

Analysis and Optimization of Wireless Power Transfer Efficiency Considering the Tilt Angle of a Coil

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Abstract

Wireless power transfer (WPT) based on magnetic resonant coupling is a promising technology in many industrial applications. Efficiency of the WPT system usually depends on the tilt angle of the transmitter or the receiver coil. This work analyzes the effect of the tilt angle on the efficiency of the WPT system with horizontal misalignment. The mutual inductance between two coils located at arbitrary positions with tilt angles is calculated using a numerical analysis based on the Neumann formula. The efficiency of the WPT system with a tilted coil is extracted using an equivalent circuit model with extracted mutual inductance. By analyzing the results, we propose an optimal tilt angle to maximize the efficiency of the WPT system. The best angle to maximize the efficiency depends on the radii of the two coils and their relative position. The calculated efficiencies versus the tilt angle for various WPT cases, which change the radius of RX ($r_2 = 0.075$ m, 0.1 m, 0.15 m) and the horizontal distance ($y = 0$ m, 0.05 m, 0.1 m), are compared with the experimental results. The analytically extracted efficiencies and the extracted optimal tilt angles agree well with those of the experimental results.

Key Words: Coupling Coefficient, Mutual Inductance, Power Transfer Efficiency, Tilt Angle, Wireless Power Transfer.

I. INTRODUCTION

Wireless power transfer (WPT) based on the magnetic resonant coupling scheme has recently become widely used in many applications, such as electric vehicles, robotics, and medical devices [1, 2]. The WPT using magnetic resonant coupling can improve the power transfer efficiency (PTE) or extend the service range compared with inductively coupled systems. To improve the PTE, researchers have used various methods, such as impedance matching [3, 4], adjusting the coupling among multiple transmitters (TXs) or multiple receivers (RXs) [5], and applying the optimum condition of the values of phase difference and amplitude ratio between two adjacent TXs [6], among others.

Adding more TXs and RXs overcomplicates the circuit and

renders it difficult to apply in practice. The most widely considered configuration of the WPT system is using two parallel coaxial circular coils: a single TX coil and a single RX coil. The PTE is known to decrease sharply when angular misalignment or lateral misalignment occurs [1, 7–9]. A WPT system with two parallel coaxial coils can achieve maximum PTE compared with other configurations [10]. However, the experimental result in [11] showed that the maximum transmission efficiency is reached when two coaxially located circular coils have an angle difference of 45° . The PTE can be improved by changing the tilt angle of coils for the given position and the radii of coils.

In this study, we analyze the effect of the tilt angle of the coil on the PTE of the WPT system. A mutual inductance between two coils with the tilt angle located at an arbitrary position in a 3D coordinate is extracted using numerical analysis through the

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Neumann equation. Using the extracted mutual inductance and the equivalent circuit model of the WPT system, the PTE depending on the tilt angle is extracted. We propose an optimal tilt angle to maximize the efficiency of the WPT system. The angle at which the efficiency is maximized depends on the radii of the two coils and their relative position.

This paper is organized as follows. Section II describes the equivalent circuit model of the WPT system based on magnetically resonant coupling, and the coupling coefficient analysis considering angular misalignment is introduced. Section III shows the simulated and experimental efficiencies of the WPT system for three different RX coil radii, and the efficiency of the WPT system is analyzed when angular misalignment or lateral misalignment occurs. We also discuss the relationship among the radii of RX, the tilt angle of the coil, and the PTE. Section IV presents the findings.

II. EFFICIENCY ANALYSIS OF THE WPT TILTED COIL

An equivalent circuit model of a magnetic resonant coupled WPT system with a single TX coil and a single RX coil is shown in Fig. 1.

In Fig. 1, k is the coupling coefficient between a TX coil and an RX coil; V is the phasor of the voltage source in the TX; L_{TX} and L_{RX} are the self-inductances of the two coils; and R_{P1} and R_{P2} are the parasitic resistances of the two coils. C_1 and C_2 are the capacitances of TX and RX, respectively, to satisfy $\omega_0 = 1/\sqrt{L_{TX}C_1} = 1/\sqrt{L_{RX}C_2}$, where ω_0 is the resonant frequency of the WPT system. R_S is the source resistance, and R_L is the load resistance.

