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Design and Analysis of MHz Range Converter for Mid Range Low Wireless Power Transfer Systems

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Abstract: With the rapid increase in the use of renewable energy in low and high power applications there is a constant increase in the demand for sophisticated power transfer techniques for the applications like electric vehicle, smart home appliances. The magnetic resonance based wireless power delivery system could set a best option to power the future devices. Operating these devices at high frequency will offer the high power transfer efficiency and compact design of charging system. In this paper we present a simple converter to derive the primary coil to operate at MHz range. To increase the distance between the coil by keeping high power transfer efficiency the four coil circuit is analysed. The converter mathematical analysis is carried out based on the linear piecewise state space representation to find the optimal switching conditions and the four coil inductive links. The results show for the mid-range applications with the use of four coil and high frequency converter the power transfer efficiency is increased upto 78%.

Keywords: Wireless Power Transfer; High Frequency converter; Mid-Range; Four Coil.

1. INTRODUCTION

Magnetic resonance based Wireless Power Transfer (MR-WPT) has reached much attention in variety of applications such as mobile charging, electric vehicle charging, smart home, implantable biomedical devices and so on [1]- [3]. In a common two coil WPT system the power transfer efficiency depends on the coupling between the coil and quality factor of the coil. As the distance increases the coupling between the coil decreases abruptly, which leads to decrease in the WPT system efficiency. The coupling coefficient between the coil is proportional to d-3, where d is the distance between two coils when they are perfectly aligned in parallel [4]. Recently, a research team from MIT has been proposed for the mid-range power transfer and proved the improvement in the system efficiency over the distance. They used a multi resonant coil (i.e. four coil) approach for the power transfer and achieved 82% of efficiency [5]. The four coil system comprises of a low Q factor driver coil connected to power supply, a high Q factor transmitter coil placed near to driver coil, a high Q receiver coil and a load coil connected with the application device. In the four coil structure the load and source can easily match by changing the mutual inductance between the load coil and receiving coil, source coil and transmitting coil. For the increase in transmission distance, coil misalignment and high level of spatial freedom the operating frequency of the WPT system has to be maintained at MHZ or high level range [6]. Also it helps to reduce the size of WPT system which is crucial in some critical applications like bio implants. But the limitations in power electronics is the switching loss of inverter and rectifier operating at high frequency. Conventional power amplifiers and bridge, push pull converters are suitable for WPT system operating at kHz range [7]. In the literature [8], the different power amplifier topologies starting from class A to Class F were analysed in detail. These conventional type power amplifiers such as class A, B, AB and C are operated at low efficiency, which makes them not the preferred choice in WPT system. Also in the MHz range WPT applications linear power amplifiers and Colpitts oscillators are offering very low efficiency [9]. On the other hand, the switching-mode power amplifiers like Class D, E, DE, and F, have their own virtues and drawbacks. For example, the upper

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frequency of Class D is limited by the output capacitance of the switching device [10]. In the class E amplifier soft switching technique conditions (zero voltage switching (ZVS) and zero derivative switching (ZDS)) are used to suppress the switching losses at high frequency [11]. But it is not so easy to obtain the class E inverter components for the derived switching conditions, which makes it one of the problems in designing class E switching sequence. In many literatures the circuit design of class E inverter has been addressed to enhance the practical usage in WPT system. However, the power transfer efficiency of WPT system decreases when the distance between the transmitter and receiver coil is high and the diameter of the receiver and transmitter coil is different. Coil diameter of the transmitter and receiver is different. Also the class E power amplifier is the best choice if the operating frequency is above 3MHz and it suffer with the drawbacks of hard control of dead time and high sensitive to the loading conditions [12]. Therefore, it is vital to find a high efficient power amplifier topology applied to resonant coupling WPT. In this paper a new converter based on class E design is used for high frequency WPT applications. In section II the four coil WPT system efficiency, converter analysis is carried out and section III discusses about the simulation and experimental results of the system.

