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Analysis of Frequency Splitting Phenomena in Four Coil Inductive Resonant Coupling System

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Abstract: In this paper the frequency splitting in four-coil magnetically coupled resonant wireless power transfer system is analyzed by using the circuit theory. First, the complete and simplified models are built to describe the whole system. The numerical formulas of the system efficiency both at and away from the resonant frequency are presented. Then the frequency-splitting phenomenon is displayed and further explained mathematically and physically. Simulation and experimental results shows that the effect of frequency splitting can be minimized by operating the circuit at the optimal coupling conditions.

Index Terms: Frequency Splitting, Four coil, Resonant Coupling.

1. INTRODUCTION

The magnetic coupling based power transfer system is attracted much in powering the implanted biomedical devices since the human body is electrically lossy conductor. However, a two frequency split phenomena will occur in the WPT system for small separation between the transmitter and receiver coil [1]. Whenever the distance between the two coil is reduced below the critical point the coupling between the coil will increase drastically which cause changes in the quality factor of the coil. Since the quality factor is related with the coefficient of coupling and resonant frequency of the coil. If there is variation in the quality factor, the original resonant frequency will be splitted into two one above the original frequency value and another below the original frequency value [2]. This effect will be the major issue in low power applications with dynamic changes of coil location, especially in biomedical capsule robot endoscopy system. The frequency splitting in magnetic resonance based wireless power transfer plays a vital role on the output power. This chapter discuss mainly on frequency splitting phenomena of two coil, three coil and four coil WPT system also present a method to eliminate in biomedical applications. First the transfer power, frequency characteristics are analysed with coupling, using circuit theory. The circuit level simulation and Finite Element Simulation are done using ADS and ANSYS HFSS tool considering various different parameters of the circuit [3]-[5]. The experimental setup has been made for an open helical coil structure and analysed based on the different coil geometry of the WPT system. An important factor for frequency splitting is introduced and the boundary condition for frequency splitting and its splitting frequency points are deduced. The amplitude–frequency and phase–frequency characteristics of the input impedance are measured and described to verify the explanation [6]. Three related factors are studied, and the sensitivity analysis is conducted. A solution is proposed that helps improve the efficiency when frequency splitting occurs. The theoretical calculations and experimental results provide a sound basis for the analysis [7]-[8].

2. 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

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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.

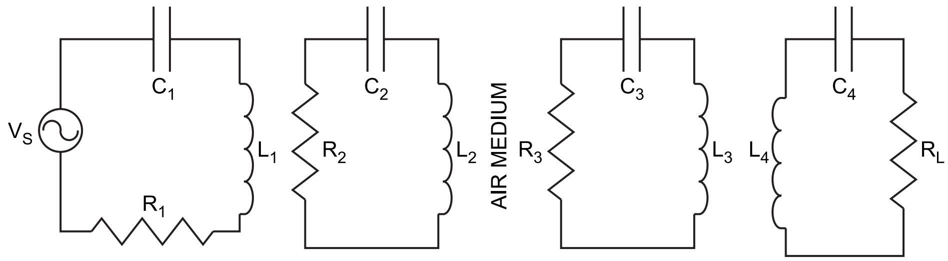


Figure 1: Four Coil WPT System circuit model

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

$$\begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

$$\text{Where,} Z_{mn} = R_n \pm j\omega L_n \pm \frac{1}{j\omega C_n} \quad \text{for } m = n \ (m, n = 1,2,3,4)$$

$$= j\omega M_{mn} \text{ for } m \neq n$$

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

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

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

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

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

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

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

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.

3. SIMULATION AND EXPERIMENTAL RESULTS

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

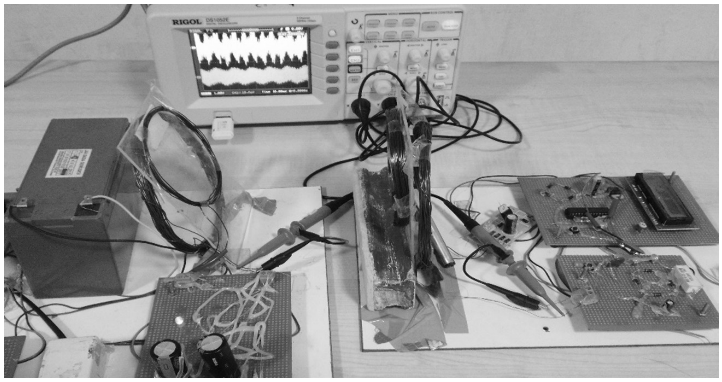
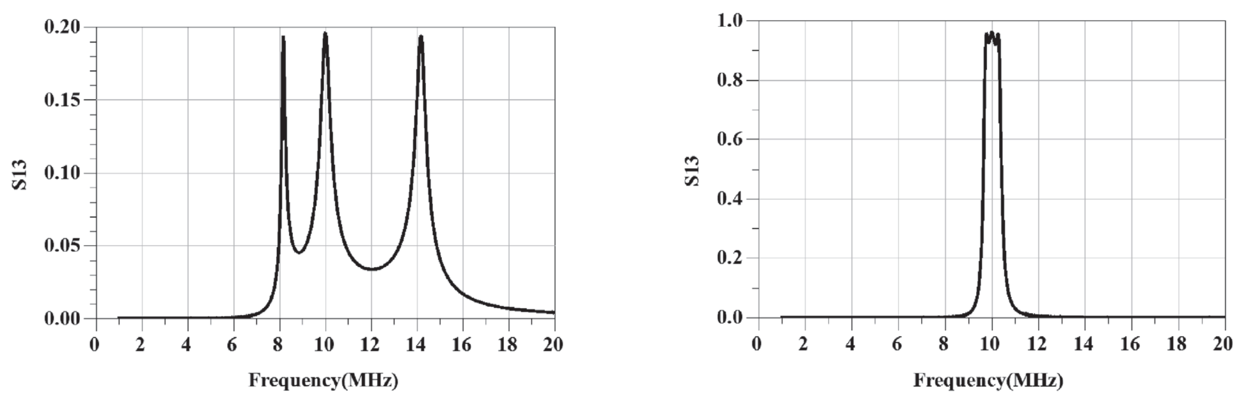


