I J C T A, 9(37) 2016, pp. 931-938

Cross Coupling Elimination and Selective Mid-Range Wireless Power Transfer to Multiple Receivers

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Abstract: With the improvement in the magnetic resonance based wireless power transfer technology the charging system of electric and electronic appliances are shifting towards cable free system. To deliver uniform power to the multiple receivers in the smart homes or other applications, identifying the optimal condition to transfer at high efficiency is the challenging problem. This paper presents a selective uniform power distribution to the load by changing the resonance frequency of the transmitter coil. By designing the receivers with different resonant frequency the individual selection can be done, also the cross coupling effect between the receivers could be eliminated. The proposed system is employed with three coil inductive link in order to increase the power delivered to the load and to minimize the effects of coil misalignment. The results show that the three coil multiple receiver inductive link achieves higher efficiency of 64% as compared with the two coil multiple receiver inductive link of 45%.

Keywords: Selective WPT; magnetic resonance; multiple receiver; cross coupling.

1. INTRODUCTION

Wireless power transfer (WPT) is an emerging technology used in powering the portable electronic devices which are used in many applications such as smart home, office, health care, bio implants [1], [2]. WPT system offers many benefits such as the elimination of trailing cables in dynamic system, lower risk of shock hazard and use in harsh atmospheres. Because of the increase in the need and opportunities in the market industries are now vigorously establishing the wireless power standards [3] for coil size, electromagnetic interference, etc. Also the number of electronic devices used by the person is increased day by day, so the simultaneous wireless power transfer to multiple devices offers a unique advantage. But, the receiver devices may have different power requirement, size, position, orientations and load which leads to some difficulties in design and optimization of multiple receiver system. Conventional WPT techniques focuses on delivering power to multiple receivers at the same time, which makes cross coupling between the receiver coils [4]. In some applications like implantable or wearable devices requires spatial freedom and fast charging of the devices, a simultaneous charging system has a limitation in delivering power uniformly to the multiple receivers. In dynamic environment, the receiver position will change result in reduce in the power transfer efficiency if the distance is less or more than the optimal limit. However, in a portable or wearable applications the precise control of the power division ratio is an important issue. Many literatures are available [5]-[7] to compensate the effects of change in location in single transmitter and receiver system, but the same kind of solutions are not suitable for the single transmitter with multiple receiver system. In order to overcome the above problems in the multiple receiver system selective power deliver to the load will be the best solution [8]. By designing the receiver system with different resonant frequency and tuning the transmitter to the selected resonance frequency of the receiver alone, the maximum power can be delivered to the selected receiver. Among those the main challenge in the WPT system is the efficient design of mid-range wireless power transfer system for powering the portable personal electronics devices. Literatures [9], [10] are addressing that the inductive coupling between the low and high Q coil increases the power transfer efficiency over the distance. In the four coil system a set coils are used in both

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transmission and receiver side, in order to improve the efficiency all, the coils are operated at the same resonant frequency by tuning the capacitors in the transmitter coil. In [11], the four coils system and three coil systems are compared and proved that the four coil systems are increases the power transfer efficiency by significant reduction in the power delivered to the load. Also it requires a high driving voltage which can reduce the transmitter efficiency and increase in the heat dissipation and other safety related problems. So in this paper a three coil based multiple receiver system is designed and the selective power transfer to the load also analysed in detail along with dynamic conditions of the circuit.

2. SYSTEM DESIGN

A. Three Coil based Single Load with Different Resonant Frequency WPT

The equivalent circuit model of the three coil with single load structure is depicted in Figure 1. The primary coil parameters inductance, capacitance and effective coil resistance are represented with subscript 1, and the drive coil and load coil parameters are represented with subscript 2, 3 respectively.

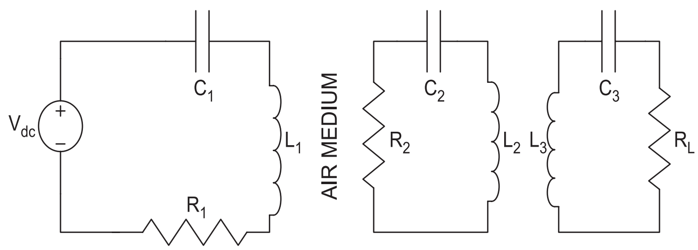

Figure 1: Equivalent circuit of three coil WPT system with single load

The power transfer efficiency and power delivered to the load coil of the system can be found from [11]

$$\eta_{1-\text{load}} = \frac{((k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3) + k_{13}^2 Q_1 Q_2) Q_3}{(\cos(\theta)(1 + k_{23}^2 Q_2 Q_3)\sqrt{A^2 + B^2})\, Q_{3L}} \tag{1}$$

$$P_L = \frac{V_S^2 ((k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3) + k_{13}^2 Q_1 Q_2) Q_3}{2 R_1 Q_{3L} (A^2 + B^2)} \tag{2}$$