2. SYSTEM DESIGN

A. Four Coil WPT System

A simple four coil WPT circuit based model is shown in Figure 1. It consists of driver coil, transmitting coil, receiving coil, and load coil. The circuit is energized by an AC voltage source V_s which is connected with the driver coil. By placing an intermediate high Q coils the effect of the low coupling and low Q factor of the coils can be compensated.

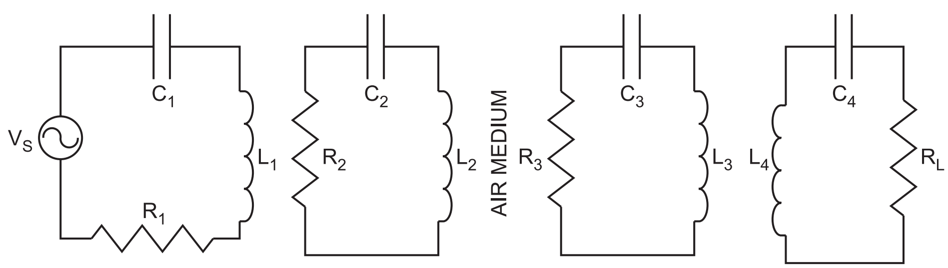

Figure 1: Four Coil WPT System circuit model

Under steady state excitation by applying circuit theory to the above system, the applied voltage and current relationship can be described in matrix form as follows [13].

$$\begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_3 \end{bmatrix} \tag{1}$$

Where, $Z_{mn} = R_n \pm j\omega L_n \pm \frac{1}{j\omega C_n}$ for $m = n$

$= j\omega M_{mn}$ for $m \neq n$ ($m, n = 1, 2, 3, 4$)

V_S is the amplitude of the source voltage, I_1, I_2, I_3, I_4 are the currents, R_1, R_2, R_3, R_4 are the effective series resistance, L_1, L_2, L_3, L_4 are the inductance, C_1, C_2, C_3, C_4 are the capacitances in the driver, transmitter, receiver and load coils respectively. The mutual inductance between the coil m and n is given by

$$M_{mn} = k_{mn}\sqrt{L_m L_n} \tag{2}$$

Where k_{mn} is the coupling factor between coil m and coil n. Operating all the coils at the same resonance frequency and neglecting the small coupling coefficients k_{13}, k_{14} and k_{24}, the power transfer efficiency of the four coil system is given as

$$\eta = \frac{(k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3)(k_{34}^2 Q_3 Q_4)}{[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + k_{23}^2 Q_2 Q_3][1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4]} \tag{3}$$

Where Q_n represents the loaded quality factor of the coil n. Since the Q factor of the transmitter and receiver coil is high and by using moderate coupling between driver and transmitter and receiver and load the efficiency of the system can be approximated as

$$(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) \approx (k_{12}^2 Q_1 Q_2)(k_{34}^2 Q_3 Q_4)$$

$$\eta \cong \frac{k_{23}^2 Q_2 Q_3}{1 + k_{23}^2 Q_2 Q_3} \tag{4}$$

In the four coil WPT system, the efficiency is maximum at low load coil Q factor and does not vary much with respect to the driver coil's Q factor. The above approximate efficiency equation is almost similar to the two coil WPT system.

B. Converter Analysis

The high frequency converter used in this paper is shown in Figure 2 [14]. It has simple structure with one switch alone and gives theoretically 100% efficiency. In this L_S represents the energy storage inductance, C_S the shunt capacitance of the switch including the junction capacitance, S represents the switch, and $R_{eq.}$, $L_{eq.}$, $C_{eq.}$ are the equivalent resistance, inductance and capacitance of the WPT system. The direction of current flow remains same in both the conditions of the switch. Because of the symmetry in the operation of the converter it can operate well up to several tens of watts.

