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Two-side Impedance Matching for Maximum Wireless Power Transmission

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ABSTRACT

The research on high-efficient non-radiant wireless power transmission (WPT) system using high-quality factor resonant coupled coils has become remarkable for powering various portable household devices, biomedical implants, and electrical vehicles since last decade. Therefore, practical WPT must be able to support complicated coil configurations and keep following magnetic resonant conditions with maximum power transfer capability during coupling distance variation. In this paper, an adaptive two-side impedance matching technique using self-tuned L-matching circuits at both the transmitting and receiving sides is proposed for maximizing transmission efficiency in resonant coupled WPT system. The tuning value of inductance and capacitance for matching networks are derived based on the *Q*-based design principle, and extracted impedance ratios and *S*-parameters. The feasibility of the theoretical model is testified against simulation and measured data. The developed model shows that using two-side matching technique maximizes transmission efficiency over 80% for a range of 15–35 cm. The proposed technique also successfully retains the resonant frequency and is much more potential to provide maximum efficiency for the resonant coupled WPT system.

KEYWORDS

Coupling coefficient; Impedance matching; Magnetic resonant coupling; Transmission efficiency; Resonant frequency; Wireless power transmission

1. INTRODUCTION

The concept of multi-coil wireless power transmission (WPT) system using magnetic resonant coupling has been emerged certain time ago [1–3] and has shown a great probability of advancement in contactless charging of portable electronic devices, biomedical implants, and high-power electric vehicles, etc. The resonant coupled approach can effectively exchange energy by creating a strong magnetic coupling between near-field coils that are tuned to resonate at the same frequency. By using additional intermediate coils as magnetic field repeaters, the power transfer capability of the system can be extended over at a long operating distance compared to the inductive coupling method [1,4–10].

In practical, however, variation in the coupling distance between near-field coils affects the physical and geometrical parameters of the resonant coupled WPT system. This incident often splits the resonant frequency to create sub-resonances [11–13] and change the overall system impedance which is a serious issue for highly efficient resonant coupled system. Therefore, an effective end-to-end system with maximum power transfer capability over a long distance is essential for WPT to be more useful. Many past works have discussed several methods for improving the power transmission efficiency in the WPT system. In [4], an automatic frequency tuning system is proposed to deal with the frequency splitting effects and improving efficiency; but this technique often moves the resonant frequency out of the usable ISM (industrial scientific, and medical) frequency band specified by wireless communication standards and regulations. Ricketts et al. [14] used digitally tuned capacitors, but is limited for a long distance variation. The capacitive compensation technique in [15] achieved wide power transmission range by using high-*Q* variable capacitor in loosely intermediate coupled coils. However, this method requires more complex dynamic tuning of capacitors to keep resonant conditions fixed during strong coupling. The work in [16] and [17] introduced adapting matching techniques based on multiple loop coils at both the source and load sides to improve efficiency. But it requires manual switching of appropriate loops at both sides during the distance variation, and each loop requires a separate external capacitor to tune them at the operating frequency that makes the designed system large and complex in size. The automated impedance matching technique using additional matching network reported in [18] satisfies the ISM band, but it considered only one-side matching on the transmitting side to maintain high-power transmission during coupling distance variation. However, the transmission efficiency cannot be maximized without considering the matching at the receiving side. In [19], an adaptive impedance matching technique based on adjustable pi-matching circuit is presented to adjust input−output impedances. However, the tuning of pi-matching circuit at close coil proximity becomes very complex due to the strong effect of parasitic cross-couplings.

This paper presents an efficient maximization method at a fixed resonant frequency by introducing self-tuned L-matching circuits at both the transmitting and receiving sides of a 4-coil resonant coupled WPT system. The value of inductance and capacitance of each matching circuit are calculated based on the Q-based design principle, and extracted input and output impedance ratios of the system. The power transfer model of the resonant coupled system is analyzed by using lumped element circuit representation of each resonating coil and established at advanced design system (ADS) to investigate the viability of the proposed efficiency enhancement technique with tuned matching circuits. A non-linear numerical optimization process based on extracted S-parameters is adopted to tune the values of matching circuit components that sets the matching conditions to optimize the forward wave transmission ratio (S_{21}) for achieving maximum transmission efficiency. The model parameters and efficiency of the designed system are extracted and compared with the measurements.