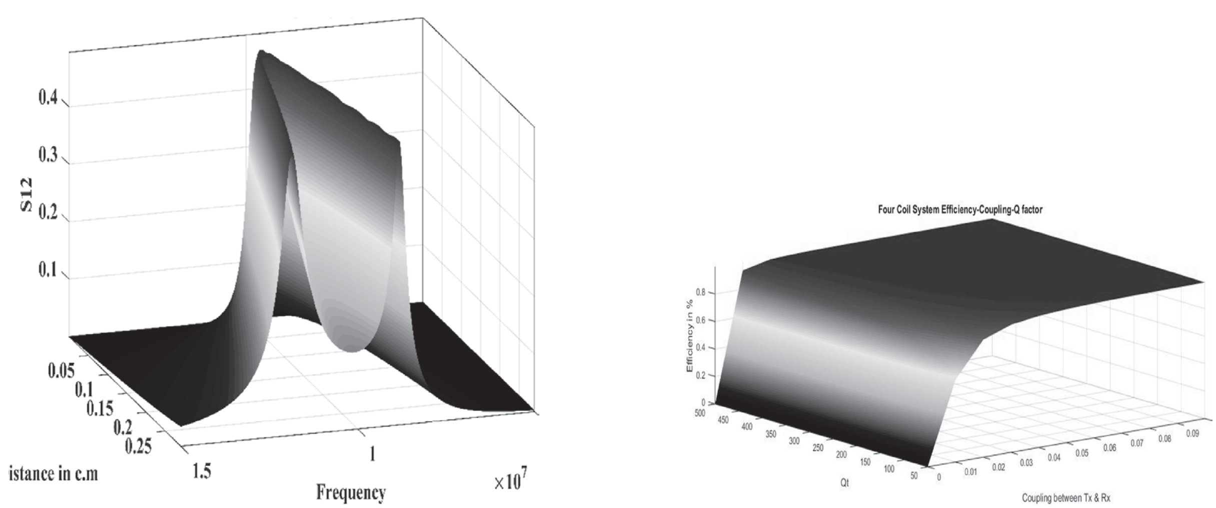
Figure 2: Experimental setup of four coil setup



(a) (b)

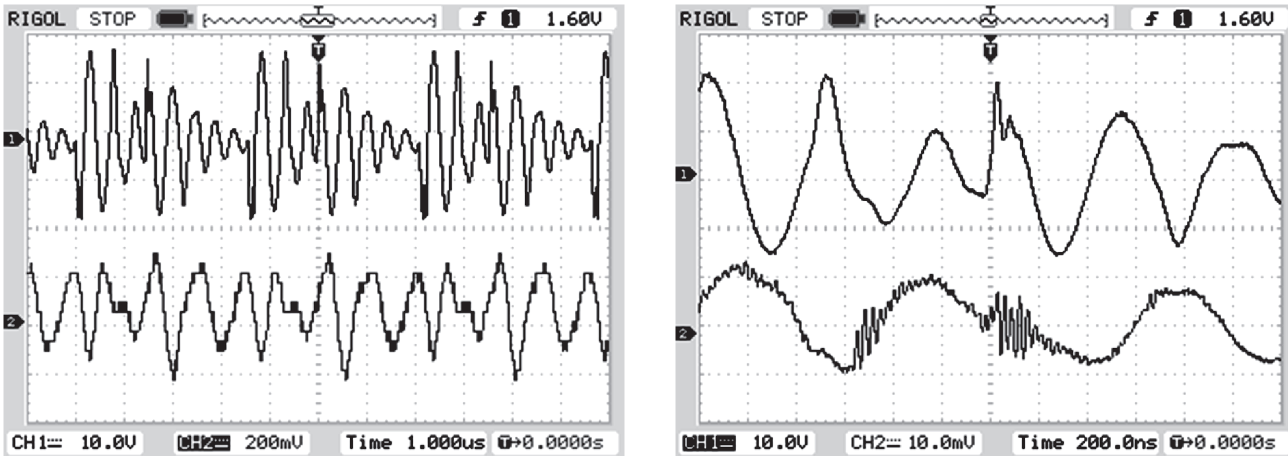
Figure 3: Frequency Splitting of Four coil

The frequency splitting at different coupling coefficients are shown in Figure 3 (a-b) and the analytical calculation of frequency and system efficiency are shown in Figure 4 (a-b). The output voltage across each coil is shown in Figure 5 (a-b).



(a) (b)

Figure 3: Analytical Simulation of Four coil efficiency



(a) (b)

Figure 5: Experimental Results of Four Coil Frequency Splitting

4. CONCLUSION

Based on the four-coil inductive resonant wireless power transfer circuit, the complete and simplified mathematical models were built and analyzed in this paper. The expressions of the efficiency were obtained through the derivation of the mathematical models both at and away from the resonant frequency. Theoretical analysis and experimental results verify the presence of frequency splitting. The agreement between the complete model and the experimental data is excellent**.**

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