretical Model of the System.

When a radio frequency oscillating signal is passed through the coil S, it generates an oscillating magnetic field, perpendicular to the coil S. The intermediate coil Q is placed near to the coil S, which is tuned at the same frequency through the inductance of the coil and a resonating capacitor C_1. The coil Q being in the area of the magnetic field generated by coil S, receives power. Not having any resistive load, the coil in turn generates its own oscillating magnetic field. The advantage of using this coil is that it is completely separated from the source internal resistance. This increases the Q-factor, allowing greater power to be radiated. In other words, the coil Q becomes the source of the system. The load coil R, tuned at the same resonant frequency, receives the power through the magnetic field generated by the intermediate coil Q. The equivalent circuit diagram of power transfer model is given in figure-8. The power transfer occurs from coil S to coil R. The power loss in coil Q is neglected here, since the coil Q has a very small resistance.

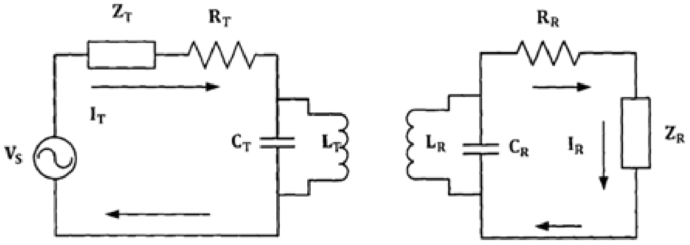

Fig-8: The Equivalent circuit diagram for Theoretical Model of the System.

The above figure can be furthered simplified and that is illustrated in the below diagram.

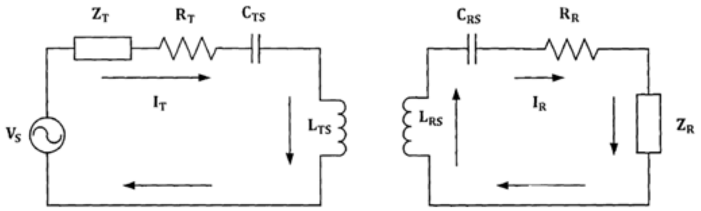

Fig-9: Further Equivalent circuit diagram for figure-8.

Where,
Z_T = Source impedance of transmitter circuit,
C_T = Total capacitance of the LC tank in transmitter circuit,
L_T = Total impedance of the LC tank in transmitter circuit,
R_T = Source resistance of transmitter circuit,
I_T = Total current of transmitter circuit,
C_R = Total capacitance of the LC tank in the receiver circuit,
L_R = Total impedance of the LC tank in the receiver circuit,
R_R = Total resistance receiver circuit,
Z_R Load impedance of receiver circuit,
I_R =Total current of receiver circuit,
C_{RS} = Equivalent series capacitance of CR,
C_{TS} = Equivalent series capacitance of CT,
L_{RS} = Equivalent series inductance of LR,
L_{TS} = Equivalent series inductance of LT.

And from the above circuit we can write,

$$X_{L_{Ts}} = \frac{x_{C_T}}{x_{L_T}} X_{C_{Ts}}$$

$$X_{L_{Rs}} = \frac{x_{C_R}}{x_R} X_{C_{Rs}}$$

$$X_{C_{Ts}} = \frac{x_{CL_T}}{x_{C_T}} X_{L_{Ts}}$$

$$X_{C_{Rs}} = \frac{x_{L_R}}{x_{C_R}} X_{L_{Rs}}$$

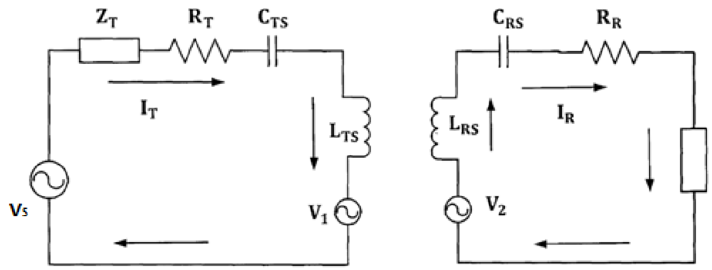

Fig-10: The equivalent circuit diagram of figure-9 with voltage drop due to mutual impedance.