Where

$$A = 1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3 + k_{13}^2 Q_1 Q_3$$

$$B = 2 Q_1 Q_2 Q_3 k_{12} k_{13} k_{23}$$

$$\theta = \tan^{-1}\left(\frac{B}{A}\right)$$

Since the coupling between the primary and load coil is less then by neglecting $k_{13,}$ equation (1) and (2) can be simplified as

$$\eta = \frac{((k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3) Q_3}{(1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3)(1 + k_{23}^2 Q_2 Q_3) Q_{3L}} \tag{3}$$

$$P_L = \frac{V_S^2 ((k_{12}^2 Q_1 Q_2)(k_{23}^2 Q_2 Q_3) Q_3}{2 R_1 Q_{3L} (1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3)^2} \tag{4}$$

Where Q_1, Q_2, Q_3 are the Q-factor of primary, driver and load coils respectively. k_{12}, k_{13}, k_{23} are the coupling coefficient between primary and driver, primary and load, driver and load coil respectively. The resonant frequency of all the three coils are f_1, f_2 and f_3 can be found

$$f_1 = \frac{1}{2\pi\sqrt{L_1C_1}}, f_2 = \frac{1}{2\pi\sqrt{L_2C_2}}, f_3 = \frac{1}{2\pi\sqrt{L_3C_3}}$$

By operating the system at $f_1 = f_2 = f_3$ the efficiency of the three coil single load structure is maximized [12].

B. Selective Multiple Receiver WPT System

Figure 2 represents the single transmitter and three receivers for three coil WPT system, where the transmitter, driver and load coils are represented with the subscript of 1, 2_i, 3_i (where n = 1, 2, 3) respectively.

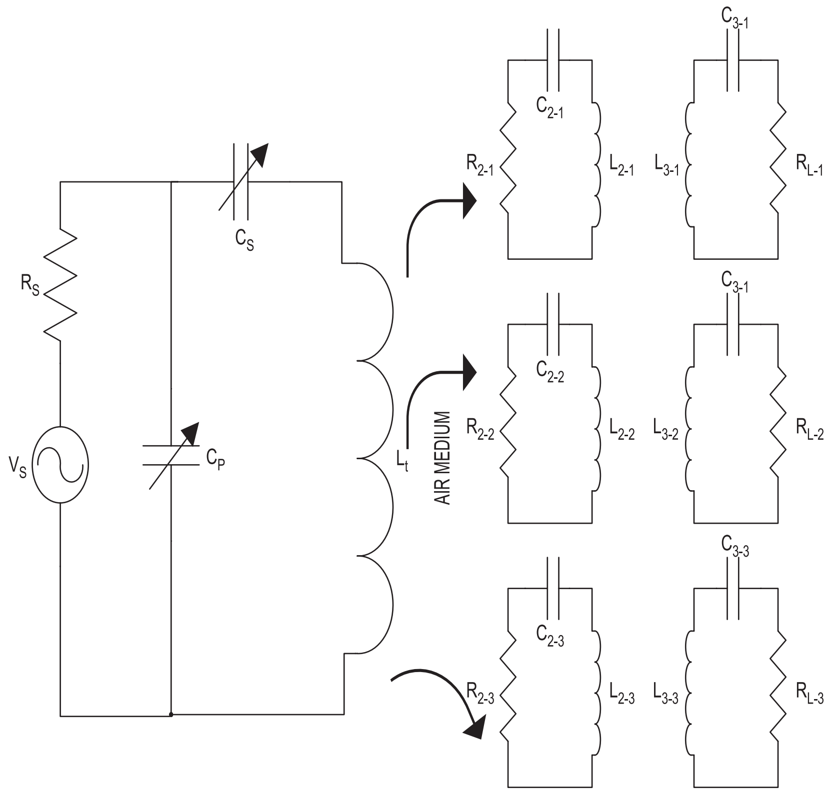

Figure 2: Multiple receiver WPT System

The resonance of the system is achieved by

$$f_1 = \frac{1}{2\pi\sqrt{L_1C_1}} = \frac{1}{2\pi\sqrt{L_{2i}C_{2i}}} = \frac{1}{2\pi\sqrt{L_{3i}C_{3i}}} \tag{5}$$