The circuit model can be analyzed by Kirchhoff's voltage law equations for two coils as follows:

$$(R_{P1} + R_S + j\omega L_{TX} + \frac{1}{j\omega C_1})\mathbf{I}_{TX} + kj\omega\sqrt{L_{TX}L_{RX}}\mathbf{I}_{RX} = 0, \quad (1)$$

$$kj\omega\sqrt{L_{TX}L_{RX}}\mathbf{I}_{TX} + (R_{P2} + R_L + j\omega L_{RX} + \frac{1}{j\omega C_2})\mathbf{I}_{RX} = 0, \quad (2)$$

where \mathbf{I}_{TX} and \mathbf{I}_{RX} are the phasors of the currents in the TX and

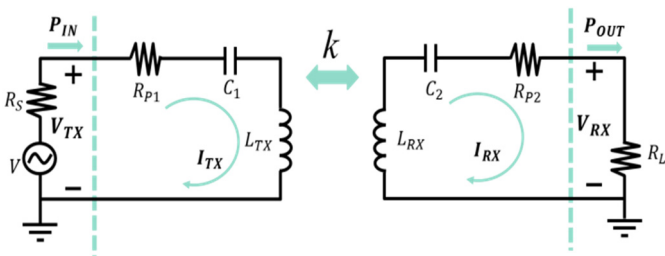


Fig. 1. Circuit modelling of the WPT system with a single TX and a single RX.

RX, respectively.

The PTE is defined as the ratio between the power delivered to a load and the power supplied by the source as follows:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\text{Re}[V_{RX} I_{RX}^*]}{\text{Re}[V_{TX} I_{TX}^*]} = \frac{k^2 \omega^2 L_{TX} L_{RX} R_L}{R_{P1} (R_{P2} + R_L)^2 + k^2 \omega^2 L_{TX} L_{RX} (R_{P2} + R_L)} \quad (3)$$

Eq. (3) can be rewritten as $\eta = Ak^2 / (B + Ck^2)$, where $A = \omega^2 L_{TX} L_{RX} R_L$, $B = R_{P1} (R_{P2} + R_L)^2$, $C = \omega^2 L_{TX} L_{RX} (R_{P2} + R_L)$, and $k \in [0, 1]$. The derivative of η for k is as follows:

$$\frac{\partial \eta}{\partial k} = \frac{2ABk}{(B + Ck^2)^2}. \quad (4)$$

By setting Eq. (4) to 0, k will be 0. Therefore, $k=0$ is an extreme point of function η . When $k \in [0, 1]$, η' is greater than zero, η is monotonically increasing in this range, and η increases when k increases.

To calculate the coupling coefficient between two coils, we consider the two coils located in the 3D space as shown in Fig. 2.

The coupling coefficient k is acquired using

$$k = \frac{M}{\sqrt{L_{TX} L_{RX}}}, \quad (5)$$

where M is the mutual inductance between the two coils.

The mutual inductance M can be calculated using the Neumann formula [12]:

$$M = \frac{N_{TX} N_{RX} \mu_0}{4\pi} \oint_{l_{TX}} \oint_{l_{RX}} \frac{d\mathbf{l}_{TX} \cdot d\mathbf{l}_{RX}}{R}, \quad (6)$$

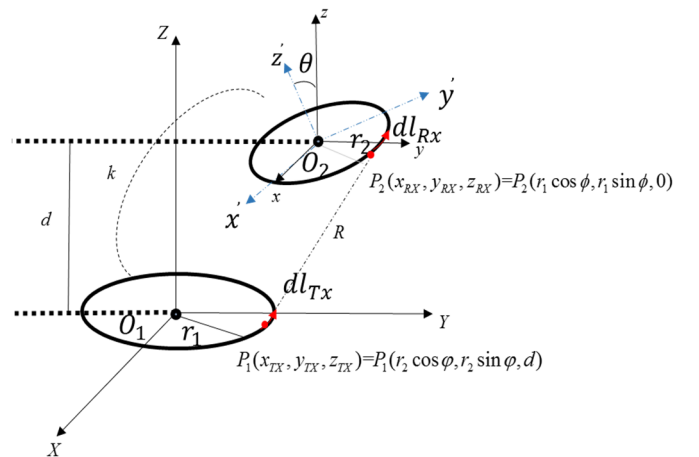


Fig. 2. Configuration of the WPT system with angle mis-alignment and horizontal misalignment.

