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Importance of Functional Parameters on the Effective Operation of Resonant Multi-Receiver Wireless Power Transfer System

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ABSTRACT: The magnetic resonance coupling based wireless power transfer (WPT) technology has been of great interest due to its usefulness and persistent characteristics in powering multiple devices simultaneously. However, it is the foremost challenge to make possible easy access and manage the effective power transmission to the multiple gadgets through the WPT technology. In order for the multi-receiver system to run at its most favourable operational area, a prompt access is necessary at this point to identify the appropriate selection of functional parameters. Thus, a circuit model analysis has been put forward, and the influences of functioning parameters such as electric load at the receivers, mutual coupling between the coils, frequency of operation on the system's performance indicators like input power, power at the receiver's load, power transfer efficiency at individual receiver, and moreover the input impedance of the system have been investigated. The perception has been validated through a bench-top experimental setup. The observed experimental result closely matches the theoretical data derived from the circuit model. The outcomes are crucial which may provide important selection criteria for the effective operation and creation of successful electromagnetic coupling based multi-receiver WPT system.

1. INTRODUCTION

Magnetic Resonance Coupling based Wireless Power Transfer (MRC-WPT) technology prevails and getting much attention due to its conveyance and suitability for various charging applications with power requirement over a wide range. Since it was proposed, many studies related to MRC-WPT system restricted to single transmitter to single receiver coil have been reported [1–5]. However, the current market witnesses a rapid growth of consumer electrical/electronic appliances due to the advancement of semiconductor technology, and these portable devices need charging for operation. Hence, the need of the hour charging technology should not to be limited to single receiver system rather multiple receivers. As reported by a couple of articles, MRC-WPT system has the potential to power up multiple devices simultaneously [6–9]. Needless to say, the concept of delivering power to multiple receivers not only widen the application range of MRC-WPT system but also mitigate the upcoming challenges in charging demands of huge number of portable electrical/electronic devices.

The system of power transfer to multiple devices using circuit theory and coupled mode theory approach are reported in [10–14]. These articles basically claim on the potential of MRC-WPT system in powering multiple receiver coils through single transmitter coil. Further, it is mentioned that power transfer efficiency of individual receiver decreases with the addition of greater number of receivers to the system as the overall system efficiency increases. A method of controllable power flow to individual load is proposed which also facilitates higher efficiency [15, 16]. The proposed method has been implemented for a two-receiver system and can be extended for multiple-receiver MRC-WPT system. In [17, 18], it is proposed to ensure sufficient current in the transmitter coil so as to make the receiver coils delivered power to the load. Again, it is mentioned that to avoid bifurcation the net power of the transmitter side should be more than the power sum of the entire receiver coil under rated load condition. With enough evidences, viability of MRC-WPT system in powering multiple devices though authenticated but not sufficient to reveal the suitable operating region for effective implementation in practical scenario. It is the foremost challenge to manage the effective power transmission to the multiple gadgets through the resonant WPT technology. There may be significant differences in the size, positioning, load characteristics, and power requirements of the receiving devices in a multi-receiver WPT system. Hence, it is becoming essential to disclose the pronounce effect of different system parameters on the performance of the system and their selection criteria to activate the multiple receiver's system operating at its optimal conditions.

In this article, the influences of design dependant parameters such as electric load at the receivers, mutual coupling between the transmitting coil and receiving coils and frequency of operation on the systems performance indicators like input power, power at the receiver's load, power transfer efficiency at individual receiver and moreover the input impedance of the system with its real and imaginary parts are investigated. In ad-

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dition, the variations of power levels and efficiency at individual receiver of the multi-receiver WPT system corresponding to the various load values for different frequencies have been discussed. It also uses the above analysis to unveil the effective adjustment of these parameters to activate the multiple receivers' system operating at its optimal conditions. Finally, the concepts are validated through simple bench setup experiments, and the results agree well with the simulation ones.