For the selective power transfer to the multiple receiver the driving frequency of the source can be changed. The efficiency of each receiver system is

$$\eta_i = \frac{P_i}{P_s} \tag{6}$$

Where P_s, P_i are the input power and power consumed by the i^{th} receiver. The overall system efficiency and power delivered to the load is

$$\eta = \sum_{i=1}^{n} \eta_i \tag{7}$$

$$P_L = \sum_{i=1}^{n} P_{Li} \tag{8}$$

Where
$$\eta_i = \frac{(k_{12i}^2 Q_1 Q_{2i})(k_{2i3i}^2 Q_{2i} Q_{3i}) Q_{3i}}{(1 + k_{12i}^2 Q_1 Q_{2i} + k_{2i3i}^2 Q_{2i} Q_{3i})(1 + k_{2i3i}^2 Q_{2i} Q_{3i}) Q_{3Li}}$$

$$P_{Li} = \frac{V_S^2 (k_{12i}^2 Q_1 Q_{2i})(k_{2i3i}^2 Q_{2i} Q_{3i}) Q_{3i}}{2R_1 Q_{3Li} (1 + k_{12i}^2 Q_1 Q_{2i} + k_{2i3i}^2 Q_{2i} Q_{3i})^2} \quad (9)$$

By fixing the receiver side capacitance value, the transmitter side capacitance is tuned. In Figure 2 the receiver 1, 2, 3 are tuned at 13 MHZ, 15.5 MHz and 18 MHz respectively. Figure 3 shows the frequency response of the three receiver system. However, there is power leakage exist due to other receiving coil and cross coupling between the receiver coils.

C. Under Dynamic Environment

The power transfer efficiency of the system is reduced when the receiver approach to the transmitter. This is because of horn effect also called as frequency splitting, as the distance reduces the original resonant frequency of the system will be divided into upper and lower side of the original value. It can be overcome by designing the coil with different dimensions in diameter or the number of turns of the transmitter and receiver coil [13]. When the distance between the coil is increased the coupling between the coil reduces, the three coil system can still deliver higher power as compared to the two coil system [14]. Therefore, the three coil with non-identical dimension can deliver the power better under the dynamic environment.

3. EXPERIMENTAL MEASUREMENT OF SYSTEM OUTPUT

Based on the applications dimensions, power requirement, distance variation the size of the coil is designed. In case of high power applications, the efficiency will be the prime consideration in the design, so choosing a high Q coil would be better with compact size. In this work we use a standard AWG-14 wire for the transmitter coil and AWG-22 wire for the receiver coil. The coil inductance and optimum capacitance values are listed in table 1 and 2 based on the designed frequency.

Table 1
Inductance value of the coil at different frequencies

Coil	*13 MHz*	*15.5 MHz*	*18 MHz*
	L(nH)	*L(nH)*	*L(nH)*
Transmitter coil	480	494	501
Driver coil 1	356	357	358
Driver coil 2	349	349	360
Driver coil 3	360	362	350
Load coil 1	182	180	175
Load coil 2	178	175	171
Load coil 3	192	188	186

Table 2
Capacitance value of the coil at different frequencies

Frequency	*Transmitter coil (pF)*		*Driver Coil (pF)*	*Load coil (pF)*
	C_s	C_p		
13 MHz	210.5	1824.6	260.2	258.4
15.5 MHz	192.6	1664.2	220.3	208.6
18 MHz	168.5	1512.6	192.5	184.6

