ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 22(3), 497-502 (2017) https://doi.org/10.4283/JMAG.2017.22.3.497

Study on Load Impedance Matching Characteristics of Magnetic Coupled Resonant Wireless Power Transfer System

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(Received 6 June 2017, Received in final form 7 July 2017, Accepted 10 July 2017)

The impedance matching problem of magnetic coupled resonant wireless power transfer system based on planar spiral coils is studied in this paper. Taken the coupling factors into account, the relationships between impedance matching, resonant frequency and transfer distance are analyzed. Supported by the simulation analyses and experimental evidences, it is indicated that the optimum matching resistances for transfer power and transfer efficiency are different. In details, the optimal matching resistance for output power decreases with the transfer distance, while that for the transfer efficiency does not vary with transfer distance. Thus, this research provides a valuable reference for the further research on adaptive impedance matching of magnetic coupled resonant wireless power transfer system.

Keywords : wireless power transfer, planar spiral coil, impedance matching

1. Introduction

With the rapid development of various low-power mobile appliances such as cell-phones, laptops, and hand-held equipment, there is substantial interest in wireless power charging. The wireless power transfer (WPT) system via magnetic coupled resonance has many advantages, such as higher efficiency, longer range and greater power output, with broad prospects [1-4].

At present, the research about magnetic coupled WPT system is mainly focused on the improvement of transfer performance, optimization of coil structure and design of parameters [5-9]. As for the applications with miniaturized receiver, it is necessary to achieve the best matching of load impedance to maximize the transfer performance. But the research about high frequency impedance matching is relatively not much. It was pointed out that the change of transfer distance would affect the frequency splitting [10]. Utilizing high frequency finite element simulation, the extraction of key parameters is proposed based on port impedance analysis [11]. For the four-coil model WPT system, the matching circuit of π type is designed at a certain frequency and transfer distance, which cannot be adapted under the various frequencies and distances [12].

In this paper, the magnetic resonance coupled WPT system is established based on single-layer planar spiral coils. Based on the equivalent circuit, the relationship between the frequency, transfer distance and impedance matching are analyzed through the simulation and experiments. As for the designed long-range and low-power WPT system, the correctness of theoretical analyses will be verified through the experiments.

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2. Wireless Power Transfer Mechanism and System Modeling

2.1. Wireless transmission system configuration and coil characteristics analysis

The structure of magnetic coupled resonant WPT system is shown as Fig. 1, which is mainly composed of high-frequency signal generation, power amplifier circuit, transmitter and receiver coil, and power conversion circuit. The core of system is the two resonant coils [9].

In order to solve the problem of calculation of the distribution parameters, the COMSOL software is adopted to simulate and analyze [13]. The relationships between coil reactance (X), impedance angle (θ) and frequency are shown in Figure 2.

The measured curve in Fig. 2 is obtained by the

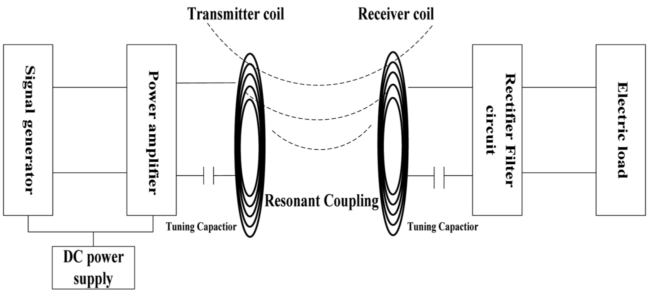


Fig. 1. The structure of magnetic coupled WPT system.