2. SYSTEM ARCHITECTURE FOR MRC BASED MULTIPLE-RECEIVER WPT SYSTEM

The system architecture of an MRC based multiple-receiver WPT system is shown in Fig. 1. The subscripts T and R are used to distinguish transmitter and receiver coils in the system, respectively. The system comprises a single transmitter coil and multiple receiver coils. The transmitter coil is driven by AC power source (V_S) with source resistance R_S.

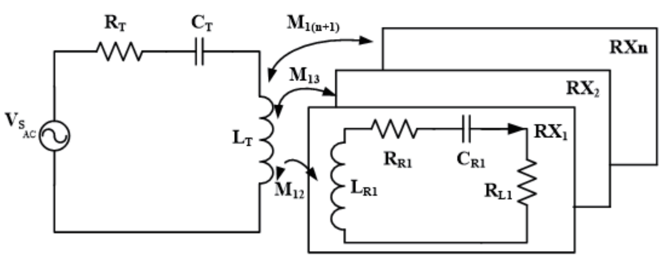

FIGURE 1. Magnetic resonance coupling based multiple receiver WPT system.

The circuit parameters R, L, and C connected at both transmitter and receiver sides represent the effective series resistance of the coil, inductance, and capacitance, respectively. Parameters at the receiver side with subscript i represent individual receiver. R_{Li} and M_{1i} denote the resistive load connected to the i^{th} receiver and mutual inductance between transmitter and the i^{th} receiver, respectively. By the principle of magnetic resonance coupling WPT, all the receivers are tuned to the transmitter circuit at the resonant frequency in order to transfer power at a faster rate between the transmitter and receiver coils. The cross-coupling effect between the receiver's coil are represented by M_{ij}, for $i \neq j$ $(i, j = 1, 2 \ldots n)$ which are usually less than $M_{1(i+1)}$.

3. EQUIVALENT ELECTRICAL CIRCUIT MODEL OF TWO-RECEIVER MRC-WPT SYSTEM AND THEORETICAL ANALYSIS

In order to outline the characteristic behaviour of a multiple-receiver WPT system, the equivalent circuit model of the most fundamental two-receiver WPT system is considered in this paper and depicted in Figs. 2 and 3.

R_{L1} and R_{L2} are the load resistors connected to receivers 1 & 2, respectively. M_{12} and M_{13} are corresponding mutual inductance between transmitter and receiver 1 and receiver 2 whereas M_{23} is the mutual inductance between the receiver 1 and receiver 2.

The input equivalent impedance seen at the transmitter side is represented as Z_{in}. The mutual inductance between the two receivers (M_{23}) is usually smaller than M_{12} & M_{13} and hence ignored to avoid complexity in the circuit analysis.

Applying Kirchhoff's voltage law (KVL) to the transmitter and receiver sides, the equations are as follows:

$$\begin{cases} I_1 Z_T - I_2 j\omega M_{12} - I_3 j\omega M_{13} - V_S = 0 \\ I_2 Z_{R1} - I_1 j\omega M_{12} - I_3 j\omega M_{23} = 0 \\ I_3 Z_{R2} - I_1 j\omega M_{13} - I_2 j\omega M_{23} = 0 \end{cases} \tag{1}$$

where,

$$\begin{cases} Z_T = R_T + j\omega L_T + {}^{1}\!/_{j\omega C_T} \\ Z_{R1} = R_{R1} + j\omega L_{R1} + {}^{1}\!/_{j\omega C_{R1}} + R_{L1} \\ Z_{R2} = R_{R2} + j\omega L_{R2} + {}^{1}\!/_{j\omega C_{R2}} + R_{L2} \end{cases} \tag{2}$$

The resonant frequency of the system under the condition that coils for transmitter and receivers are of same design ($L_T = L_{R1} = L_{R2} = L$, $C_T = C_{R1} = C_{R2} = C$) will be expressed as,

$$\omega = \sqrt{\frac{1}{LC}} \tag{3}$$

By solving Equation (1), the efficiency of the system can be evaluated as,

$$\eta = \frac{I_2^2 R_{L1} + I_3^2 R_{L2}}{I_1^2 Z_{IN}} = \frac{\frac{\omega^2 M_{12}^2 R_{L1}}{(R_{R1}+R_{L1})^2} + \frac{\omega^2 M_{13}^2 R_{L2}}{(R_{R2}+R_{L2})^2}}{R_T + \frac{\omega^2 M_{12}^2}{(R_{R1}+R_{L1})} + \frac{\omega^2 M_{13}^2}{(R_{R2}+R_{L2})}} \tag{4}$$

