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Wireless Power Transfer System via Magnetic Resonant Coupling

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***Abstract*— In this paper, we present the concept of Transmitting Power without wires. The Wireless power transmission is implemented by the concept called Magnetic Resonant Coupling. We present new analysis that yields critical insight into design of practical systems.A circuit model is presented which works on Adaptive frequency tuning technique which compensates for efficiency variations encountered when the transmitter to receiver distance and/or orientation are varied. The method demonstrated in this paper allows a fixed-load receiver to be moved to nearly any position and/or orientation within the range of the transmitter and still achieve a near constant efficiency of over 70% for a range of 11-52 cm**.

***Keywords*—Wireless power transfer, Magnetic Resonant Coupling, Impedance Matching, Adaptive tunning.**

I. INTRODUCTION

Advances in wireless communication and semiconductor technology have enabled a wide variety of portable consumer electronic, medical, and industrial devices. However, users are still required to manually plug in these mobile devices, limiting ultimate mobility and disrupting use when charge is depleted. Furthermore, as portable devices shrink, connectors become a larger fraction of system size. Wireless power offers the possibility of connector-free electronic devices, which could improve both size and reliability. Thus, there is the desire to use wireless power technology to eliminate the remaining wired power connection. Presently, several wireless power techniques are being pursued. It is useful to categorize these efforts in terms of their underlying power transfer mechanism to understand implications for range, adaptation and efficiency. Far-field techniques use propagating electromagnetic waves that transfer energy the same way radios transmit signals. This method has been successfully used to power UHF RFID tags, which have no batteries and an operating range of 10 meters [1], [2]. One of the drawbacks to far-field approaches is the inherent tradeoff between directionality and transmission efficiency. There are many examples of RF and microwave systems that use high gain antennas to transfer power over kilometer distances at efficiencies of over 90% [3], [4]. These systems suffer from the need for sophisticated tracking and alignment equipment to maintain a line of sight (point to point) connection in unstructured and dynamic environments. Alternatively, RF broadcast methods, which transmit power in an Omni-directional pattern, allow for power transfer anywhere in the coverage area. In this case, mobility is maintained, but end to end efficiency is lost since power density decreases with a $1/r^2$ dependence, resulting in received power levels many orders of magnitude less than what was transmitted [5].

In this work, we extend prior analysis of coupled magnetic resonance to elucidate several key system concepts including: Magnetic Resonant coupling, Impedance matching and Adaptive Tunning for range independent maximum power transfer. A method for automatically tuning the wireless power system is demonstrated, so that the maximum possible transfer efficiency is obtained for nearly any distance and/or orientation as long as the receiver is within the working range of the transmitter. This is important from a practical standpoint because in many applications, such as laptop recharging, Electric vehicle Charging the range and orientation of the receive device with respect to the transmit device varies with user behavior [6].

II. SYSTEM OVERVIEW

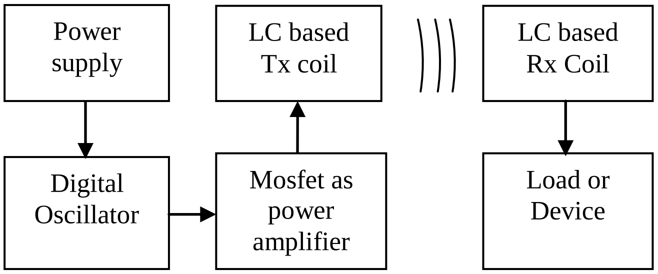


Figure1. Sketch of magnetic coupled resonance wireless power system

Figure. 1 presents wireless power system using magnetically coupled resonators. The transmit antenna consists of a LC based Transmitting coil. The Digital Oscillator generates a signal at frequency where maximum power transfer takes place, the signal is then amplified through N-channel Mosfet which act as a power amplifier thus results in an oscillating magnetic field which excites the Tx coil which stores energy in the same manner as a discrete LC tank The key interaction occurs between the two coils each of which is a high-Q LCR tank resonator. Just as the coils are magnetically coupled, the transmit and receive coils share a mutual inductance which is a function of the geometry of the coils and the distance between them. Another significant property of coupled oscillators is that the amount of coupling defines the rate of energy transfer, not its efficiency [7]. To the extent that these losses can be neglected, energy not transferred to the receive coil remains in the transmit coil. Thus even if the coupling is very small (limiting the rate of energy transfer), the efficiency can still be very high, for coils that are high in Q. This is a somewhat counterintuitive result for wireless power systems, especially when compared to the case of Omni directional far-field antennas which show a $1/r^2$ dependence for efficiency, and inductive coupling which has a $1/r^3$ dependence. Finally, the mechanisms for driving and extracting work from coupled resonant systems add additional constraints. This means that for every load there is minimum amount of coupling that is necessary to maintain the system at equilibrium. The amount of coupling defines how much energy is transfered per cycle. This means that there is a distance (called the critical coupling point) beyond which the system can no longer drive a given load at maximum efficiency.The following sections will build upon the concepts of Magnetic Resonant Coupling, Frequency characteristics of Magnetic Resonant Coupling, adaptive frequency tunning technique. First, an analytical model of magnetic resonant coupling is presented in section III.This is followed by theory of Impedance matching under same Section. Section IV presents the experimental setup of Wireless power transfer system. Finally section V describes adaptive tuning techniques used to achieve near constant efficiency vs. distance while the receiver is within range of the transmitter.