In this paper, the overview and power transfer model of the resonant coupled 4-coil system are described in Section 2. Section 3 explains the design fundamentals of impedance matching networks. Validation with results is presented in Section 4. Finally, Section 5 provides concluding remarks.

2. ANALYSIS OF RESONANT COUPLED SYSTEM

2.1 Overview

The schematic representation of the magnetic resonant coupled 4-coil WPT system consists of radio-frequency (RF) signal generator, input and output matching networks, two loop coils (power and load coils) having single or two turns, and two intermediate multi-turn coils (TX and RX coils), which is shown in Figure 1. Both intermediate coils act as a high-Q LCR tank resonator because of a large number of turns, and can effectively compensate the effect of low Q-factor and low couplings

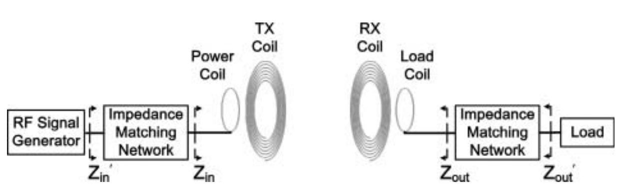


Figure 1: Schematic of the resonant coupled 4-coil WPT system

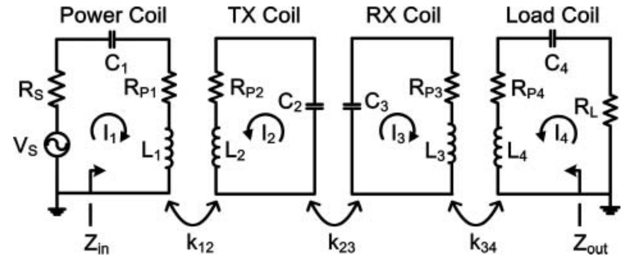


Figure 2: Equivalent circuit model of the WPT system

of loop coils. Generally, external capacitor is added with each loop coil to tune them at the same resonant frequency of intermediate coils. When all four coils resonate at the same frequency, the magnitude of the inductive and capacitive reactance of each coil becomes equal which results the RX coil to cut enough of oscillating field induced in the TX coil and transfer power to the load,

$$j\omega_0 L_i + \frac{1}{j\omega_0 C_i} = 0; \quad (\text{here}, i = 1-4). \tag{1}$$

The resonant coupled 4-coil system can be easily represented as an equivalent circuit model based on lumped parameters (L_i, C_i, R_i) illustrated in Figure 2. The key interaction for power transfer occurs mainly between the TX and RX coils and the efficiency practically depends on the distance between them. The input impedance Z_{in} looking into the coupled coils is a function of the mutual coupling between TX and RX coils, and the output impedance Z_{out} is a function of the transferred power. Each coupled coil is considered as a circuit resonator of having a cross-section a and radius r. Therefore, the self-inductance of each circular coil can be stated as

$$L_{\text{self}} \cong \mu_0 r\left[\ln\left(\frac{8r}{a}\right) - 1.75\right]; \quad \text{assuming } \frac{a}{r} << 1. \tag{2}$$

If ω_0 is the resonant frequency, then the capacitance can be calculated from Equation (3) as follows:

$$C_{\text{self}} = \frac{1}{\omega_0{}^2 L_{\text{self}}}. \tag{3}$$

The voltage source V_S with an internal resistance of R_S is used to excite the power coil connected and the current (I_1) flowing through L_1 results an oscillating magnetic field. A portion of these field lines cut by the other coils to produce flux linkages and can be expressed in terms of the mutual inductance M_{ij} between the coils via the Neumann form,

$$M_{ij} \cong \frac{\pi\mu N_i N_j r_i{}^2 r_j{}^2}{2\left[d_{ij}{}^2 + r_j{}^2\right]^{\frac{3}{2}}} \qquad (\text{here}, \ i, \ j = 1, \ldots, 4). \tag{4}$$