Where, $V_1 = \mathrm{j}\omega \mathrm{M} \mathrm{I}_\mathrm{R}$,

$V_2 = \mathrm{j}\omega \mathrm{M} \mathrm{I}_\mathrm{T}$

$Z_M = \mathrm{j}\omega \mathrm{M} = \mathrm{j}\mathrm{X}_\mathrm{M}$

Now, $Z_T = Z_S + R_T + \mathrm{j}\left(\omega \mathrm{L}_\mathrm{TS} - \frac{1}{\omega \mathrm{C}_\mathrm{TS}}\right)$

$$Z_R = Z_L + R_R + \mathrm{j}\left(\omega \mathrm{L}_\mathrm{RS} - \frac{1}{\omega \mathrm{C}_\mathrm{RS}}\right)$$

$$Z_S = R_S + \mathrm{j}X_S$$

$$Z_L = R_l + \mathrm{j}X_L$$

Mesh Equation for the Transmitter circuit,

$$V_S - V_1 - Z_T I_T = 0$$

$$\Longrightarrow I_T = \frac{v_S - v_1}{Z_T}$$

$$\Longrightarrow I_T = \frac{v_S - Z_M I_R}{Z_T}$$

Mesh equation for the receiver circuit,

$$V_2 - Z_R I_R = 0$$

$$\Longrightarrow I_R = \frac{V_2}{Z_R} = \frac{Z_M I_T}{Z_R}$$

$$\Longrightarrow I_R = \frac{Z_M (V_S - Z_M I_R)}{Z_T Z_R}$$

$$\Longrightarrow (Z_T Z_R + Z_M^2) I_R = Z_M V_S$$

$$\Longrightarrow I_R = \frac{Z_M V_S}{Z_T Z_R + Z_M^2}$$

$$\Longrightarrow I_T = \frac{Z_T}{Z_R} I_R = \frac{Z_M V_S}{Z_T Z_R + Z_M^2}$$

Hence the delivering power by the transmitter circuit,

$$P_1 = R_e\{V_s I_T^*\} = V_s R_e\{I_T^*\}$$

$$\Longrightarrow P_1 = V_s R_e \left\{ \frac{Z_R^* V_S}{Z_T^* Z_R^* + Z_M^{2*}} \right\}$$

And the receiving power by the receiver load,

$$P_2 = I_T I_R^* R_e\{Z_L\} = I_T I_R^* R_L$$

$$\Longrightarrow P_2 = \frac{Z_M Z_M^* V_S R_L}{(Z_T Z_R + Z_M^2)(Z_T^* Z_R^* + Z_M^{*2})}$$

A.C.M de Queiroz [7] provides details information about these equations. Power can be figure out by using these above equations for this experiment. For the rectifying purpose the simple full wave bridge model is used just for the simplicity of the experiment. At the same time the capacitor is used for smoothing the output curve. The circuit diagram is given below.

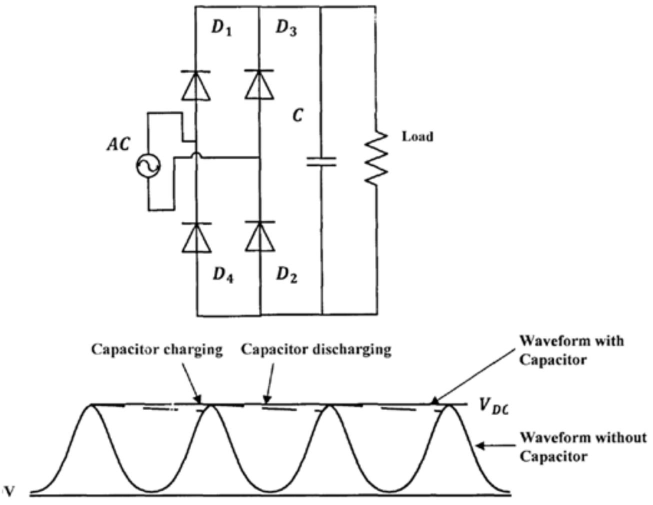

Fig-11: Full-wave bridge rectifier with smoothing capacitor.