The input impedance seen at the transmitter side will be expressed as,

$$Z_{IN} = \frac{V_S}{I_T} = R_T + \frac{\omega^2 M_{12}^2}{R_{R1} + R_{L1}} + \frac{\omega^2 M_{13}^2}{R_{R2} + R_{L2}} \tag{5}$$

The output power at each of the individual receiver can be derived as follows:

$$\begin{cases} P_{L1} = \dfrac{V_S^2}{\left(R_T + \frac{\omega^2 M_{12}^2}{R_{R1}+R_{L1}} + \frac{\omega^2 M_{13}^2}{R_{R2}+R_{L2}}\right)^2} \dfrac{\omega^2 M_{12}^2}{R_{R1}+R_{L1}} \dfrac{R_{L1}}{R_{R1}+R_{L1}} \\ P_{L2} = \dfrac{V_S^2}{\left(R_T + \frac{\omega^2 M_{12}^2}{R_{R1}+R_{L1}} + \frac{\omega^2 M_{13}^2}{R_{R2}+R_{L2}}\right)^2} \dfrac{\omega^2 M_{13}^2}{R_{R2}+R_{L2}} \dfrac{R_{L2}}{R_{R2}+R_{L2}} \end{cases} \tag{6}$$

From the above equations, the efficiency, input impedance, and the output power across each individual receiver are found to be dependent basically on the frequency of operation, mutual coupling coefficient, and receiver load resistance value.

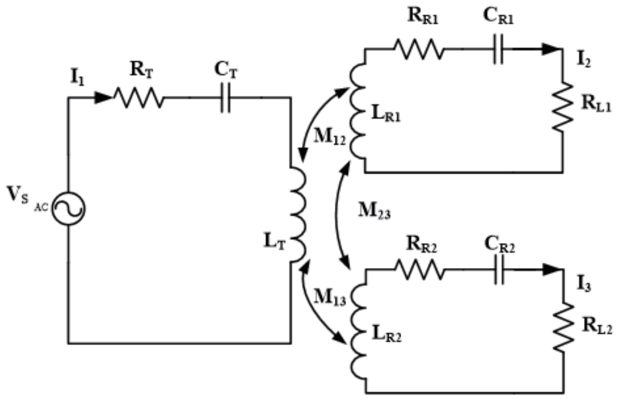

FIGURE 2. Equivalent circuit model of two-receiver magnetic resonance coupled WPT system.

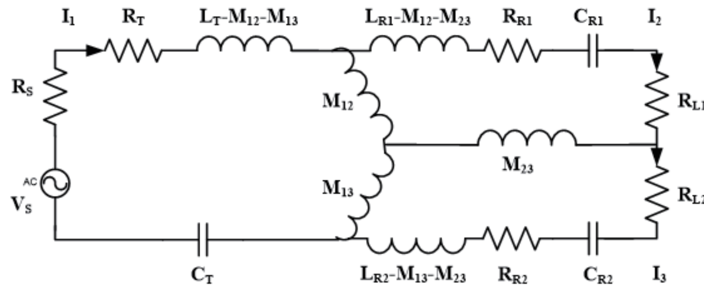

FIGURE 3. Equivalent circuit model of two-receiver magnetic resonance coupled WPT system.

4. RESULTS AND DISCUSSION

The simulation results of various parameters corresponding to the theoretical analysis carried out in previous section are portrayed in this segment to closely investigate the performance of the system. The results primarily focus on the delivered load power, individual receiver efficiency, input impedance corresponding to load, and operating frequency. The circuit parameters used for the simulation purpose are as shown in Table 1.