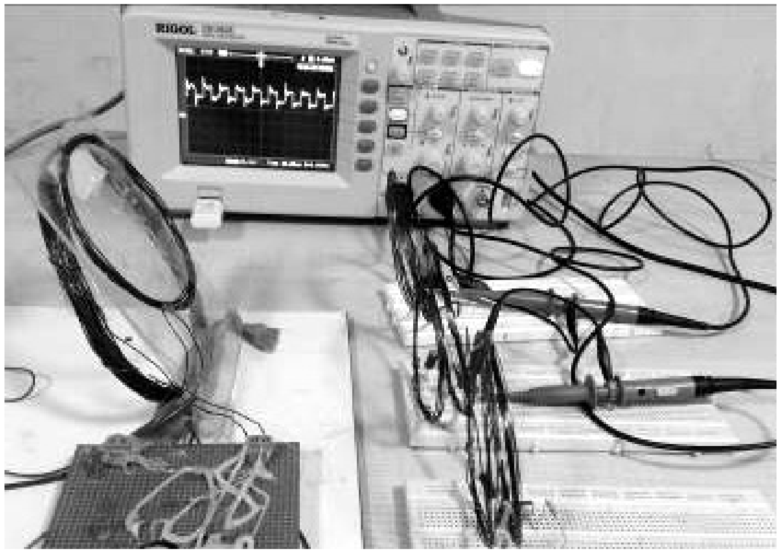

Figure 3: Experimental Setup of 3 Rx in Parallel with Tx

Figure 4: Experimental Setup of 3 Rx in at different angle with Tx

Figure 3 and 4 shows the experimental setup of the proposed system and the output voltage of receiver 1 is shown in Figure 5 and 6 for the distance of 3 and 5 cm between transmitter and receiver coil.

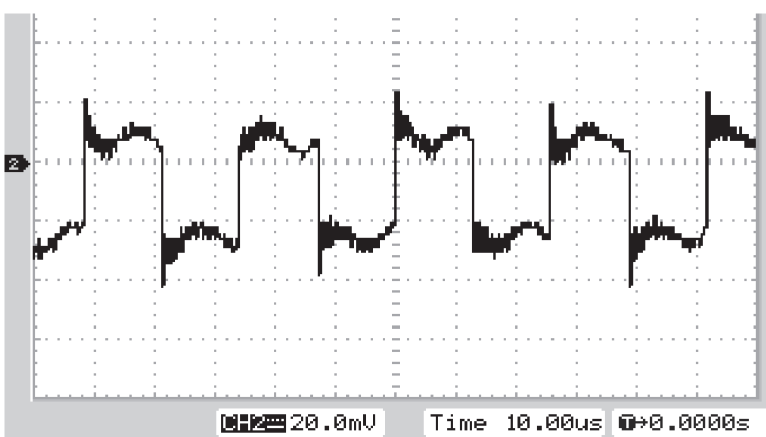

Figure 5: Receiver 1 Output Voltage at 3 cm distance

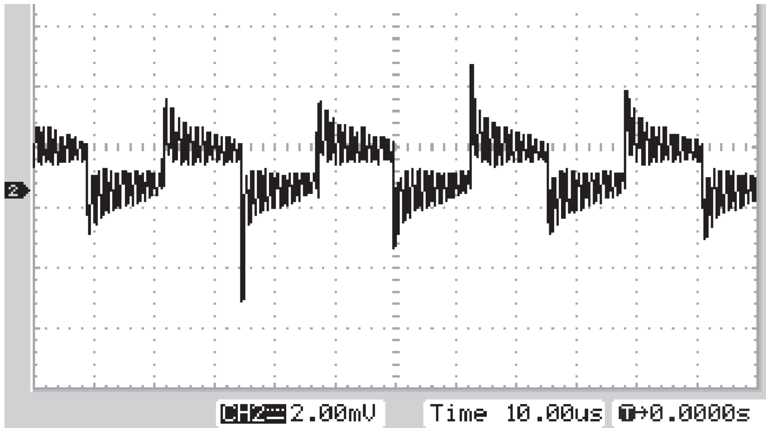

Figure 6: Receiver 1 Output Voltage at 5 cm distance

When the receiver coil 1 is changed dynamically changed with the distance of 3 cm to 5 cm and 5 cm to 3 cm the variation in the output voltage is shown in Figure 7. If receivers 2 and 3 are placed at 90 degree to the transmitter and receiver 1 is placed parallel with the transmitter the output voltage of receiver 1 (Figure 8) is higher as compared with the receiver 2 and 3 voltage (Figure 9), due to reduction in the coupling between the Tx and Rx2 and Rx3 are reduced.