III. THEORY ON MAGNETIC RESONANT COUPLING

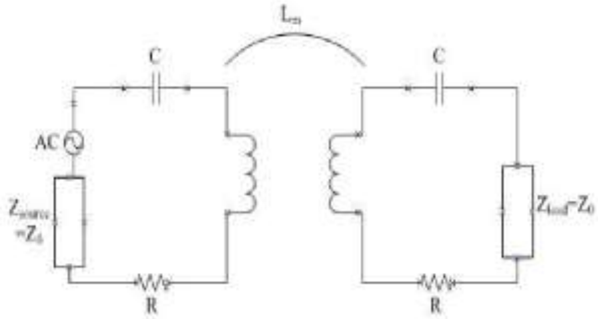


Figure2. Equivalent circuit of Magnetic Resonant Coupling

Magnetic resonant coupling involves creating an LC resonance, and transferring the power with electromagnetic coupling. Hence magnetic coupling can be represented as mutual inductance Lm as in Fig 2.1. Zsource represents the characteristic impedance, and Zload is the impedance of the load. In this paper, they are both considered to be the same at Z0, 50Ω the default characteristic impedance of most high frequency systems. The ohm loss and the resonance frequency can be calculated from the equivalent circuit. To satisfy the resonance condition, the reactance of Figure 2 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 k 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.

$$\frac{1}{wl_m}+\frac{2}{w(l-l_m)-\frac{1}{w_c}}=0 \tag{1}$$

$$w_m=\frac{w_0}{\sqrt{(1+k)}}=\frac{1}{\sqrt{(l+l_m)c}} \tag{2}$$

$$w_e=\frac{w_0}{\sqrt{(1-k)}}=\frac{1}{\sqrt{(l-l_m)c}} \tag{3}$$

$$k=\frac{l_m}{l}=\frac{w_e^2-w_m^2}{w_e^2+w_m^2} \tag{4}$$

Next the efficiency of the power transfer is calculated based on the equivalent circuit. The ratio of power reflection η_{11} and transmission η_{21} can be defined by equations (5) and (6), where S_{11} is the reflected wave ratio and S_{21} is the transmitted wave ratio. To simplify the calculations, R is considered to be 0Ω. Here, S_{21} can be calculated with equation (7) [8].

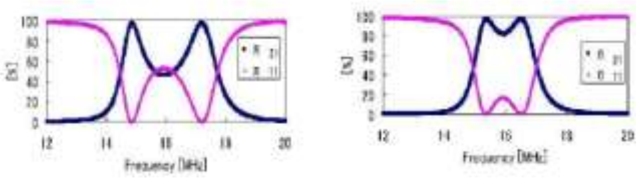
$$\eta_{11} s_{11\times}^2 100[\%] \tag{5}$$

$$\eta_{21}=s_{21}^2\times 100[\%] \tag{6}$$

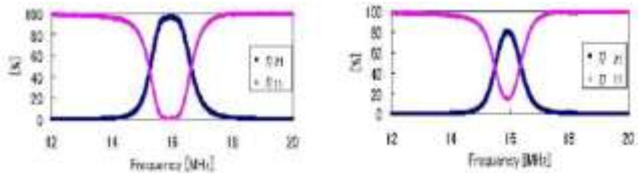
$$s_{21}=\frac{2jl_m z_0 w}{l_M^2-(wl-\frac{1}{wc})^2+2jz_0\left(wl-\frac{1}{wc}\right)+z_0^2} \tag{7}$$

A. *Frequency Characteristic of Resonant Magnetic Coupling*

As the air gap between the Coil increases, the coupling in between the coil weaken, and the coupling coefficient will be smaller. Therefore, the impedance of the circuit will change, affecting the power transfer efficiency and resonance frequency.Figure.3 shows the ratio of power reflection η11 and transmission η21, and the frequency characteristics of the system when the air gap, g, is changed between 100mm-250mm .When the gap is small and the coupling is strong two resonance frequencies that permit power transfer at maximum efficiency exist. As the gap becomes larger, the two resonance frequencies moves closer to each other and eventually merges into one . If the gap gets even larger, the maximum efficiency will drop.