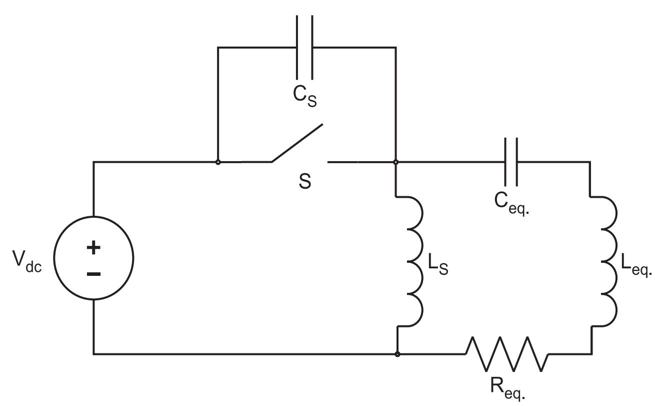

Figure 2: High Frequency Converter

The circuit of the proposed mid-range MHz wireless power transfer circuit is shown in Figure 3. The four coil WPT system is energized by the high frequency converter with the operating frequency in the range of several MHz. The switch ON and OFF conditions are represented by R_{ON} and R_{OFF} resistances respectively. The equivalent circuit can be described by the following general state space representation for both the intervals of the switch.

$$\dot{X}(\omega t) = AX(\omega t) + BU(\omega t) \tag{5}$$

Where $X = [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9]^T$ is the state vector and the state variables x_1, x_2, x_3, x_4 are the voltage across capacitors C_1, C_2, C_3, C_4 for only ON state of the switch. The state variables x_5, x_6, x_7, x_8, x_9

represents the current flowing through inductor L_s, L_1, L_2, L_3, L_4 for only ON state of the switch. During on time period the voltage across the capacitors C_s also needs to be considered. After writing the voltage equations of each loop of Figure 4 using KCL and KVL, the solution for equation () is found as

$$x_{on}(\omega t) = e^{A_{on}\omega t} x_{on}(0) + A_{on}^{-1}(e^{A_{on}\omega t} - I)B$$
$$x_{off}(\omega t) = e^{A_{off}\omega t} x_{off}(0) + A_{off}^{-1}(e^{A_{off}\omega t} - I)B \quad (6)$$

The initial conditions $x_{on}(0)$ and $x_{off}(0)$ can be obtained by applying continuity conditions of the voltage and current in capacitors and inductors

$$x_{on}(0) = x_{off}(\omega t)|_{\omega t = 2\pi(1-D)}$$
$$x_{off}(0) = x_{on}(\omega t)|_{\omega t = 2\pi D} \quad (7)$$

From (), () the average current flowing through the inverter is the average current of inductor L_S

$$I_{av} = \int_0^{2\pi D} x_{on5}(\omega t)\, d\omega t + \int_0^{2\pi(1-D)} x_{off6}(\omega t)\, d\omega t \quad (8)$$

In order to operate the inverter at the optimal switching conditions the following conditions needs to be satisfied

