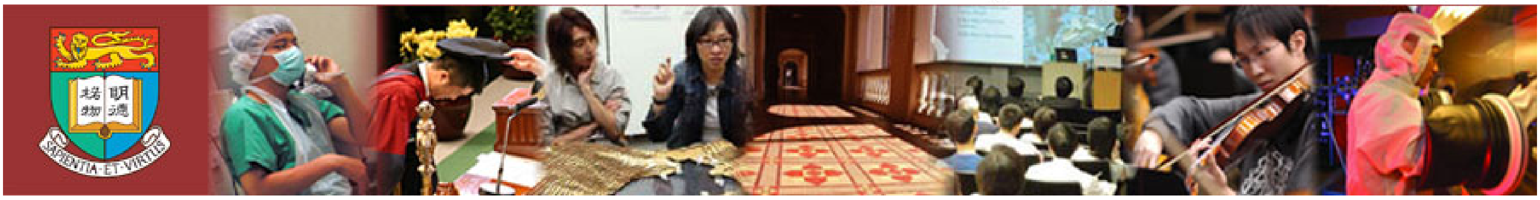

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Quantitative Analysis of Mutual Inductance for Optimal Wireless Power Transfer via Magnetic Resonant Coupling

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This paper presents the quantitative analysis for the optimal design of wireless power transmission (WPT) systems based on magnetic resonant coupling (MRC) mechanism. In this paper, the exemplified MRC-based WPT system adopts the series–series topology and one resonant coil, which shows that the energy efficiency and transferred power are both significantly affected by the mutual inductance of the primary-resonant coils and the resonant-secondary coils. In addition, the simulated and experimental results are both provided to illustrate the influence of the mutual inductance on the performance of MRC-based WPT systems regulating the relative displacement among coils. Thus, this quantitative analysis can offer the significant theoretical and experimental basis for the optimal design of MRC-based WPT systems in various application fields.

Index Terms—**Magnetic field analysis, magnetic resonant coupling (MRC), optimization, wireless power transmission (WPT).**

I. Introduction

RECENTLY, the wireless power transmission (WPT) technology has made fruitful achievements [1]–[3], which can be utilized to various application fields, such as charging portable electronic devices, implanted medical instruments, integrated circuits, and electric vehicles. This epoch-making technique significantly influences our usage pattern of the traditional and sustainable energies.

In particular, the magnetic resonant coupling (MRC) mechanism has obtained increasing attentions to improve the transmission performance of WPT systems. In [4], the MRC-based WPT system was experimentally demonstrated, which significantly extends the transmission distance by comparing with the traditional inductive power transmission. Also, the MRC-based WPT system can fulfill transferring the energy to multiple receptors [5]. In addition, the transfer efficiency and air-gap length can be maximized using the equivalent circuit and Neumann formula [6]. In [7], the systematic design procedure was proposed to maximize the power transfer efficiency for bio-implantable devices. Besides, the characteristic of the frequency sensitivity was also utilized to encrypt the energy for improving the security performance of WPT systems [8]. However, previous studies seldom focus on the matching issue of mutual inductances among coils for optimal MRC-based WPT systems.

This paper deals with the quantitative analysis for the optimal design of MRC-based WPT systems. By adopting the series–series topology, the exemplified experimental prototype is utilized to reveal the influence of the mutual inductance on the wireless transmission performance, which determines the optimal configuration of the relative displacement among coils. The presented quantitative analysis offers the theoretical and experimental basis for optimal MRC-based WPT systems in various application fields.

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II. MRC-Based WPT System

Fig. 1 shows the MRC-based WPT system adopting series–series topology, which comprises of three basic components: 1) the primary unit; 2) the resonant unit; and 3) the secondary unit, where r_p, r_r, and r_s are the internal resistances of the primary, resonant, and secondary coils, respectively, R_L is the load resistance, C_p, C_r, and C_s are the capacitances of the primary, resonant, and secondary units, respectively, and L_p, L_r, and L_s are the inductances of the primary, resonant, and secondary units, respectively.