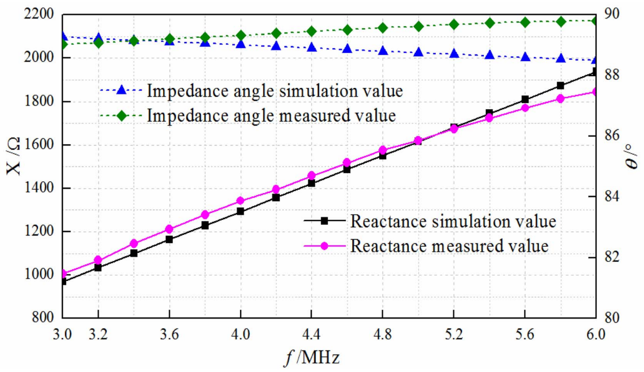


Fig. 2. (Color online) The curve of coil reactance and impedance angle.

impedance analyzer (LCR-8110G). It is shown that, for the impedance angle, the measured value and simulation value are both close to 90°, the maximum error is within 1.48 %. For the reactance, the simulation and measured value both increase with frequency, the maximum error is within 5.05 %, which indicates that the simulation model is basically consistent. Thus, the correctness of simulation model is verified. Besides, the planar spiral coil is always inductive without the self-resonant point, so it is necessary to add a tuning capacitor to improve the transfer performance [14].

2.2. System modeling and transmission characteristics analysis

Considering the parametric characteristics of planar spiral coil, the equivalent circuit model of the magnetic coupling resonant WPT system is shown as Fig. 3. Where, $\dot{U}_S$ is high frequency excitation power supply, R_S is the internal resistance of the power supply. L_1, L_2 is the equivalent inductance of the transmitter coil and receiver coil, R_1, R_2 is the equivalent resistance, respectively. L_1, R_L is the load resistance, C_1, C_2 is the external series capacitor, $\dot{\boldsymbol{I}}_1$, $\dot{\boldsymbol{I}}_2$ is the transmitter and receiver circuit current reference direction.

The impedance of the transmitter and receiver circuit Z_{11} and Z_{22} can be obtained as:

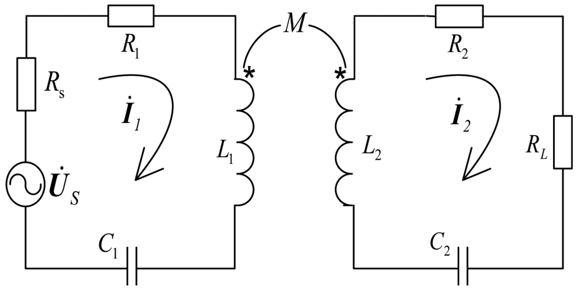


Fig. 3. The equivalent circuit of transfer system.

$$\begin{cases} Z_{11} = R_S + R_1 + j\left(\omega L_1 - \dfrac{1}{\omega C_1}\right) \\ Z_{22} = R_2 + R_L + j\left(\omega L_2 - \dfrac{1}{\omega C_2}\right) \end{cases} \tag{1}$$

According to the equivalent circuit, the Kirchhoffs Voltage Law (KVL) equations can be obtained as:

$$\begin{cases} Z_{11}\dot{I}_1 - j\omega M\dot{I}_2 = \dot{U}_s \\ Z_{22}\dot{I}_2 - j\omega M\dot{I}_1 = 0 \end{cases} \tag{2}$$

Keep the same resonant frequency for each loop ($\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}$). From equation (1) and (2), the transfer power and efficiency at the resonant frequency can be computed as:

$$\begin{cases} P_L = \left|\dot{\boldsymbol{I}}_2\right|^2 R_L = AB\dfrac{k^2Q_SQ_P}{(1+k^2Q_SQ_P)^2} \\ \eta = \left|\dfrac{\dot{\boldsymbol{I}}_2^2 R_L}{\dot{\boldsymbol{U}}_S\dot{\boldsymbol{I}}_1}\right| = B\dfrac{k^2Q_SQ_P}{1+k^2Q_SQ_P} \end{cases} \tag{3}$$

Where $A = \dfrac{U_S^2}{R_1 + R_S}$, $B = \dfrac{R_L}{R_2 + R_L}$, the coupling coefficient $k = \dfrac{M}{\sqrt{L_1L_2}}$, the quality factor of transmitter loop $Q_S = \dfrac{\omega L_1}{R_1 + R_S}$ and the quality factor of receiver loop $Q_P = \dfrac{\omega L_2}{R_2 + R_L}$. Mutual inductance M is a function of transfer distance between coils, the expression is:

$$M = \frac{\pi\mu_0 (N_1N_2)^{0.5}(r_1r_2)^2}{2D^3} \tag{4}$$

Where μ_0 is the vacuum permeability, N_1, N_2 is the number of turns, r_1, r_2 is the average radius of coil and D is the axial distance between coils.