(a) Gap=100mm (b) Gap=150mm



(c) Gap=200mm (d) Gap=250mm

Figure3. Efficiency versus Frequency graph [8]

B. *Necessity of Impedance Matching*

When this wireless power transfer system is applied in the MHz range (which allows smaller antennas), the usable frequency range is bounded by the Industrial -Scientific-Medical(ISM) band as shown in Figure4. The ISM band dictates the usable frequency range for purposes other than communication. According to the ISM band, the usable frequency ranges are extremely narrow. For example, at 13.56MHz, the usable frequency range is 13.56MHz±7kHz.

As a result, to apply this technology in restricted frequency ranges such as the MHz range, the frequency of the power source must be fixed at a usable range, and the system has to be tuned so that its resonance frequency matches the frequency of the power source. In this paper, a tuning circuit based on the IM theory is used to match the resonance frequency of the antennas to that of the power source fixed at 13.56MHz [8].

C. *Impedance Matching theory*

IM 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 4, the power transferred to the load is written as equation (8) 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(9).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} , vice versa The IM circuit can be considered as a two-port network that can be described with equation (10). The matching conditions are satisfied when parameters satisfy equations (11) and (12).

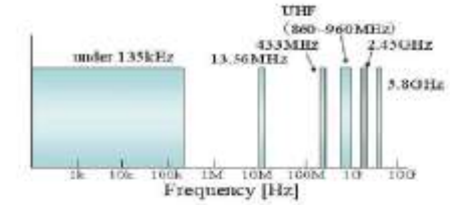


Figure4. ISM Band [8]

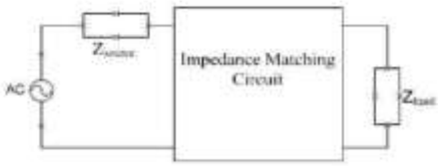


Figure5. Theory of impedance matching [8]

$$P = I^2 Z = \frac{v^2}{Z_{source}} \left(\frac{1}{\frac{Z_{source}}{Z_{load}} + 2 + \frac{Z_{load}}{Z_{Source}}} \right) \tag{8}$$

$$P_{max} = \frac{V^2}{4Z_{Source}} \tag{9}$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{10}$$

$$Z_{Source} = \sqrt{\frac{AB}{CD}} \tag{11}$$

$$Z_{load} = \sqrt{\frac{DB}{CA}} \tag{12}$$

IV. EXPERIMENTAL SETUP

Figure.6 shows the experimental setup of Transmitting section for wireless power system. The transmitter section consist of LC based transmitting coil, Digital oscillator, Mosfet based power amplifier. Coil wire guage is selected as 16 SWG with number of turns as 4. It is connected with paper polyester capacitor of 0.1uF for proper coupling at Resonance frequency with Receiver section. The Receiver section is shown in the form of vehicle model which consist of LC based Receiving coil at the bottom of the vehicle. Here coil with same wire guage is selected with number of turns as 8. It is connected to paper polyester capacitor of 0.47uF for efficient reception of power from transmitting coil.A resonance frequency of 13.65MHZ was determined experimentally. Since it is difficult to accurately predict self capacitance of the coil, the resonance frequency is tuned by digital oscillator until each coil individually resonates at 13.65 MHZ.

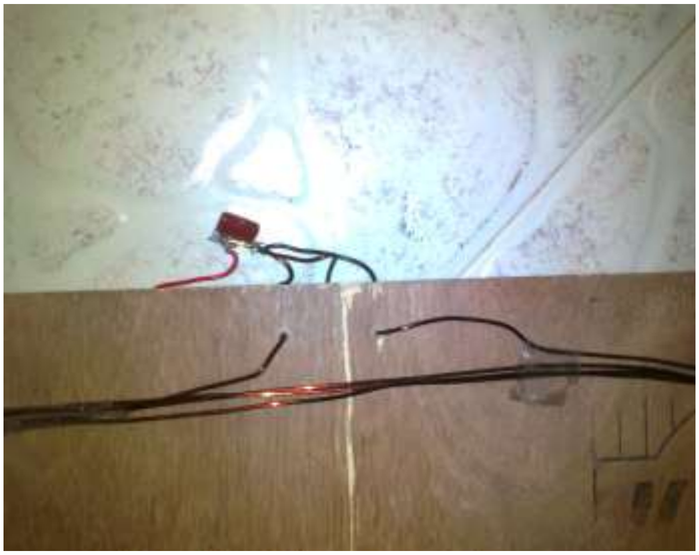


Figure6. .Photograph of LC based Tx coil used in wireless power system

Figure7.Photograph of Tx Coil (plywood)and Rx Coil(Bottom of the vehicle) inside the magnetic field region

In the experiment, the transmitter coil and receiver coil are placed such that they are in the magnetic field of each other. This is depicted in figure.7 which represents the top view of experimental setup. The transmitting and receiving loop are set at a fixed distance of 11cm. As the distance and orientation between both the coils changes power received by receiving coil changes. In order to have continous power transmission, both transmitter and receiving coil should be inside their magnetic field region.The maximum distance upto which power transmission between the coils to take place is determined experimentally as 52cm.