TABLE 1. The circuit parameters for the experimental setup.

Parameters	Symbol	Value
Input voltage (AC)	V_s	7.1 V
Transmitter coil	L_t	168 µH
Receiver coil	L_r	168 µH
Transmitter tuning capacitance	C_t	330 nF
Receiver tuning capacitance	C_r	330 nF
ESR of transmitting coil	R_t	145 mΩ
ESR of receiving coil	R_r	145 mΩ
Resonant frequency	f_0	21.2 kHz

Figures 4(a) & (b) show the frequency characteristics of individual receiver (receivers 1 & 2) efficiency corresponding to different load values for the specific value of mutual inductance $M_{12} = M_{13} = 0.205\,\mu\text{H}$. All the coils are identical in design and positioned equidistant from the transmitter coil. Again, the load value for receiver 1 has been considered as half that of receiver 2 ($R_{L1} = 1/2R_{L2}$).

It is evident from both the figures that optimum efficiency occurs at the resonant frequency which satisfies the operating principle of MRC-WPT system. Moreover, for both the cases, higher load values ensure better efficiency. The efficiency initially increases with the increases in load but up to certain extent. There exist a particular set of R_{L1} and R_{L2} corresponding to the position of the receiving coil where the efficiency is maximum, and the set of R_{L1} and R_{L2} values corresponding to a specific system configuration are fixed. Hence, load value in receiver coil needs to be considered carefully at the time of designing the MRC based multi-receiver WPT system.

The results depicted in Figs. 5(a) & (b) show the frequency characteristics of delivered load power in receiver 1 & receiver 2 corresponding to different load values when both the receivers are placed equidistant from the transmitter. In both the cases, the power delivered to the load is maximum under resonance condition and eventually higher for higher value of load.

The variation in input impedance seen at the transmitter side for different load values in a particular receiver keeping other load constant corresponding to frequency is presented in Figs. 6(a) & (b). In Fig. 6(a), $|(Z_{in})|$ is considered when R_{L1} is varied for different frequency values keeping R_{L2} constant. In both the cases, $|Z_{in}|$ is found to be maximum when the system is at resonance and gradually decreases with the decrease in load values.

In order to delineate the dependencies of overall power transfer efficiency (PTE) of MRC based multi-receiver WPT system on the receiver load values, PTE of the two-receiver WPT system corresponding to receiver's different load values at resonant frequency is illustrated in Fig. 7. From the figure, both receivers' load values are not necessarily to be considered higher value in order to ensure maximum PTE rather based on proper selection of R_{L1} & R_{L2} pair. Moreover, the selection of R_{L1} & R_{L2} pair to achieve optimal PTE is not random rather specific. In broader sense, receivers with different load values can be driven with ensured maximum overall system efficiency, if the receivers' load values are properly selected.

Figure 8 depicts the inclusive relation of input impedance of the two-receiver MRC-WPT system with the load variation in the receiver's coil. The absolute value of the input impedance is observed to maximum for specific combination of R_{L1} & R_{L2} pair, particularly for lower value. Furthermore, with the increase in R_{L1} & R_{L2} values, the input impedance decreases.

The input power profile corresponding to both receivers' load values is displayed in Fig. 9. From the result, the input power is observed to be maximum for lower values of R_{L1} & R_{L2} and gradually decreases as load values increase. This implies that the required power level at the input of the MRC based two-receiver WPT system is much higher to drive re-