Here, N is the number of turns in a circular coil aligned coaxially with a coupling distance of d_{ij}. As all coils are magnetically coupled to each other (shown in Figure 2); therefore, the power transferred can be determined by the amount of coupling factors calculated as

$$k_{ij} = \frac{M_{ij}}{\sqrt{L_i L_j}}. \tag{5}$$

2.2 Power transfer model

Each coil in Figure 2 is modeled as a series compensated resonant circuit that consists of lumped elements. This structure makes the compensation capacitance at the power coil independent of the load and helps to maintain resonance during load variation. To make the analysis simple, the cross-coupling parameters (k_{13}, k_{24}, and k_{14}) are neglected. To ensure effective power transmission with high Q-factor, following conditions should be satisfied: $L_1 \ll L_2$, $L_4 \ll L_3$, $k_{23} \ll k_{12}$, and $k_{23} \ll k_{34}$. Therefore, the impedance of individual coil can be written as

$$\begin{aligned} Z_1 &= R_S + R_{P1} = R_1; \quad & Z_2 &= R_{P2}, \\ Z_4 &= R_L + R_{P4} = R_4; \quad & Z_3 &= R_{P3}. \end{aligned} \tag{6}$$

Now, with the aforementioned equations and Kirchhoff's voltage law taken at each loop, following matrix can be developed:

$$\begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega_0 M_{12} & 0 & 0 \\ j\omega_0 M_{12} & Z_2 & -j\omega_0 M_{23} & 0 \\ 0 & -j\omega_0 M_{23} & Z_3 & j\omega_0 M_{34} \\ 0 & 0 & j\omega_0 M_{34} & Z_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}. \tag{7}$$

If $Q_i = \omega_0 L_i / R_i$ represents the loaded Q-factor of ith, then the individual current in source and load coils can be extracted respectively by using the substitution method,

$$I_1 = \frac{\left(1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4\right) \frac{V_S}{Z_1}}{1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4 + k_{12}^2 k_{34}^2 Q_1 Q_2 Q_3 Q_4}, \tag{8}$$

$$I_4 = \frac{k_{12} k_{23} k_{34} Q_2 Q_3 \sqrt{Q_1 Q_4} \cdot \frac{j V_S}{\sqrt{Z_1 Z_4}}}{1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4 + k_{12}^2 k_{34}^2 Q_1 Q_2 Q_3 Q_4}. \tag{9}$$

From Equations (8) and (9), S_{21} can be derived from the system voltage transfer function (V_L/V_S) as

$$|S_{21}| \cong \frac{2 k_{12} k_{23} k_{34} Q_2 Q_3 \sqrt{Q_1 Q_4}}{1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4 + k_{12}^2 k_{34}^2 Q_1 Q_2 Q_3 Q_4}. \tag{10}$$

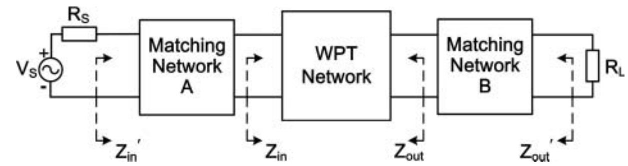


Figure 3: Block diagram of resonant coupled system including impedance matching networks

The transmission efficiency of the system can be expressed as a ratio of the output power to the input power as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{I_4^2 R_L}{I_1^2 \left(\frac{R_S}{4}\right)} = |S_{21}|^2. \tag{11}$$

3. SETUP OF IMPEDANCE MATCHING NETWORK

To maximize the efficiency in communication and radio transmitting and receiving systems, the Q-based design principle of impedance matching network [20] is most commonly used. In this paper, two-side impedance matching approach using L-matching circuits is considered to enhance the transmission efficiency of the resonant coupled WPT system without changing the operating frequency. Compared to the pi and T network, L-matching circuit is quite simple and can be easily tuned for strong coupled coils. The block diagram of the proposed system, including impedance matching network at both sides of the WPT network is depicted in Figure 3. As seen, the matching network A at the transmitting side acts to match the input impedance Z_{in} to the complex conjugate of the source resistance R_S. Similarly, the matching network B at the receiving side performs to match the output impedance Z_{out} with the complex conjugate of load resistance R_L.