where N_{TX} and N_{RX} are the number of TX and RX coil turns, respectively, and μ_0 is the magnetic permeability of free space. In Fig. 2, r_1 represents the radius of TX, and r_2 is the radius of RX. The centers of the TX coil and RX coil are $O_1(0, 0, 0)$ and $O_2(0, y, d)$, respectively. The horizontal distance is represented by y , and d is the vertical distance from the center of the TX coil to the center of the RX coil. The point P_1 on the TX coil is (x_{TX}, y_{TX}, z_{TX}) , and the point P_2 on the RX coil is (x_{RX}, y_{RX}, z_{RX}) . The dl_{TX} and dl_{RX} are counter-clockwise directional differential length change vectors for the TX and RX coils, respectively. R is the distance between P_1 and P_2 as follows:

$$R = \sqrt{(x_{TX} - x_{RX})^2 + (y_{TX} - y_{RX})^2 + (z_{TX} - z_{RX})^2}. \quad (7)$$

The parametric equations of the TX coil and the RX coil are described using ϕ and φ ($0 \leq \phi, \varphi \leq 2\pi$), respectively. When two coils have no angular misalignment, the parametric equations of the two coils can be represented as follows:

$$(x_{TX}, y_{TX}, z_{TX}) = (r_1 \cos \phi, r_1 \sin \phi, 0). \quad (8)$$

$$(x_{RX}, y_{RX}, z_{RX}) = (r_2 \cos \varphi, r_2 \sin \varphi, d). \quad (9)$$

In Fig. 2, two coils are non-coaxial if $y \neq 0$. The normal direction of the RX coil plane is z' , and the normal direction of the TX coil plane is z . The angle θ represents the tilt angle between the two coils, and it is defined as the angle between the normal vector of plane z and the normal vector of plane z' . On the basis of the TX coil plane, we build a Cartesian coordinate system xyz . According to the xyz coordinate system, the $x'y'z'$ coordinate system can be established by drawing x' parallel to x in the RX coil plane and drawing y' perpendicular to $x'z'$. The rotation matrix, which performs the rotation relationship between xyz and $x'y'z'$, can be represented as follows:

$$T = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & -\sin \theta \\ 0 & \sin \theta & \cos \theta \end{bmatrix}. \quad (10)$$

Therefore, the P_2 of the RX coil considering the tilt angle can be represented using Eqs. (9) and (10) as follows:

$$\begin{bmatrix} x_{RX} \\ y_{RX} \\ z_{RX} \end{bmatrix} = T \begin{bmatrix} r_2 \cos \varphi \\ r_2 \sin \varphi \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ y \\ d \end{bmatrix} = \begin{bmatrix} r_2 \cos \varphi \\ r_2 \cos \theta \sin \varphi + y \\ r_2 \sin \theta \sin \varphi + d \end{bmatrix}. \quad (11)$$

The dl_{TX} and dl_{RX} for P_1 in Eq. (8) and P_2 in Eq. (11), respectively, are as follows:

$$dl_{TX} = (-\sin \phi \mathbf{x} + \cos \phi \mathbf{y}) r_1 d\phi \quad (12)$$