V. ADAPTIVE TUNNING FOR RANGE INDEPENDENT MAXIMUM POWER TRANSFER

A necessary component for a compelling wireless power system is the ability to operate at a multitude of distances and orientations without the need for precision manual tuning. Using frequency splitting presented here, it is possible to design a system that automatically adjusts to provide maximum possible efficiency as a user moves the receiver to locations within the system’s working range. Since this system forms a transmission line, the power not consumed by the load or lost to parasitic resistance is reflected back to the source. Figure.8 shows a graph of transfer efficiency vs. distance for the fixed frequency case of fo = 13.65MHz, and the auto frequency tuning case When the frequency tuning is enabled, the controller picks the maximum resonant peak and tracks it as the receiver is moved away from the transmitter. The plot shows that at short ranges the system is very efficient compared to the fixed-frequency case. As distance is increased the efficiency decreases slowly until the critical coupling point where the two modes merge and the system returns to the under coupled regime. One of the key principles of this system is that frequency splitting is a function of the coil to coil coupling coefficient. In the above analysis, we show how the coupling, and therefore the power transfer, varies as a function of distance along the transmission axis. The coupling will also vary with orientation. As long as the receiver is sufficiently close to the transmitter, almost any orientation and/or position will cause some amount of mutual inductance between the two coils .If this mutual inductance results in sufficient coupling automatic frequency tuning can be used to find the frequency that will result in the highest possible transfer efficiency.

VI. CONCLUSION

Magnetically coupled resonant structures offer a unique set of benefits as well as design challenges when used for wireless power transfer. One of the remarkable results is the existence of the ‘magic regime’, where efficiency remains nearly constant over distance, as long as the receiver is within the operating range of the transmitter. This is not the case for conventional far- field and near-field wireless power systems, whose efficiencies decline sharply with range. The work in our project provides a deeper understanding of the underlying principles of coupled magnetic resonance, as well as a simple circuit model of the system.If the system is driven at some frequency and the wireless power system is operating in the over-coupled regime, frequency splitting will result in the system being off resonance and little to no power will be transferred to bring efficiency of the system back to maximum, number of turns can be varied at which point

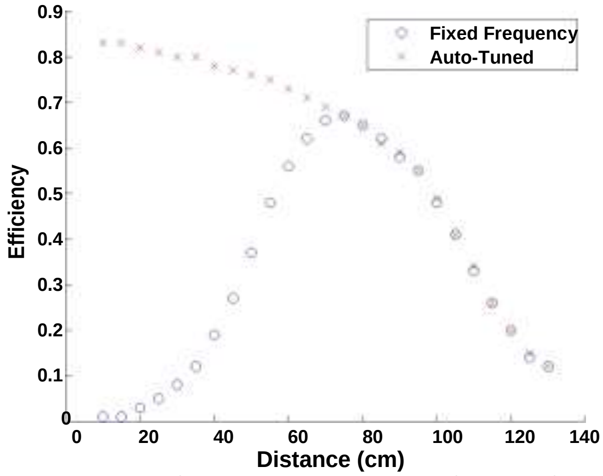


Figure8. Automatic frequency tuning compared to a fixed drive frequency as a function of distance between the transmitter and receiver

maximum power transfer can resume. In a demonstration as shown in Figure.7, we have successfully implemented a form of this tuning method that allows tuning for a variety of Tx-Rx distances with a hand adjustment of a loop that can be rotated about its coil, thereby changing number of Turns. This kind of varying number of turns adaptation method has the advantage of allowing operation at a single frequency, which would be advantageous for band-limited operation.

VII. FUTURE SCOPE

Clearly the advantages of high and near constant transfer efficiency at mid-range distance compared to near-field and far-field techniques make this technology exciting for many applications. There are any number of low power wireless recharging scenarios that would benefit from increased range vs. efficiency at power levels typically used in RFID. Finally this paper has focused on the delivery aspect of RF power while consumer electronics require DC power for operation and recharging. Adaptive rectifier designs will need to be developed that do not interfere with the operation of the magnetically coupled resonators.

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