The main advantages of a full-wave bridge rectifier is that it has a smaller AC ripple value for a given load and a smaller reservoir or smoothing capacitor than an equivalent half-wave rectifier. Therefore, the fundamental frequency of the ripple voltage is twice that of the AC supply frequency (100Hz) where for the half-wave rectifier it is exactly equal to the supply frequency (50Hz).

The following oscillator circuit is used. This oscillator circuit is incredibly simple yet a very powerful design. Very high oscillating current can be achieved with this circuit depending on the semiconductor used. Here high current is necessary to increase the strength of the magnetic field. Although Insulated Gate Bipolar Transistors (IGBT) is recommended for this type of oscillator, but IGBTs have limitations in high frequencies.

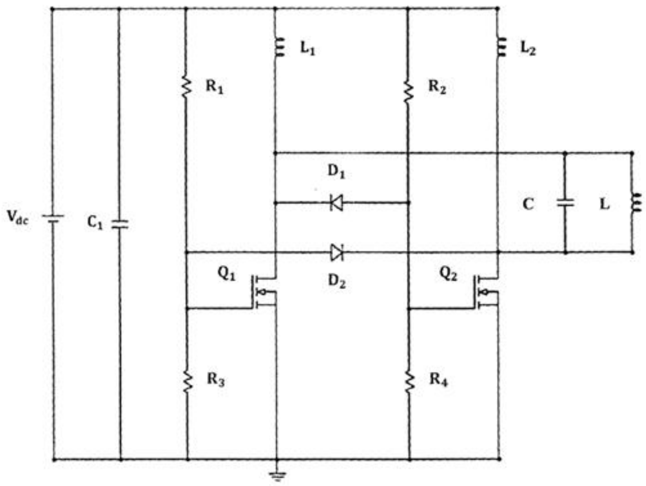

Fig-12: Oscillator circuit for Wireless power transfer System.

The values of the parameters that have used in this oscillator circuit are given below.

Component's Name	**Component's Value or code**
Voltage Source, Vdc	1 5V
Capacitor, C_1	l00nF
Capacitor, C	60nF
Resistor, R_1	100 ohm
Resistor, R_2	100 ohm
Resistor, R_3	10k ohm
Resistor, R_4	10k ohm
Diode, D_1	1N4142
Diode, D_2	1N4 142
MOSFET,Q_1	IRF1OIO
MOSFET, Q_2	IRF1OIO
Radio Frequency Choke,L_1	lOOuH
Radio Frequency Choke, L_2	1OouH
Transmitter coil, L	187.5nH

The circuit consists of with two chokes labeled L_1 and L_2, two semiconductors (Here N-channel Enhancement power-MOSFETS) labeled Q_1 and Q_2, a resonating capacitor labeled C and an inductor (here the transmitter Coil) labeled L. Cross-coupled feedback is provided via the diodes D_1 and D_2. R_1, R_3 and R_2, R_4 are the biasing network for MOSFETS Q_1 and Q_2. When power is applied, DC current flows through the two sides of the coil and to the transistors' drain. At the same time the voltage appears on both gates and starts to turn the transistors on. One transistor is invariably a little faster than the other and will turn on more. The added current flowing in that side of the coil does two things. One, it takes away drive from the other transistor. Two, the auto-transformer action impresses a positive voltage on the conducting transistor, turning it hard on. The current would continue to increase until the coil (transformer) saturates. The resonating capacitor C causes the voltage across the primary to first rise and then fall in a standard sine wave pattern.

Assuming that Q_1 turned on first, the voltage at the drain of Q_1's will be clamped to near ground while the voltage at Qz's drain rises to a peak and then falls as the tank formed by the capacitor and the coil primary oscillator through one half cycle. The oscillator runs at the frequency determined by the inductance of the Coil, the capacitor value and to a lesser extent, the load applied to the secondary (Source coil).