And

$$dl_{RX} = (-\sin \varphi \mathbf{x} + \cos \theta \cos \varphi \mathbf{y} + \sin \theta \cos \varphi \mathbf{z}) r_2 d\varphi, \quad (13)$$

where x, y, z are the base vectors in the xyz coordinate. Substituting Eqs. (7), (8), (11), (12), and (13) into Eq. (6), the coupling coefficient between the TX coil and the RX coil can be calculated. If the centers and the radii of the two coils are given, then the coupling coefficient is a function of the tilt angle as follows:

$$k(\theta) = \alpha_1 \cdot \oint_{l_{TX}} \oint_{l_{RX}} \frac{\alpha_2 + \alpha_3 \cos \theta}{\sqrt{(\alpha_4 + \alpha_5 \cos \theta + \alpha_6 \sin \theta)}} d\phi d\varphi \quad (14)$$

where $\alpha_1 = \frac{N_{TX} N_{RX} \mu_0}{4\pi \sqrt{L_{TX} L_{RX}}}$, $\alpha_2 = r_1 r_2 \sin \phi \sin \varphi$, $\alpha_3 = r_1 r_2 \cos \phi \cos \varphi$, $\alpha_4 = r_1^2 + r_2^2 + y^2 + d^2 - 2r_1 y \sin \phi - 2\alpha_3$, $\alpha_5 = 2r_2 \sin \varphi y - 2\alpha_2$, and $\alpha_6 = 2r_2 d \sin \varphi$.

In Eqs. (3) and (4), we show that η increases when k increases. To achieve an optimal tilt angle θ_{opt} , which gives the maximum PTE for the given center positions and radii of the two coils, we set θ_{opt} as a value that satisfies $\partial k(\theta) / \partial \theta = 0$ and $\partial^2 k(\theta) / \partial \theta^2 < 0$.

III. SIMULATED AND EXPERIMENTAL RESULTS

To verify the above analysis and to determine the maximum transmission efficiency, we implement a WPT system. The parameters of the implemented WPT system are listed in Table 1.

We execute simulations and experiments for various cases. Three different receivers are considered; cases I, II, and III have different radii of the RX coils. The results show that the inductances and resistances of these three cases differ. Different capacitors are used to ensure that the LC resonance for each case occurs at the same resonant frequency as described in Table 1.

For the given vertical distance d , we simulate the PTE using Eqs. (3) and (14) by changing the horizontal distance (y) and the tilt angle of the RX coil (θ). Fig. 3 shows the numerical extracted coupling coefficients for cases I, II, and III when $O_2(0, 0.05, 0.15)$, respectively. Fig. 3 clearly shows that the coupling coefficient is related to the tilt angle of the RX coil.

To examine the effect of the tilt angle on the coupling coefficient for the coaxially parallel circular TX and RX coils, we extract the coupling coefficients using Eq. (14) versus the radii of the RX coil, r_2 . In this simulation, we change the tilt angle of the RX coil in the range of -90° to 90° and change r_2 from 0 to 0.15 m. The simulated results are shown in Fig. 4.

The results show that the optimal tilt angle is not always zero and depends on the radius of the RX coil. The simulation results indicate that the angle between the TX and the RX for the

Table 1. Parameters of the WPT system

Parameter	Sym- bol	Value
Resonant frequency	f	100 kHz
Transmitter coil inductance/radius	L_1 / r_1	217.5 $\mu\text{H} /$ 0.15 m
Transmitter coil resistance	R_{P1}	4.5 Ω
Transmitter capacitance	C_1	11.65 nF
Load resistance	R_L	20 Ω
Source impedance	R_S	50 Ω
Number of turns	$N_{TX},$ N_{RX}	18,18
Receiver coil inductance/radius	L_2 / r_2	
Case I		80.3 $\mu\text{H} /$ 0.075 m
Case II		120.64 $\mu\text{H} /$ 0.1 m
Case III		217.5 $\mu\text{H} /$ 0.15 m
Receiver capacitance	C_2	
Case I		31.54 nF
Case II		20.45 nF
Case III		11.65 nF
Receiver coil parasitic resistance	R_{P2}	
Case I		2.1 Ω
Case II		3.2 Ω
Case III		4.5 Ω