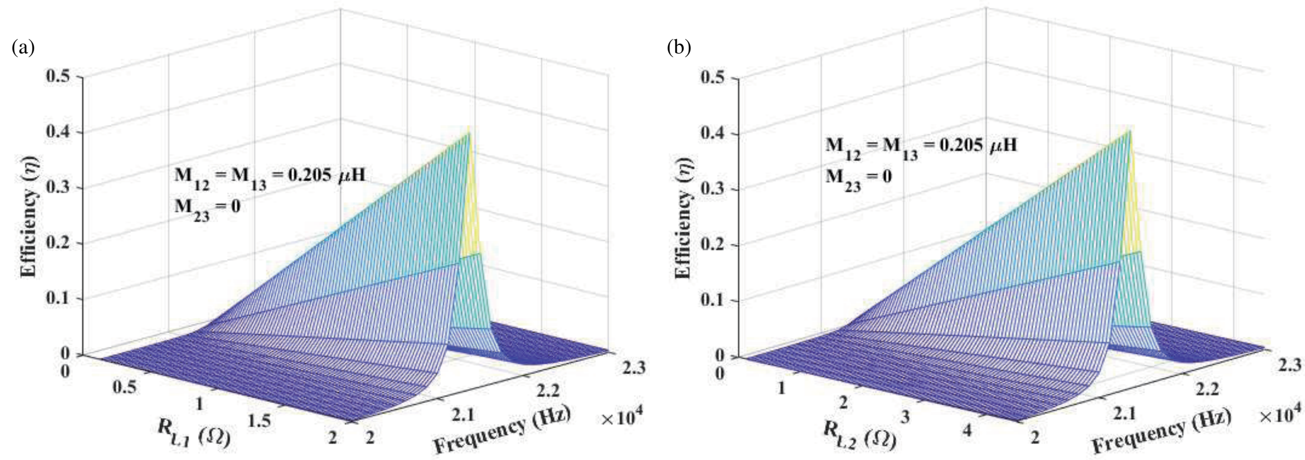

FIGURE 4. (a) and (b) Frequency characteristics of efficiency for receiver 1 and receiver 2 corresponding to different load values.

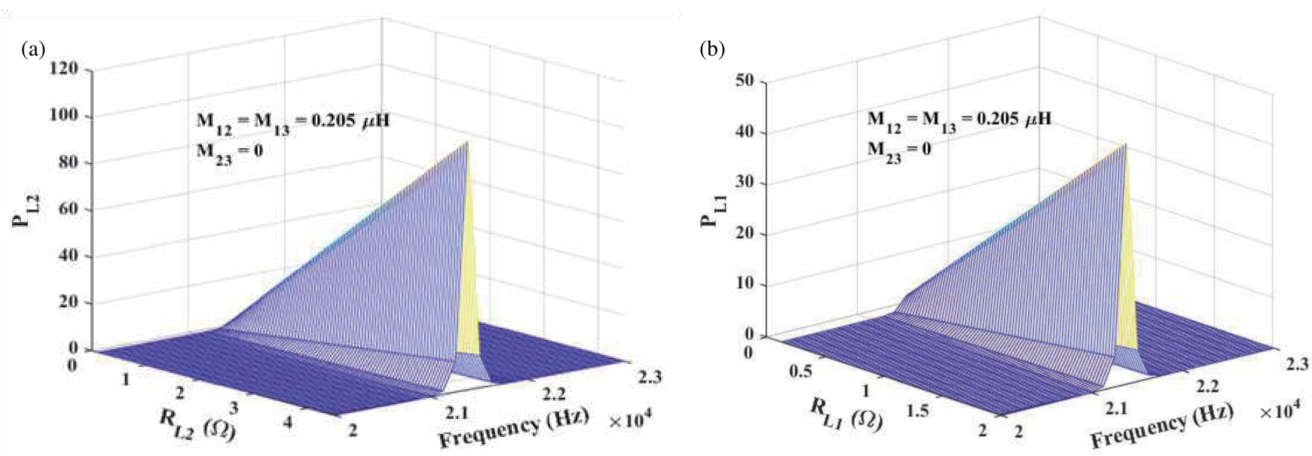

FIGURE 5. (a) and (b) Frequency characteristics of delivered load power in receiver 1 & receiver 2 corresponding to different load values.