$$x_{off1}(0) = 0$$
$$x_{on5}(0) - x_{on6}(0) = 0$$

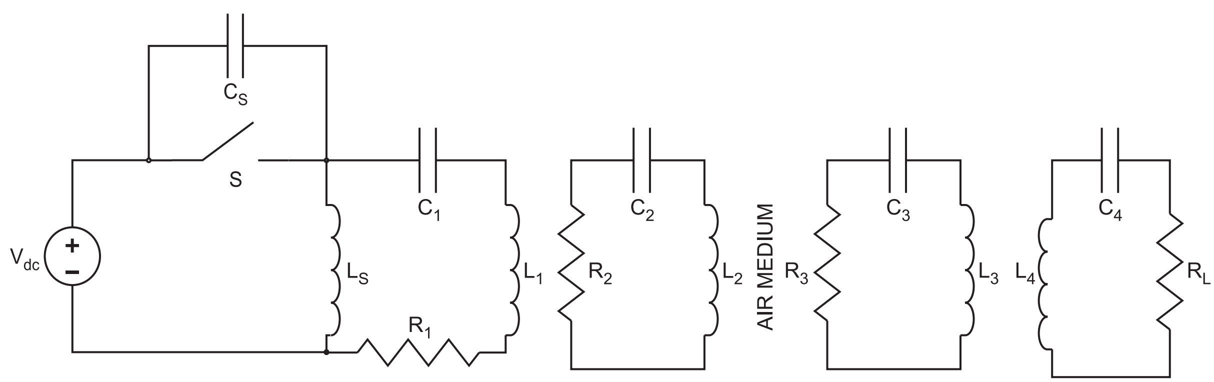

Figure 3: Four Coil System with High Frequency Converter

3. EXPERIMENTAL ANALYSIS

The transmitter and receiver coils are kept at a distance of 2 and 5 cm and the MOSFET is switched by the rate of 2MHz. Table 1 gives the experimental parameters for the converter and coil. Figure 4 shows the experimental setup for the proposed system. The gate voltage across the MOSFET is shown in Figure 5.

Table 1
Experimental Parameter

Parameter	*Converter*	*Primary coil*	*Transmitter Coil*	*Receive Coil*	*Load Coil*
L	148uH	198uH	156uH	164uH	186uH
C	470uF	100nF	270nF	270nF	100nF

By varying the distance between the coil to 5 cm the load voltage is slightly decreased as shown in Figure 7. The output waveform distortion and the efficiency can be improved by adopting low-loss capacitor or inductor.