A. Primary Unit

The impedance Z_p can be calculated as

$$Z_p = j\omega L_p + \frac{1}{j\omega C_p} + r_p \tag{1}$$

where ω is the switching frequency of the power supply. Meanwhile, the voltage of the power source V_{source} can be expressed as

$$V_{\text{source}} = V_p + I_p r_p + \frac{1}{j\omega C_p} I_p \tag{2}$$

where I_p as the current of the primary unit, which is normally maintained at a constant value. The primary coil voltage V_p can be written as

$$V_p = j\omega L_p I_p - j\omega L_{pr} I_r \tag{3}$$

where L_{pr} is the mutual impedance between the primary and resonant coils and I_r is the current of the resonant unit.

B. Resonant Unit

The impedance Z_r is given by

$$Z_r = j\omega L_r + \frac{1}{j\omega C_r} + r_r. \tag{4}$$

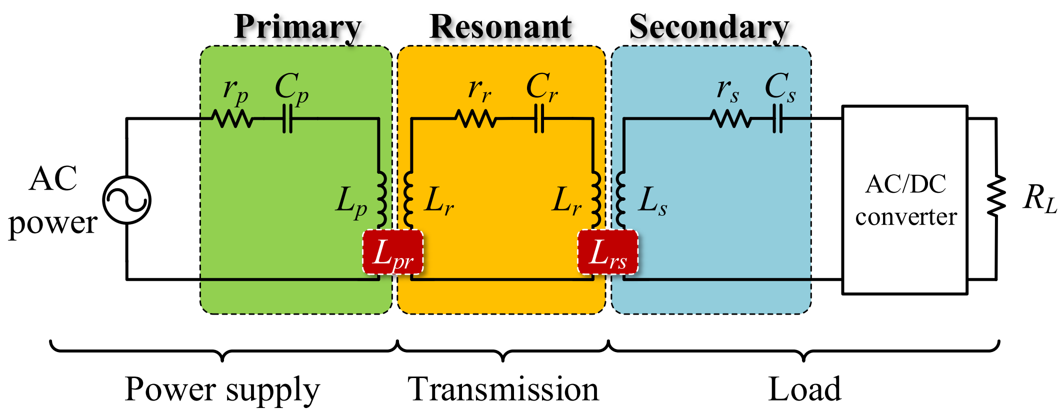

Fig. 1. Schematic view of exemplified MRC-based WPT system.

Thus, the current I_r can be calculated based on the induced potential by the primary coil, which is given by

$$I_r = \frac{j\omega L_{pr} I_p}{Z_r}. \tag{5}$$

C. Secondary Unit

The impedance Z_s can be calculated as

$$Z_s = j\omega L_s + \frac{1}{j\omega C_s} + r_s. \tag{6}$$

Similarly, the current I_s of the secondary unit can be obtained from the induced potential by the resonant unit, which is given by

$$I_s = \frac{j\omega L_{rs} I_r}{Z_s} \tag{7}$$

where L_{rs} denotes the mutual impedance between the resonant and secondary coils. Then, the secondary coil voltage V_s can be expressed as

$$V_s = j\omega L_{rs} I_r - j\omega L_s I_s. \tag{8}$$

Hence, the pickup voltage of the energy receptor V_{pickup} is given by

$$V_{\text{pickup}} = V_s - I_s r_s - \frac{1}{j\omega C_s} I_s. \tag{9}$$

In addition, the transferred power relies on the reflected impedances to the primary unit, which is given by

$$P = \text{Re}\left(Z_{rp}\right) I_p^2 \tag{10}$$

where Z_{rp} is the reflected impedance from the resonant unit to the primary unit. It can be calculated by

$$Z_{rp} = \frac{\omega^2 L_{pr}^2}{Z_r + Z_{sr}} \tag{11}$$

where Z_{sr} is the reflected impedance from the secondary unit to the resonant unit. It can be expressed as

$$Z_{sr} = \frac{\omega^2 L_{rs}^2}{Z_s + R_L}. \tag{12}$$

TABLE I
PARAMETERS OF THREE COILS

Item	Value
Primary coil inductance	95.89 µH
Primary coil internal resistance	0.2215 Ω
Primary coil number of turns	20
Resonant coil inductance	94.77 µH
Resonant coil internal resistance	0.07032Ω
Resonant coil number of turns	20
Secondary coil inductance	9.372 µH
Secondary coil internal resistance	0.03565 Ω
Secondary coil number of turns	10

Then, the energy efficiency η can be calculated as

$$\eta = \text{Re}\left(\frac{Z_p Z_r\,(Z_s+R_L)+\omega^2 L_{rs}^2 Z_p}{\omega^2 L_{pr}^2\,(Z_s+R_L)+Z_p Z_r\,(Z_s+R_L)+\omega^2 L_{rs}^2 Z_p}\right). \tag{13}$$

Since the MRC-based WPT system works at the fixed switching frequency, the transferred power and energy efficiency mainly depend on the mutual inductances among the primary, resonant, and secondary coils.