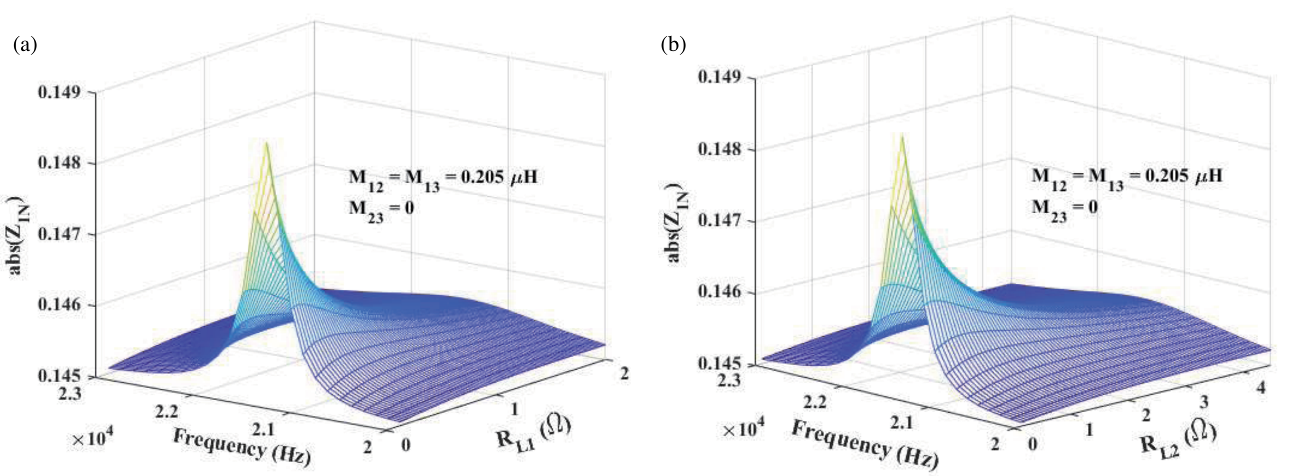

FIGURE 6. (a) and (b): Frequency characteristics of input impedanceseen at the transmitter side corresponding to different load values.

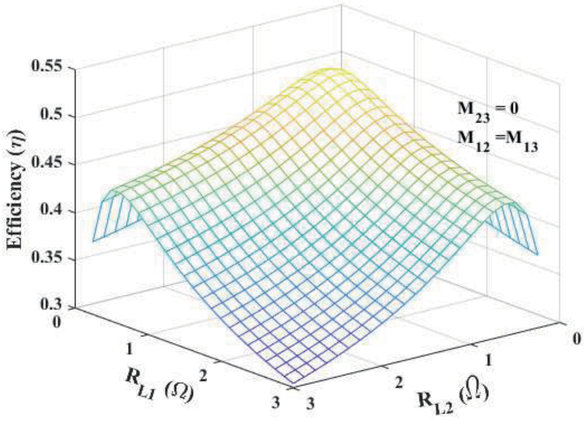

FIGURE 7. Dependencies of overall efficiency on receiver load.

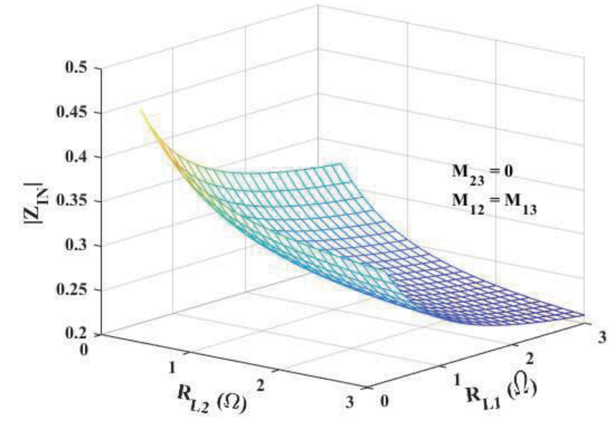

FIGURE 8. Dependencies of $|Z_{in}|$ on the load values of receiver's coil.