From equation (2), the power supply input impedance Z_i is:

$$Z_i = \frac{\dot{U}_S}{\dot{I}_1} = Z_{11} + \frac{\omega^2 M^2}{Z_{22}} \tag{5}$$

Where $Z_{12} = \frac{\omega^2 M^2}{Z_{22}}$ is the reflecting impedance from receiving circuit to transmitting loop. At resonance frequency, the input impedance is only related with R_S, R_1 and reflecting resistance $R_{ref} = \frac{\omega^2 M^2}{R_2 + R_L}$. The input impedance Z_i varies with f and M, which affects the impedance matching.

2.2.1. The relationship between frequency and impedance matching

Based on equation (3), when $\partial P_L / \partial R_L = 0$ and $\partial \eta / \partial R_L = 0$, the matching resistance for the maximum transfer power and optimal transfer efficiency is:

$$\begin{cases} R_{LP_L\_max} = R_2 + \dfrac{\omega^2 M^2}{R_1 + R_S} \\ R_{L\eta\_max} = \sqrt{R_2^{\,2} + \dfrac{\omega^2 M^2 R_2}{(R_1 + R_s)}} \end{cases} \tag{6}$$

From (3) and (6), the maximum transfer power and optimal efficiency is:

$$\begin{cases} P_{LR_L\_max} = \dfrac{A\omega^2 M^2}{4\left[R_2(R_1+R_S)+\omega^2 M^2\right]} \\ \eta_{R_L\_max} = \sqrt{\dfrac{R_2}{R_2+C}}\,\dfrac{C}{C+(R_2+\sqrt{R_2^{\,2}+R_2 C})} \end{cases} \tag{7}$$

Where $C = \omega L_2 Q_s k^2$.

2.2.2. The relationship between transfer distance and impedance matching

From equation (3), it is found that the transfer efficiency is a monotonic function of coupling coefficient. But for the transfer power, there is an optimal value for maximum transfer power.

Through $\partial P_L / k = 0$, it can be obtained:

$$k_0 = \frac{1}{\sqrt{2Q_S Q_P}} \tag{8}$$

The k_0 is called as critical coupling point [14]. It is indicated that under different R_L, the k_0 is also different, which means the optimum matching resistance changes with the distance. Thus, the matching resistance $R_{L\text{-}k_0}$ for maximum transfer power is determined when transfer distance is fixed, shown as:

$$R_{L\_k_0} = \frac{N_1 N_2 (\omega\pi\mu_0)^2 d^8}{512(R_1+R_S)D^6} - R_2 \tag{9}$$

So the maximum transfer power and efficiency at the optimum distance can be obtained as:

$$\begin{cases} P_{Lk_0\_max} = \dfrac{2AB}{9} \\ \eta_{k_0\_max} = \dfrac{B}{3} \end{cases} \tag{10}$$

3. Simulation Analysis

The COMSOL Multiphysics simulation software is adopted for modeling and analysis. In simulation, the AC/DC module is selected; the coil model is established according to the parameters shown in Table 1, which is same with that used in experiments.

The boundary conditions such as the external circuit and excitation source are set up; the fine degree of mesh subdivision and the post-processing of results are solved. The transfer distance, frequency, load resistance, transfer efficiency, transfer power and reflecting impedance are all discussed.

3.1. The effect of frequency on impedance matching

When D = 15 mm, the parametric sweep of frequency f is 3 MHz-6 MHz, the relationship between P_L, η and f under different 8 groups of R_L can be described as Fig. 4.