III. SIMULATION RESULTS

To analyze the influence of mutual inductances on the performance of MRC-based WPT systems, the simulation model is set up using MATLAB/SIMULINK. In addition, the electromagnetic field analysis is carried out using JMAG. In the exemplified prototype, the working frequency is chosen as 100 kHz. The corresponding key parameters are listed in Table I, where the coil inductance is directly measured utilizing the LCR meter (ISO-TECH LCR821).

Fig. 2(a) and (b) shows the dimensions of the primary and resonant coils, where both have a hollow circular shape with the inside diameter of 125 mm and the outside diameter of 215 mm. The secondary coil has a similar geometry as shown in Fig. 2(c), where the inside and outside diameters equal 50 and 94 mm. As shown in Fig. 2(d), the primary and resonant coils directly face each other. In addition, this paper mainly discusses about the impact of the vertical displacement of coils on the optimal MRC-based WPT system based on the constant horizontal configuration. Consequently, the horizontal

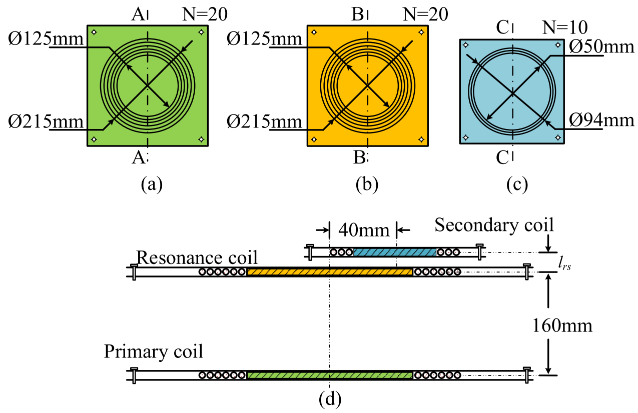

Fig. 2. Geometry of MRC-based WPT system. (a) Primary coil dimension. (b) Resonant coil dimension. (c) Secondary coil dimension. (d) Displacements among coils.

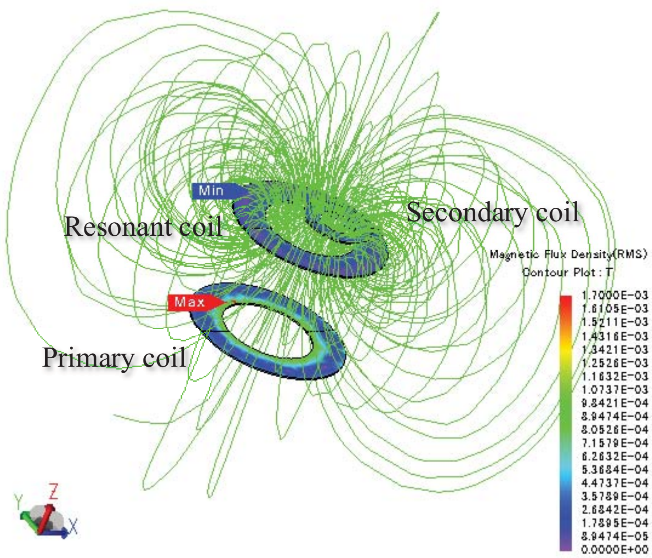

Fig. 3. Simulated magnetic flux density.

offset is constantly chosen as 40 mm between centers of the resonant and secondary coils. In the exemplified MRC-based WPT system, the distance between the primary and resonant coils is fixed at 160 mm and L_{pr} constantly equals 5.3052 μH. In addition, the L_{rs} can be varied by regulating the distance l_{rs} between the resonant and secondary coils.