Two types of L-matching circuit topology are generally used: (1) series L circuit [Figure 4(a)] and (2) shunt L circuit [Figure 4(b)]. The selection of proper L-matching circuits actually depends on the extracted value of the correspondent real component of Z_{in} and Z_{out}. As observed, the input impedance R' seen by matching network A and matching network B are actually equal to R_S and R_L, respectively. Therefore, the impedance ratio (R/R') is an important consideration for selecting a proper matching

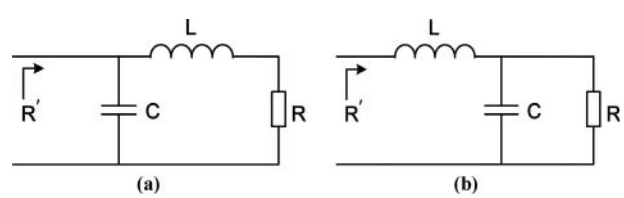


Figure 4: L type matching circuits: (a) series and (b) shunt

network. The series L circuit is used to match when the system operates in strong coupled regime and the overall impedance ratio is low, i.e. $R/R' < 1$. Likewise, when the overall impedance of the system becomes higher ($R/R' > 1$) for operating in weak coupled regime, the shunt L circuit is used. The key design parameters used to determine the value of inductance and capacitance of matching circuits are the loaded Q-factor and impedance of the network. For a specified source and load, the Q value of L-matching circuits can be calculated via Equation (12). Therefore, the matching condition requires to satisfy Equations (13) and (14),

$$Q_m = Q_L = Q_C = \sqrt{\frac{\text{Max }(R', R)}{\text{Min }(R', R)} - 1}, \qquad (12)$$

$$C = \frac{L}{Z^2\ (1 + Q_m^2)}; \quad \text{when } R < R', \qquad (13)$$

$$C = \frac{L\ (1 + Q_m^2)}{Z^2}; \quad \text{when } R > R'. \qquad (14)$$

4. MODEL VALIDATION AND MEASUREMENT

The effects of the proposed impedance matching are verified through establishing an equivalent WPT model with L-matching circuits at both sides in ADS. In simulation, symbolic-defined device and frequency-defined device models are used on linear simulation platform to set the model that includes Equations (6)–(11). To determine the component values of each matching circuit, the scattering parameters and equivalent input–output impedances of the WPT system are extracted for various configurations.

4.1 Coil parameters

Figure 5 shows the experimental model of resonant coupled WPT used to validate the theoretical and simulation model. In system, the TX coil is designed as a flat spiral resonator starts with an outer diameter of 29 cm and wind inward for approximately 6.5 turns with a pitch of 1 cm. To achieve the high-Q in both TX and RX coils, the self-capacitance is used for resonance. Therefore, the RX coil is carefully constructed and tuned to achieve same resonant frequency. With the self-capacitance of the spiral resonators, the measured resonant frequency is 17.1 MHz. On the other hand, the power and load coils are fabricated as a double turn loop of 15 cm diameter and 0.25 cm pitch. External capacitors are connected in series with the loop coils to tune them at 17.1 MHz. All the coils are fabricated with copper wire of 1.4 mm diameter. The measured electrical parameters of each coil are shown in Figure 5.

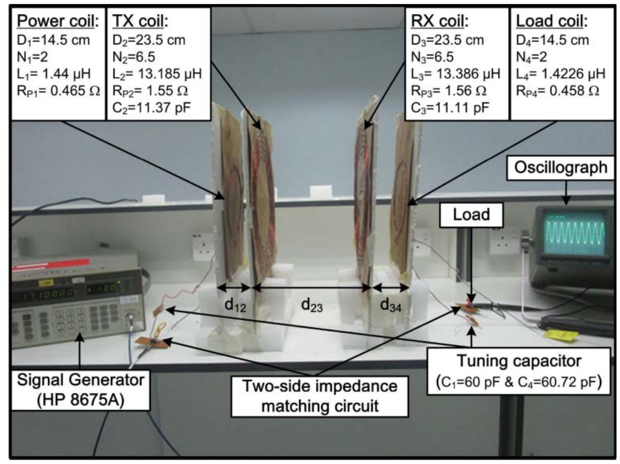


Figure 5: The experimental setup for resonant coupled WPT equipped with matching circuits

In experiment, all the coils are placed in coaxial direction and the distance d_{23} between the TX and RX coils varies from 10 to 85 cm. Both the source and load resistance of the system is 50 Ω. The values of coupling coefficient k_{23} are measured through a series-aiding series-opposing method by using VNA and are illustrated as a function of d_{23} in Figure 6. As observed, the extracted k_{23} are very much equal to the calculated coupling values obtained via the Neumann formula. During the measurement, the coupling values k_{12} and k_{34} are set equal to 0.1231 and 0.1284, respectively, by setting the distance d_{12} and d_{34} fix at 7 cm. In theoretical analysis, the parasitic cross-coupling parameters (k_{13}, k_{24}, and k_{14}) are neglected to avoid the complexity. But these parameters cannot be avoided when the coils are close to each other. Therefore, for accurate analysis, the effect of cross-coupling coefficients is taken into account. As seen in Figure 6, the