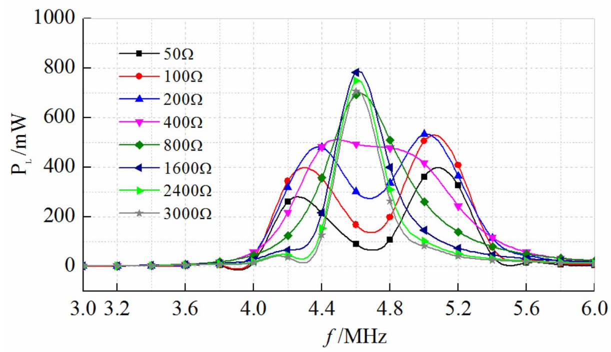
It is shown that the resonant frequency of this system is 4.6 MHz, the largest transfer power P_L = 783.03 mW when R_L = 1600Ω. The largest transfer efficiency η = 91.32 % when R_L = 100Ω.

As for the transfer power, when R_L = 50-400Ω, the transfer power has two maximum points, for instance, 4.3 MHz and 5.2 MHz. When R_L = 400-3000Ω, the transfer power increases first and then decreases with the frequency, reaches the maximum value at 4.6 MHz.

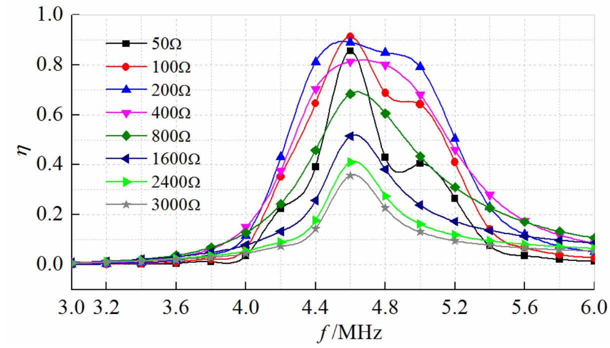
As for the transfer efficiency, under different R_L, the transfer efficiency increases first and then decreases with

Table 1. Parameters of simulation model.

Parameters	Value
Copper wire radius a/mm	0.14
Inner diameter d_1/mm	3.00
Outer diameter d_2/mm	35.15
Average diameter d/mm	19.08
Coil turns N	62
Power supply U_S/V	13
Internal resistance R_S/Ω	50



(a) When D=15mm, the relationship between P_L and f under different R_L



(b) When D=15mm, the relationship between η and f under different R_L

Fig. 4. (Color online) When D = 15 mm, the relationship between P_L, η and f under different R_L.

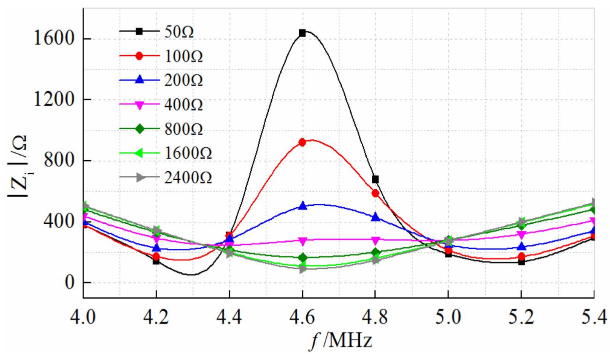


Fig. 5. (Color online) When D = 15 mm, the relationship between $|Z_i|$ and f under different R_L.

the frequency, reaches the maximum value at 4.6 MHz.