When the exemplified MRC-based WPT system works in the magnetic resonant state, as shown in Fig. 3, the resonant and secondary coils can be effectively excited and the corresponding flux density reach around 0.25 mT. By regulating l_{rs} to vary L_{rs}, the numerical simulation verifies the influence of the mutual inductance on the transmission performance. Specifically speaking, Fig. 4 shows the simulated load voltage and current, respectively. It illustrates that the maximum values can be obtained when L_{rs} equals around 13.5152 μH. In addition, as shown in Fig. 5, the exemplified MRC-based WPT system can reach to the maximum energy efficiency (84.8%) when L_{rs} equals around 6.6327 μH and the maximum transferred power (31.6 W) when L_{rs} equals around 13.5152 μH. Therefore, the MRC-based WPT system can obtain maximum transferred power and transmission efficiency

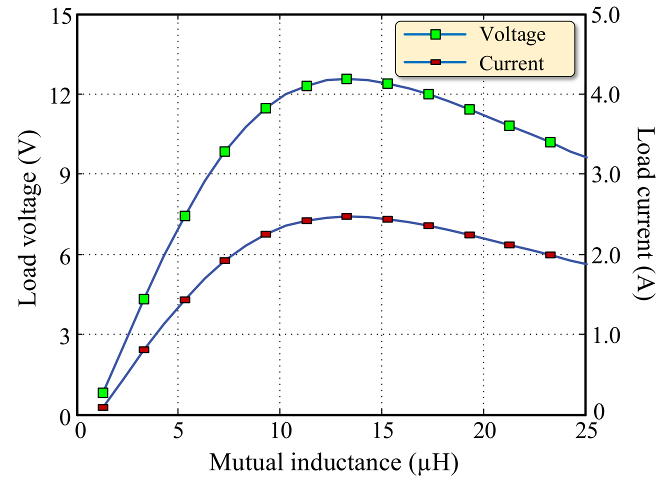

Fig. 4. Simulated load voltage and current.

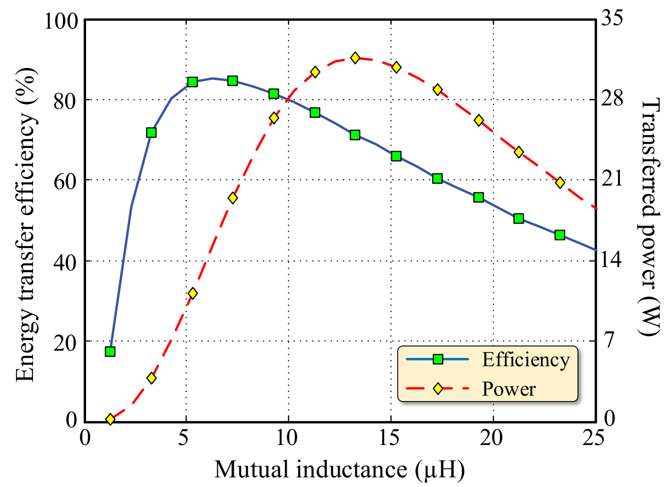

Fig. 5. Simulated transmission performance.

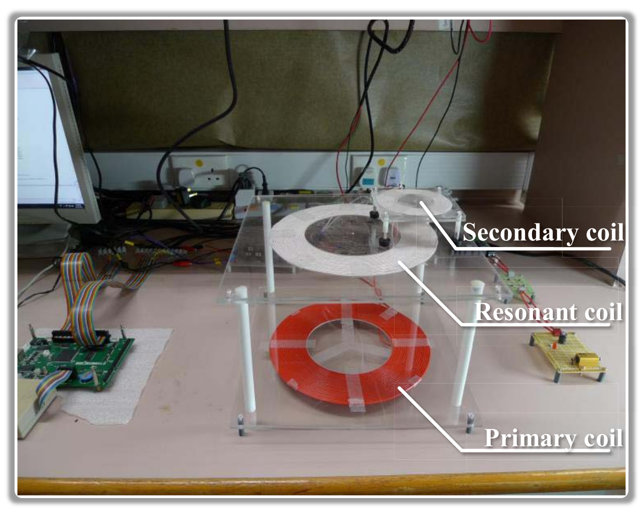

Fig. 6. Prototype of exemplified MRC-based WPT system.

by regulating the configuration of mutual inductances according to various functional requirements.