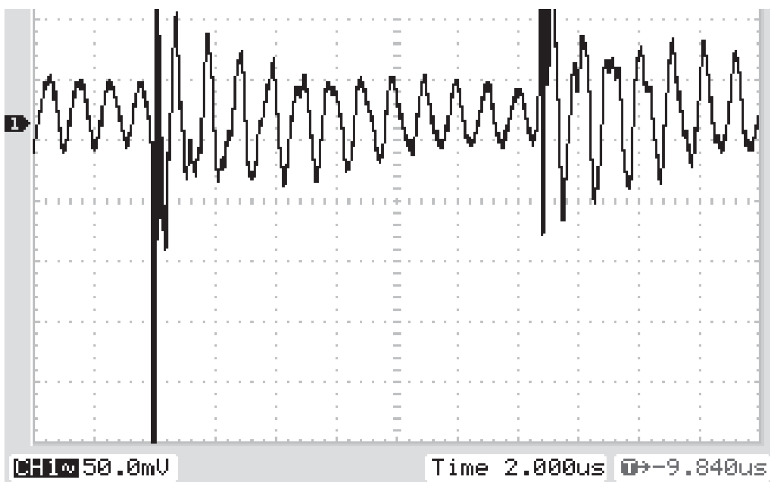

Figure 7: Receiver 1 Output Voltage at under dynamic variation

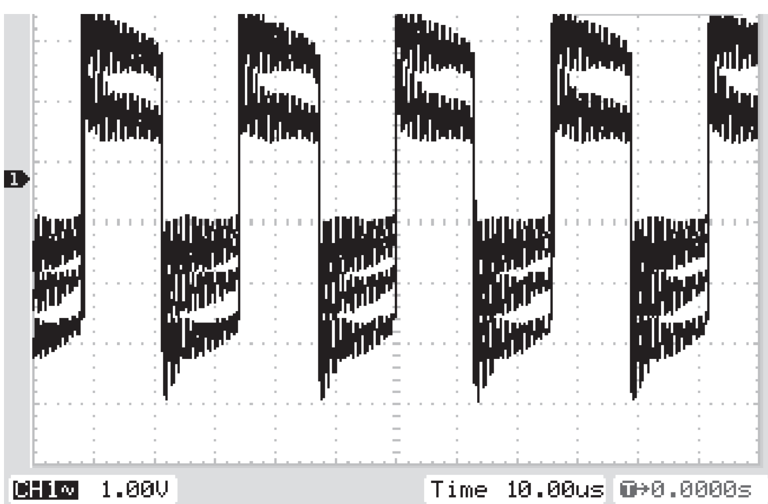

Figure 8: Receiver 1 Output Voltage at under different angle

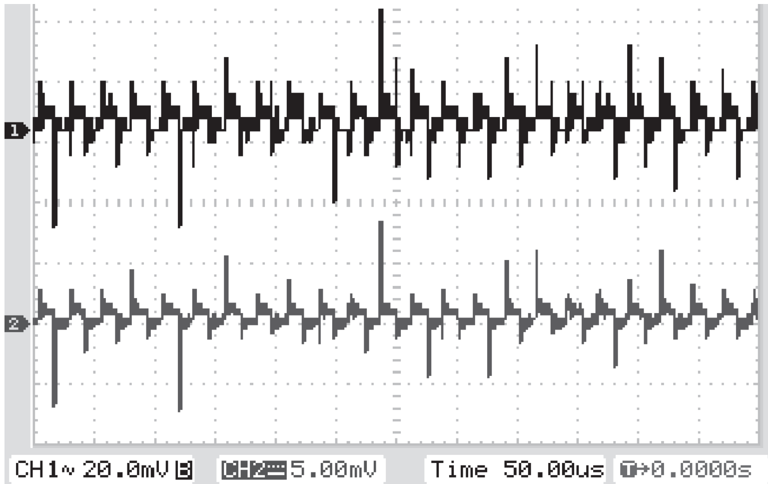

Figure 9: Receiver 2 and 3 Output Voltage at 90 degrees between Tx and Rx

4. CONCLUSION

Selective Magnetic resonance based WPT system with single transmitter and multiple receiver system is discussed in this paper. By designing the receivers with different resonant frequency and tuning the transmitter to the particular frequency the receiver selection can be achieved. Also in this paper a three coil inductive link is analysed for the multiple receiver system, which gives an increase in power delivered to receiver and improves the overall system efficiency as compared with two coil multiple receiver inductive link. The mathematical equations of efficiency and power delivered to load of three coil multiple receiver WPT system are analysed. The experimental results show the multiple receiver WPT system gives efficiency of 64% under static conditions and 51-54% for the variation of distance between 3 to 5 cm.

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