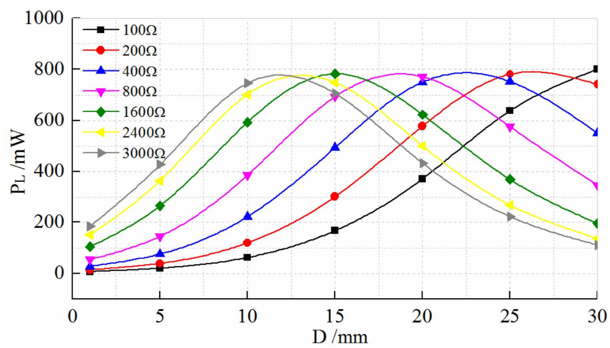
In above, the transfer power appears two peaks when the load resistance is small, which dues to that the reflecting impedance changes with frequency and load resistance. So the impedance does not match, which leads to the minimum transfer power at non-resonant point. Only at the resonant frequency, the reflecting impedance will be the minimum value. The relationship between $|z_i|$ and frequency under different load resistances are shown as Fig. 5.

As shown, the $|z_i|$ is smallest at the 4.3 MHz and 5.2 MHz when load resistance is smaller than 400Ω; the $|z_i|$ reaches the minimum value at 4.6 MHz when load resistance is greater than 400Ω, and there is an optimum impedance matching at 4.6 MHz, making the transfer power maximum.

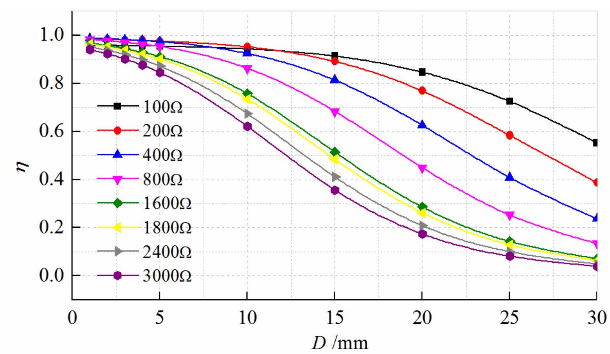
3.2. The effect of transfer distance on impedance matching

When f = 4.6 MHz, the parametric sweep of transfer distance D is 1 mm-30 mm, the relationship between P_L, η and D under different 7 groups of R_L are described as Fig. 6.

It can be seen from Fig. 6(a) that the matching resistance for the maximum transfer power is different at different distances and the matching resistance decreases with transfer distance. When D = 15 mm, the optimum matching resistance R_L = 1600Ω. But when D = 20 mm, the optimum matching resistance $R_L \approx$ 800Ω and the maximum transfer power P_L = 771.33 mW, η = 44.96 %. In Fig. 6(b), the transfer efficiency decreases gradually with the load



(a) When f=4.6MHz, the relations between P_L and D under different R_L



(b) When f=4.6MHz, the relations between η and D under different R_L

Fig. 6. (Color online) When f = 4.6 MHz, the relations between P_L, η and D under different R_L.

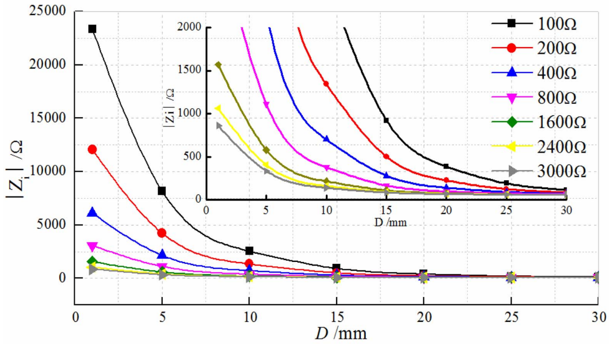


Fig. 7. (Color online) When f = 4.6 MHz, the relations between $|Z_i|$ and D under different R_L.

resistance and transfer distance.

When frequency is fixed, the Z_{12} is decreased with the distance, which leads to the matching impedance for transfer power is different at different distances and decreases with the distance. Thus, the correctness of equation (8) and (9) in part of theoretical analysis is verified. However, when the load resistance is certain, the coupling strength between coils decreases with the distance, which causes the decrease of transfer efficiency. The relationship between $|z_i|$ and frequency at different load resistances are shown in Fig. 7, its upper right figure is a local amplification graph.

It is shown that the $|z_i|$ decreases with transfer distance and load resistance, so the optimum matching resistance varies with the transfer distance.