IV. Experimental Result

As shown in Fig. 6, the experimental prototype is also established according to the simulation parameters as listed

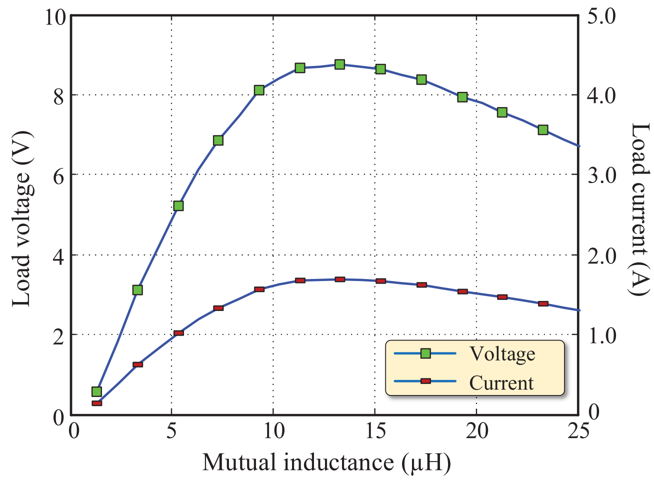

Fig. 7. Measured load voltage and current.

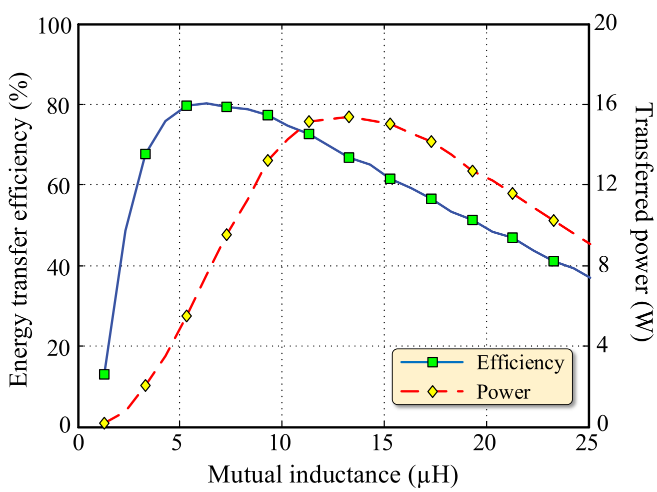

Fig. 8. Experimental transmission performance.

in Table I. The power source is provided by the programmable ac power supply (Amplifier Research 75A250A). The current is sensed using a wideband current transducer (Tektronix TM502A). In addition, the voltage and power are measured using a power analyzer (LeCroy WR6100A).

By regulating the distance between the resonant and secondary coils, the corresponding mutual inductance can be changed within the range utilized in the aforementioned numerical simulation. Fig. 7 shows the measured load voltage and current, respectively. It shows that the load can obtain the maximum voltage of 8.7 V and the maximum current of 1.8 A when L_{rs} equals around 13.5 μH. In addition, Fig. 8 shows the wireless transmission performance of the exemplified MRC-based WPT system. The maximum energy efficiency can reach around 80.2% when L_{rs} equals around 6.3 μH. In addition, the exemplified WPT system can offer the maximum transferred power of around 15.3 W when L_{rs} equals around 13.5 μH. With respect to the varying L_{rs}, the measured transferred power and the energy efficiency show the similar changing trends as the simulated results. It illustrates that the maximum transferred power and the maximum energy efficiency can be obtained based on different mutual inductances, which means that the configuration of the coil displacement is important for the optimal MRC-based WPT system in various applications. Therefore, the experimental results well agree with the aforementioned theoretical analysis and the simulated results, which quantitatively illustrates that the optimal design of MRC-based WPT systems needs to properly regulating the configuration of mutual inductances.

V. Conclusion

In this paper, the quantitative analysis is carried out to illustrate the impact of mutual inductances among the primary, resonant, and secondary coils on the transmission performance of MRC-based WPT systems. By properly regulating the displacement of coils to change the corresponding mutual inductances, the exemplified WPT system can effectively achieve the maximum transferred power or energy efficiency to fulfill various functional requirements. For example, an implanted medical device needs the charging duration as short as possible. Accordingly, the optimal wireless charging system can obtain the maximum transferred power by properly regulating the distance between the resonant and secondary coils. Besides, a large-scale charging system desires high-energy efficiency, especially for roadway-powered electric vehicles. Thus, the optimal design is also required to consider the mutual inductance between the resonant and secondary coils. Finally, the simulated and experimental results well agree with the theoretical analysis. Therefore, this paper provides the theoretical and experimental basis to implement the optimal design of MRC-based WPT systems, which can be utilized to meet different technical requirements for various industrial applications.

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