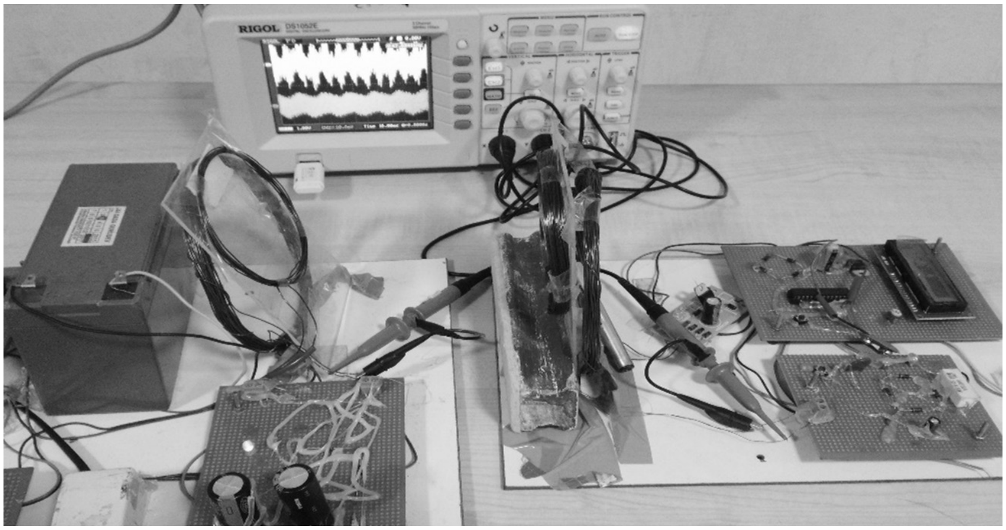

Figure 4: Experimental Setup

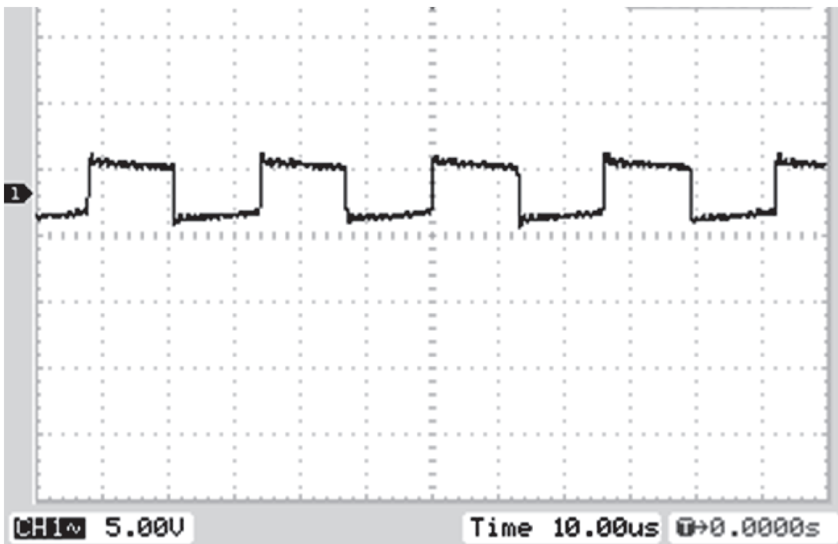

Figure 5: Voltage across Capacitor C_s

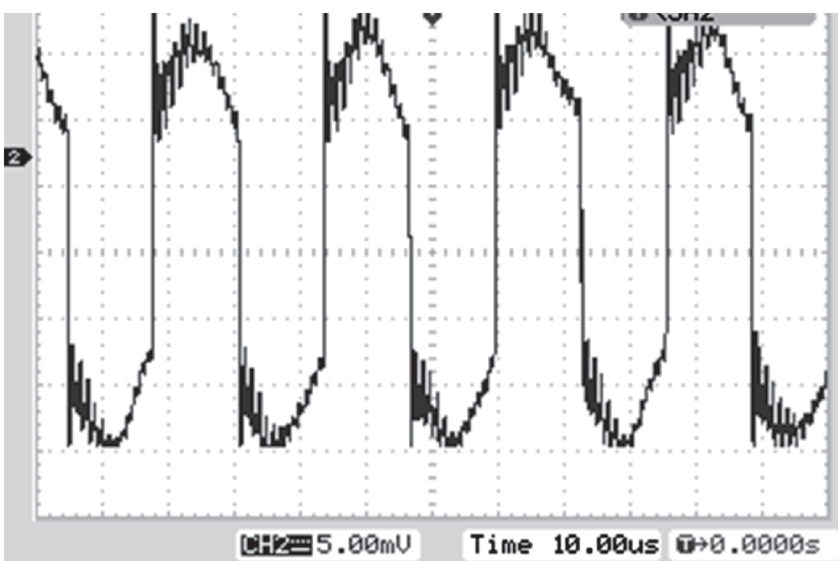

Figure 6: Load Voltage Waveform at the distance of 2 cm

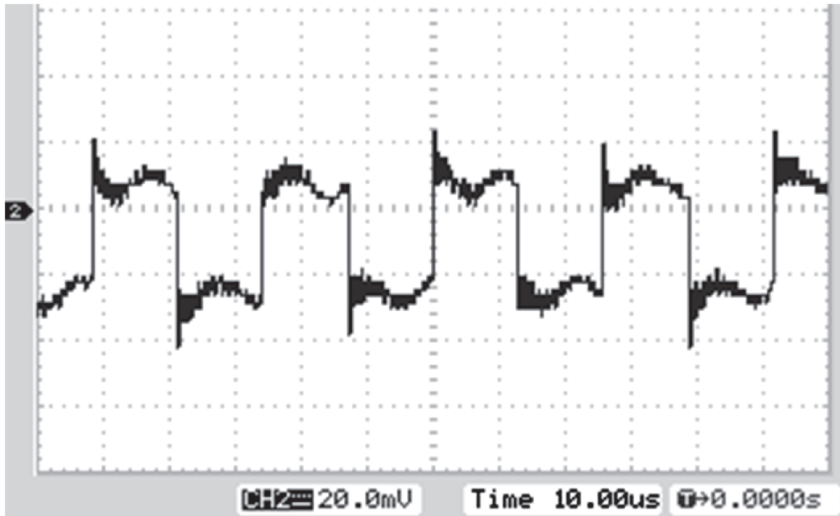

Figure 7: Load Voltage Waveform at the distance of 5 cm

4. CONCLUSION

An efficient wireless power transfer system for low power applications with simple high frequency converter and four coil system is discussed in this paper. The mathematical analysis of four coil WPT and converter with four coil setup are analysed. The results show that for mid-range low power applications which operate on solar power the proposed method will give high power transfer efficiency. In the future a detail experimental analysis needs to be performed on the selected low power applications by considering the frequency splitting and cross coupling effect.

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