4. Experimental Verification

A magnetic coupled resonance WPT system is constructed as shown in Fig. 8. The high-frequency supply of system is composed by the signal generator and power amplifier. The equivalent parameters of the transmitter and receiver coils and the tuning capacitance are measured by impedance analyzer and shown in Table 2. The voltage U_L of the load resistance is detected by the oscilloscope and the load power $P_L = U_L^2 / R_L$. A 1Ω resistor is

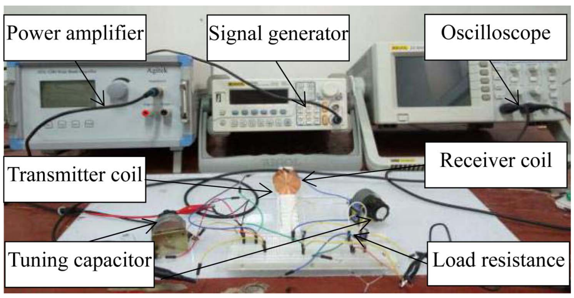


Fig. 8. (Color online) The experiment devices.

Table 2. Components of the system parameters.

Parameters	Transmitter coil	Receiver coil
Tuning capacitor C/pF	20	20
Equivalent inductance L/μH	59.47	59.45
Resonant frequency/MHz	4.60	4.60
Equivalent resistance/Ω	14.03	14.05
Material	Copper	Copper

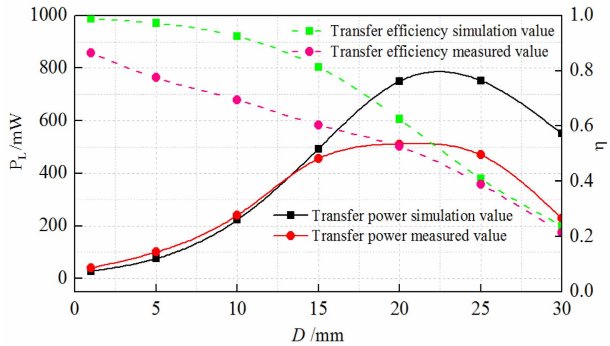


Fig. 9. (Color online) When f = 4.6 MHz and R = 400Ω, the relationship between P_L, η and D.

selected in series with the driver coil to sense the current. The comparison between experimental values and theoretical values of transfer power and transfer efficiency under different distances are shown in Fig. 9.

It can be found that the transfer power increases first and then decreases with the distance. The maximum transfer power P_L = 532.9 mW when D = 22 mm, and the transfer efficiency decreases gradually with the distance. The experimental and simulation results are basically consistent. Certainly, the loss of various electronic components and external electromagnetic interference leads to that the experimental measured value is slightly lower than the ideal simulation results.

5. Conclusion

In this paper, the magnetic coupled resonance WPT system is established based on single-layer planar spiral coils. The relationship between the frequency, transfer distance and impedance matching are analyzed. Supported by the simulation analysis and experimental evidences, the results show that the optimum matching resistances for the transfer power and transfer efficiency are different. When the load resistance is small, the transfer efficiency is largest at the resonant frequency, while the transfer power is not largest. The optimal matching resistance for transfer power decreases with distance, but the optimal matching resistance for transfer efficiency does not alter with distance. As for the WPT system based on planar spiral coils, the parameters such as frequency, distance and resistance can be reasonably set up to ensure the higher transfer power, efficiency and stability of performance. In this study, the optimum matching resistance should be set as $R_L = 400\Omega$, the system can still achieve a high voltage, power and efficiency under far transfer distance, for instance $U_L = 14.6$ V, $P_L = 511.2$ mW, $\eta = 52.5$ % when transfer distance $D = 22$ mm.

Acknowledgements

This work was supported by the State Key Laboratory of Power transfer Equipment and System Security and New Technology Visiting Scholar Program [No. 2007DA10512713407], Scientific Research Foundation for Distinguished Scholars, Shihezi University [No. RZCX201544].

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