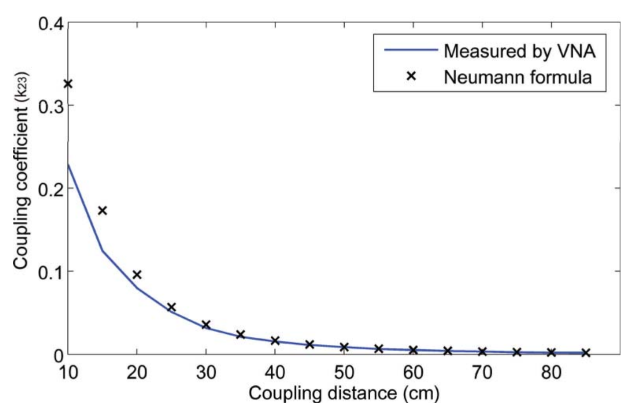


Figure 6: Coupling coefficient (k_{23}) versus coupling distance (d_{23})

coupling k_{23} becomes high at close coupling distance and sub-resonances often happen in this regime. As the coupling distance gets higher, the k_{23} becomes weaker.

4.2 Efficiency with two-side impedance matching

To make the resonant coupled WPT system operate at a fixed resonant frequency with maximum power transfer capability, the designed WPT model is being tested with L-matching circuits at both the transmitting and receiving sides. Initially, the transmission efficiency and circuit impedances of the system are measured for the distance 10−85 cm without using the matching circuits. Next, the S-parameters are extracted for a full range of coupling k_{23}, and the equivalent input and output impedances are measured. Based on the extracted impedances and S-parameters, the series and shunt L circuits are implemented on WPT during the strong and weak coupling conditions, respectively. For tuning the component values of the matching network, a non-linear numerical optimization process based on the gradient solver and extracted S-parameters is setup in the ADS simulator. Without defining the equations of matching components, this optimization process helps to meet the matching conditions for achieving optimum S_{21} and transmission efficiency corresponding to a specific source and load impedances. In measurement, capacitors ranging from 10 to 800 pF (in tens of MHz range with low ESR) and inductor ranging from 0.1 to 3 μH are modeled for the L-matching circuit.

As the overall circuit impedance in 4-coil WPT configuration changes as a function of distance, a mismatch between the source and load impedance substantially affects the power transfer capability. Therefore, maximum transmission efficiency cannot be possible without ensuring the adaptive matching at both the transmitting and receiving sides. Figure 7 illustrates the measured impedance ratio as a function of the normalized coupling distance to coil dimension for the resonant coupled WPT. Without matching, both the input and output impedance ratios are low for resonant coupled system at close distance, and then increased by a factor $1/k_{23}^2$. The one-side matching technique only secures the impedance matching either at the transmitting or receiving side, but not in both sides. But the adopted two-side matching technique confirms the adequate matching of source and load impedances to ensure the optimum transmission efficiency.

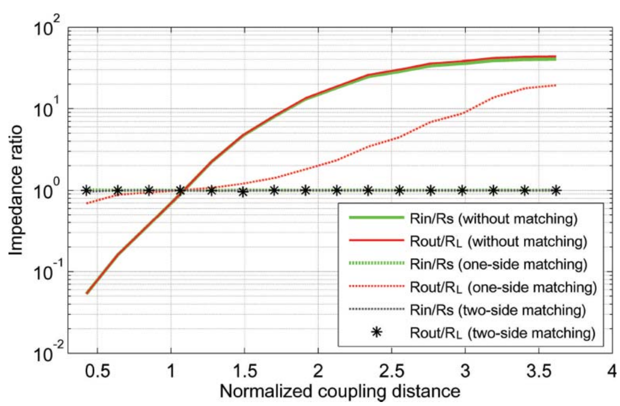


Figure 7: Extracted input and output impedance ratio of the resonant coupled system where $R_S = R_L = 50\ \Omega$