The operating frequency is the familiar formula for resonance,

$$F=\frac{1}{2}\times\pi\times\surd(LC)$$

For the experiment, the source coil, intermediate coil and the load coil was constructed using 3mm copper tube with radius 25 inches. Initially a coil of having only single turn have been used and later on the same coil have been used but with 10turns in each of the coils. This is done just to increase the magnetism property and hence more current. This phenomenon gave better result than the previous one. However, both of these models showed one common property i.e. the voltage drop decreases with an increase in the distance.

The theoretical model and circuit implementation of the wireless power transfer system was designed based on the concept of magnetic resonant coupling. Various optimization factors were also considered while designing the whole system. Due to generalized approach, presented wireless power transfer system can be optimized for new design constraints or for different applications. One of the practical implementation views of this model is given below.

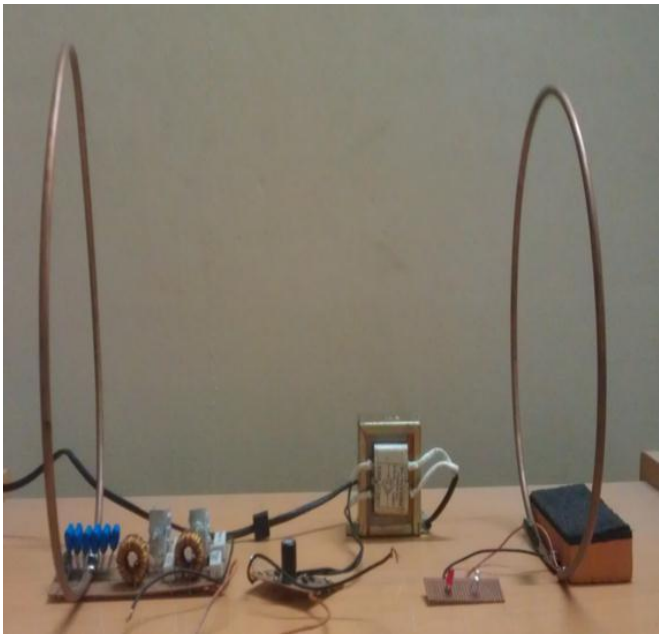

Fig-13: Mechanical Implementation of the project.

At the end of the transmitter circuit an antenna was connected, which transmits the power. Another antenna was used to receive the power wirelessly from the transmitter circuit. In this project hollow copper pipes were used as antenna, because it has high Q-factor and high power handling performance.

IV. PERFORMANCE AND ANALYSIS

The frequency is tuned in between from 1.5MHz to 10MHz. From the oscilloscope it is measured for the resonant frequency property.

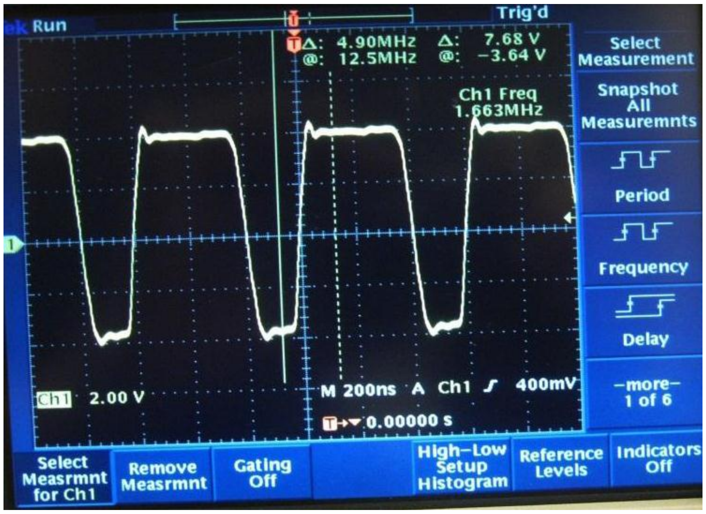

Fig-14: Oscilloscope view for 1.5 MHz – 3.9 MHz signal.