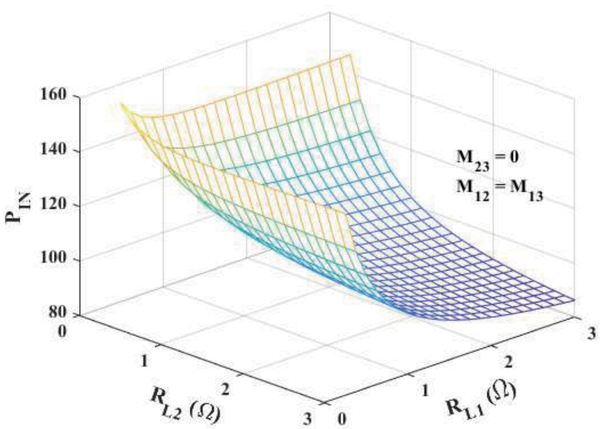

FIGURE 9. Load characteristics of input power.

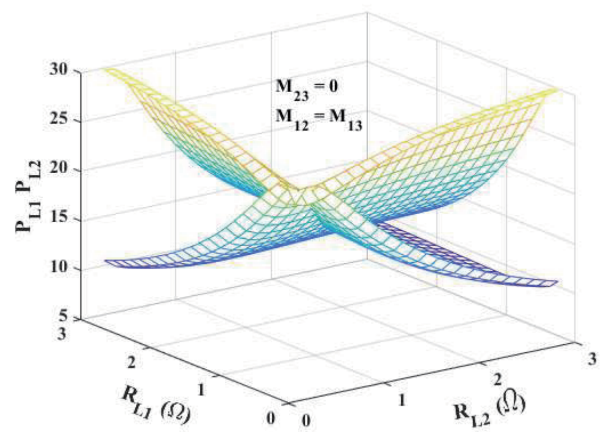

FIGURE 10. Load characteristics of delivered load power to both receivers.

ceivers with lower value of electric load than receivers with higher electric load values. Moreover, receivers with load R_{L1} & R_{L2} with opposite combinations such as R_{L1} = high & R_{L2} = low or R_{L1} = low & R_{L2} = high also need comparatively higher input driving power though not maximum one.

The power delivered to both receivers' loads verses R_{L1} and R_{L2} is depicted in Fig. 10. The power delivered to each of the loads is observed to be higher when R_{L1} & R_{L2} are taken with opposite combination. The selection of R_{L1} & R_{L2} to achieve equal load power at both receivers' loads can be estimated where both P_{L1} and P_{L2} intersect each other.

5. EXPERIMENTAL VALIDATION AND DISCUSSION

The bench setup as depicted in the Fig. 11 is considered for experimental validation of the simulation results discussed in this article. The setup consisting of a single transmitter and two receivers which are similar in design and are kept equidistant from the transmitting coil. The circuit parameters used for the experimental validation are the same as given in the Table 1.

The operating resonant frequency for both theoretical and experimental results is selected as 21.2 kHz. For a particular setup, the optimal load selection is very much dependant on M_{12} & M_{13} which are basically a function of the position of the coils. The frequency characteristic of PTE at receiver 1 corresponding to frequency for two different electric load value is depicted in Fig. 12. As shown in the figure, PTE is optimal at the resonant frequency 21.2 kHz for both the load values. Moreover, PTE is observed decreasing with decrement in electric load value keeping all other parameters remaining the same which has also been validated through the result illustrated in Fig. 13 with two different electric load conditions.

The power delivered to load and efficiency for multiple-receiver WPT system with equidistant receiver operated at resonant frequency gradually increases with the increase in the load value. As a case study, the PTE measured experimentally at receiver 1 corresponding to the resonant frequency (21.2 kHz) with load value of 1.8 Ω is 43% whereas the same measured at receiver 2 with load value 4.5 Ω is 47%. Under similar operating conditions, from the theoretically derived numerical results,