The measured data of both S_{21} and transmission efficiency for the resonant coupled WPT using two-side matching approach is illustrated in Figure 8. The proposed impedance matching with the L-circuit is also compared with the results obtained with optimum frequency tuning and one-side matching techniques. The result shows that the proposed two-side impedance matching technique is very effective compared to both the techniques. For the conventional WPT without matching, both S_{21} and efficiency becomes low at close coil proximity due to the frequency splitting (blue curves

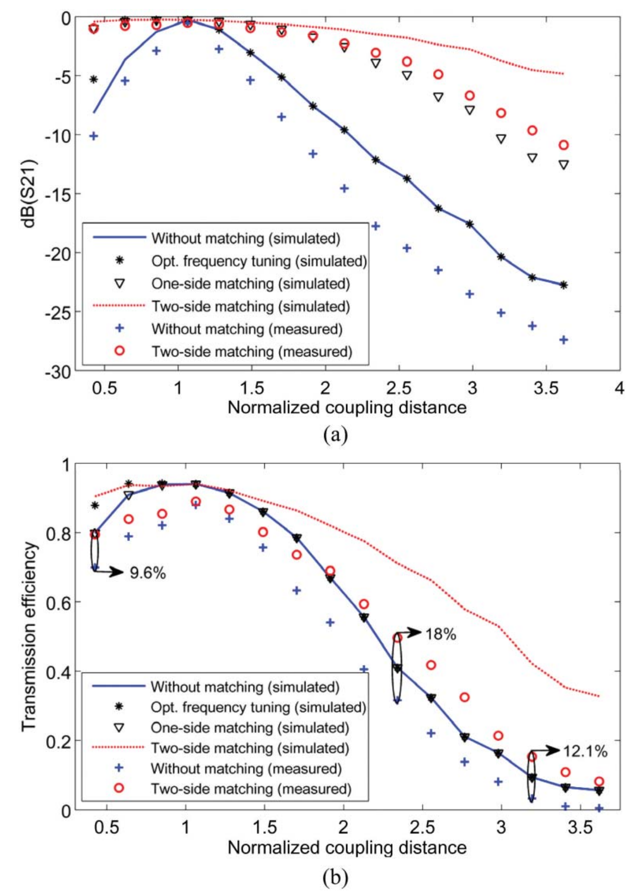
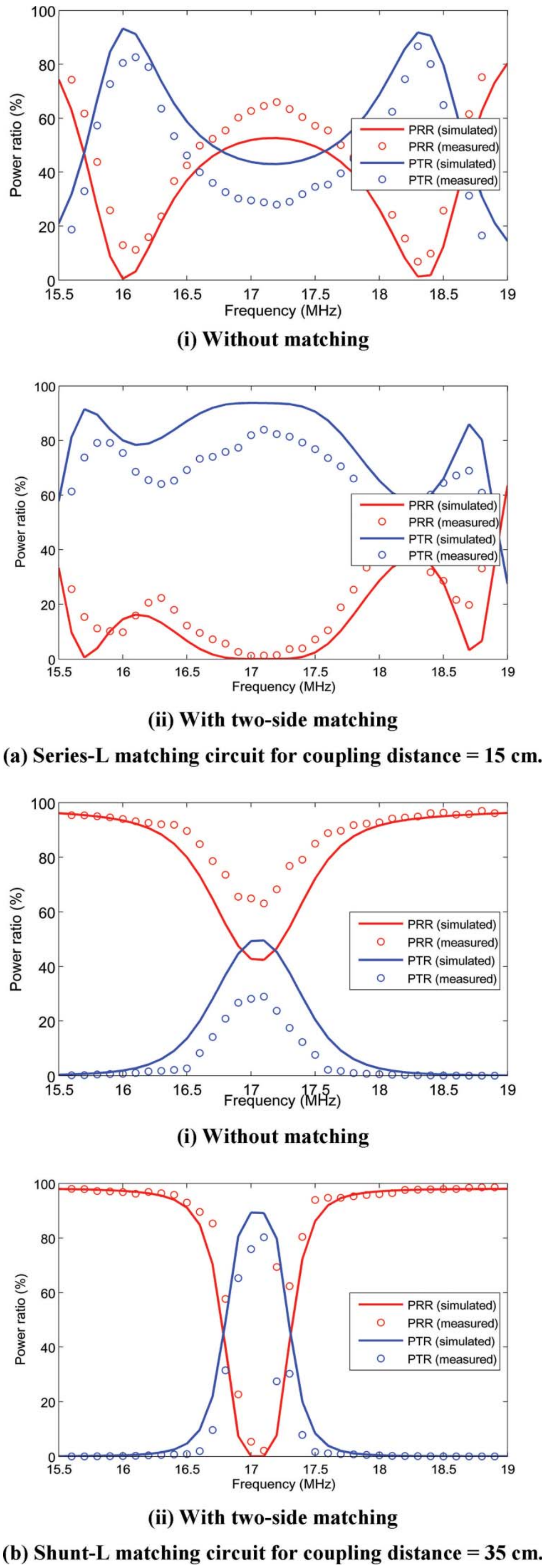