At frequency range from 1.5 MHz – 3.9 MHz, the signal was a square wave.

Fig-15: Oscilloscope view for 3.9 MHz – 10 MHz signal.

At frequencies range from 3.9 MHz – 10 MHz, the signal looked like a triangle wave.

Measurements taken providing 30V with resonant frequency 1.5 MHz across the transmitter and without the intermediate coil:

- A 3 watt bulb lit up at its full strength at a distance of 17 centimeter with voltage measured 15 volt
- A 3 watt bulb lit up to a maximum distance of 41 centimeter with voltage measured 10 volts.
- A LED lit up to a maximum distance of 70 centimeter with voltage measured 2.2 volts
- Voltage measured at a distance 5.25 meter was 3 mill-volts

Measurements taken with intermediate coil placed in between transmitter and receiver at a distance 12cm apart from the transmitter:

- A 3 watt bulb lit up at its full strength at a distance of 34 centimeter with voltage measured 15 volt
- A 3 watt bulb lit up to a maximum distance of 61 centimeter with voltage measured 10 volts.
- A LED lit up to a maximum distance of 91 centimeter with voltage measured 2.2 volts
- Voltage measured at a distance 5.9 meters and the voltage measured 6 mili-volts
- For this experimental setup, the rms voltage across the transmitter is 21.2V. The output rms voltage across a 192-Ω resistive load 34cm away from the transmitting coil is 10.6 V.

The coils were arranged in the configuration as shown below and voltage measurements were taken as a function of distance between the coils.

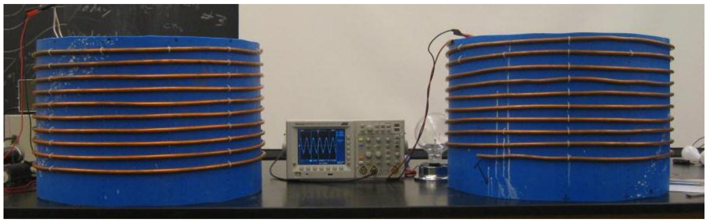

Fig-16: Mechanical Implementation of the project with 10turns of the coil.

The difference between supplied and received power for the system with a single receiver is accounted for power dissipation in the resistances. 50% of the power that leaves the terminals of the actual source (ideal source in series with internal resistance) is delivered to the load resistance. The percentages of the total power that is supplied by the ideal source are dissipated in:

1) 50% to load resistance;
2) 45.95% to internal source resistance;
3) 1.35% to source coil resistance;
4)1.35% to intermediate coil resistance.
5)1.35% to load coil resistance.

The dominant loss occurs in the internal source resistance. This loss occurs whenever a source delivers power to a load, whether through wires or through a wireless power transfer method. The high internal resistance of the oscillator, used here only for concept demonstration, can be significantly reduced by using a more practical power source [8]. Approximately half of the remaining power is delivered to the load resistance. With dissipation in the source coil resistance, the largest loss beyond the actual source terminals. By using an intermediate coil close to the source coil increases the Q-factor to a great extent. The intermediate coil takes up most of the power from the source coil and delivers to the load coil. The Q-factor increases as the intermediate coil does not have source internal resistance in it. Thus the power transfer efficiency and the power transfer range increases significantly.

V. CONCLUSION

The goal of this paper was to design and implement a wireless power transfer system via magnetic resonant coupling. After analyzing the whole system step by step for optimization, a system was designed and implemented. Experimental results showed that significant improvements in terms of power-transfer efficiency have been achieved. Measured results are in good agreement with the theoretical models. It is described and demonstrated that magnetic resonant coupling can be used to deliver power wirelessly from a source coil to a load coil with an intermediate coil placed between the source and load coil and with capacitors at the coil terminals providing a simple means to match resonant frequencies for the coils. This mechanism is a potentially robust means for delivering wireless power to a receiver from a source coil.

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