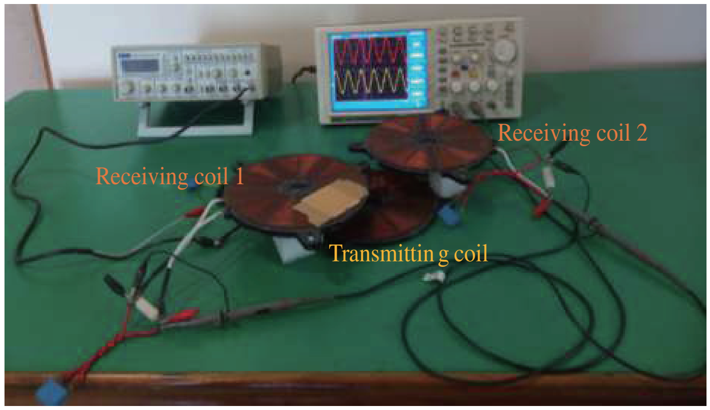

FIGURE 11. Bench top setup for experimental validation.

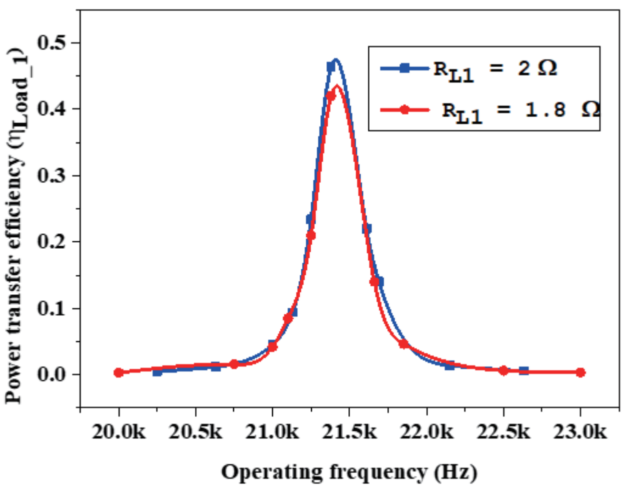

FIGURE 12. Frequency characteristic of PTE at receiver 1 for different electric load condition.

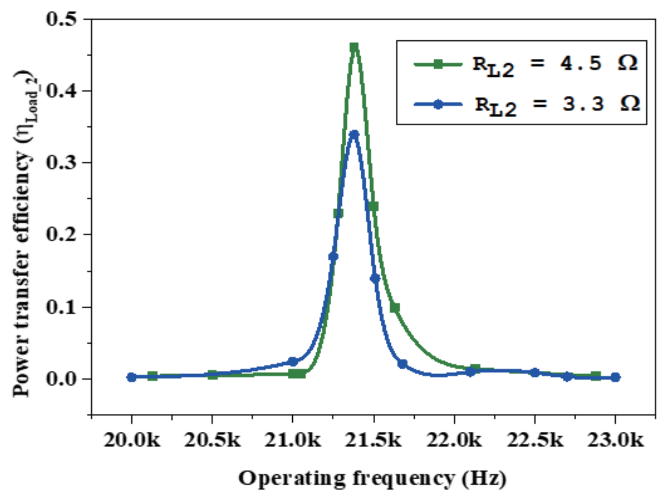

FIGURE 13. Frequency characteristic of PTE at receiver 2 for different electric load condition.

the PTEs at the two receiver loads are found to be 45% and 49%, respectively. The experimental data for both the cases are quite comparable to the simulation results with negligible deviations.

6. CONCLUSIONS

The comprehensive analysis of the MRC based WPT system for multiple receivers is presented in this article. The equivalent circuit model of fundamental multiple receivers WPT system is developed to pronounce the performance of the system. The efficacy of the system considering delivered load power, input power, current level at the transmitting and receiving coils, input impedance in correspondence to operating frequency and different load conditions is accomplished. The theoretical and analytical studies are supported with the simulation, and bench setup experiments have been carried out in order to disclose the functional dependencies and the correlation between the parameters of the system. The simulation responses obtained through the circuit model analysis are in good agreement with the experimental results. It is found tat the power delivered to the load is maximum under resonance condition and eventually higher for the higher value of load. The input impedance is found to be maximum when the system is at resonance and gradually decreases with the decrease in load values. The receivers with different load values can be driven with ensured maximum overall system efficiency, if the receiver's load values are properly selected.

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