Figure 8: (a) S_{21} in dB vs. normalized coupling distance, (b) transmission efficiency vs. normalized coupling distance of the resonant coupled WPT system with two-side L-matching



(i) Without matching

(ii) With two-side matching

(a) Series-L matching circuit for coupling distance = 15 cm.

(i) Without matching

(ii) With two-side matching

(b) Shunt-L matching circuit for coupling distance = 35 cm.

Figure 9: Frequency characteristics comparison of the resonant coupled WPT system without and with two-side matching

in Figure 8). Then, both parameters become higher with the distance and reach at peak when both the TX and RX coils are critically coupled to each other. When the coupling distance is increased further, these parameters decrease rapidly due to the weak coupling between coils. The optimum frequency tuning is mostly used for improving the power transfer capability at close coupling distance and requires manual adjustment of the source frequency. On the other hand, the one-side matching (either at transmitting or receiving side) only improves S_{21} , not the efficiency. In contrast, the two-side matching with series-L circuit is very effective for close coupling distance and maximizes the transmission efficiency to 85.4% at a distance of 20 cm. Comparing with the conventional WPT system, the proposed two-side matching with shunt-L circuit also improves efficiency of about 18% and 12.1% at 55 and 75 cm, respectively. These measured results are also verified by the simulation in Figure 8. In experimental analysis, the decrease of 3%−18% in efficiency is mainly due to the ohmic loss of component and copper wires, and also due to the radiation loss of the resonators.

Figure 9 shows a comparison study of the extracted frequency characteristics between resonant coupled WPT system without and with two-side matching. The frequency characteristics of the system are analyzed based on the power reflection ratio (PRR) and power transmission ratio (PTR). PRR and PTR can be represented as a function of wave reflection ratio (S_{11}) and wave transmission ratio (S_{21}), respectively. For the system without matching, the resonant frequency splits to achieve maximum efficiency when the coils are strongly coupled to each other [Figure 9(a)(i)]. In reverse, the adopted series-L matching circuit successfully retains the resonant frequency to 17.1 MHz along with improved frequency characteristics. Similarly, the shunt-L matching circuit minimizes the PRR to enhance the transmission efficiency. This can be ensured by having zero wave reflection ratio at 17.1 MHz for different coupling distance [Figure 9(b)(ii)].

5. CONCLUSION

Coupling distance variation between near-field resonant coupled coils changes the overall circuit impedances in the WPT system and lowers the power transmission to the load. Also, sub-resonances often happen in strong coupling condition. Since the efficiency becomes maximum at resonance, a WPT system using matching circuit must be able to retain the resonant frequency. This paper demonstrates how an adaptive two-side impedance matching approach based on self-tuned L-matching circuit can be used to maximize the transmission efficiency without shifting the resonant frequency. Design guidelines for the resonant coupled WPT with the proposed two-side matching approach have been analyzed using the equivalent circuit model. The component values of the matching networks are calculated using the Q-based design principle and extracted S-parameters and input−output impedance ratios. Experimental results have shown that the conceptual matching technique maximizes the efficiency compared to the optimum frequency tuning and one-side matching techniques, and extend the power transmission range of the WPT system. The resonant frequency can also be changed and kept fixed at their original operating frequency through the proposed matching technique. The effects are also studied through simulation, and a decent agreement between the simulation and the measurement has been observed. To tune the value of matching circuit components, a non-linear numerical optimization process based on the extracted S-parameters is used during simulation.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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