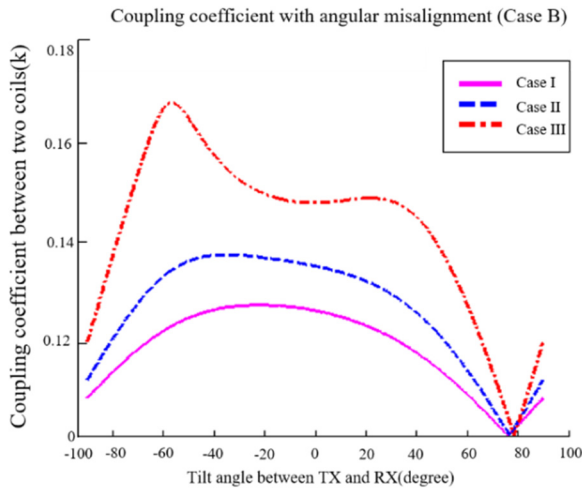


Fig. 3. Coupling coefficient with angular misalignment.

maximum efficiency is 0° when the radius of the RX coil is less than 0.1 m for the case with $d = 0.15$ m. When the radius is larger than 0.1 m for this case, the angle for the maximum efficiency is non-zero. We plot the change of the optimal tilt angle for the various radii of the RX coil for the coaxially located TX and RX coils in Fig. 5.

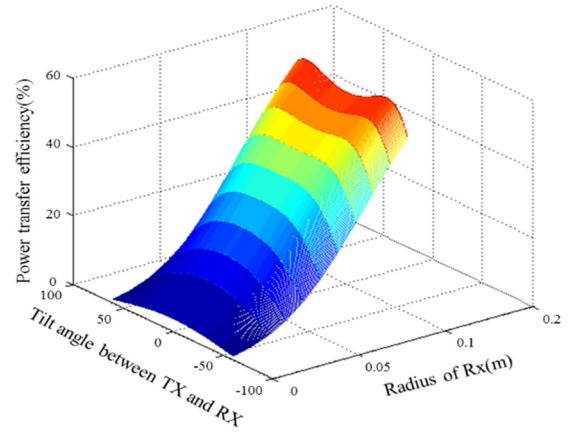


Fig. 4. Simulated coupling coefficient with various tilt angles and radii of RX.

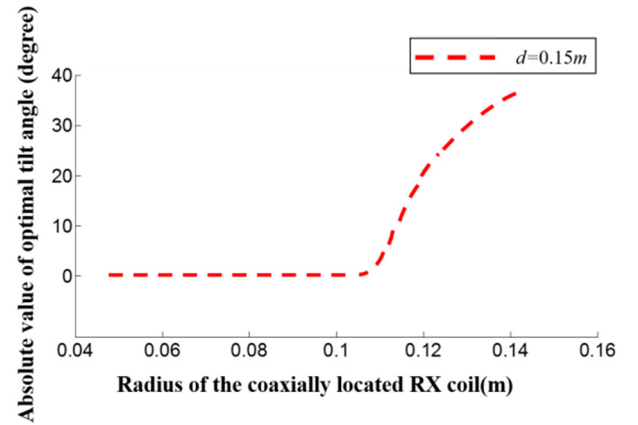


Fig. 5. Extracted optimal tilt angle versus radii of the coaxially located RX coil.

In addition, we analyze the PTE for various cases with the horizontal offset between the TX and RX coils. We extract the PTE by rotating the RX coil in the range of -90° to 90° and by changing the horizontal distance, y , from 0 to 0.15 m along the y -axis positive direction. The simulated results are shown in Figs. 6(a), 7(a), and 8(a) for cases I, II, and III, respectively. The results show that the PTE strongly depends on the tilt angle of the RX coil. The condition for the maximum PTE and its value for each case are summarized in Table 2.

The simulated maximum PTE is denoted by η_{\max} , which is obtained by utilizing the optimal values of the angle between the two coils and the horizontal distance. When the radius of the RX coil is small ($r_2 = 0.075$ m), such as in case I, the RX coil, which is coaxially aligned with the TX coil with no tilt angle, gives the maximum PTE. However, as the radius of the RX increases ($r_2 = 0.1$ m, $r_2 = 0.15$ m) in cases II and III, the maximum PTE is achieved by using the non-coaxially located RX coil with the non-zero tilt angle.

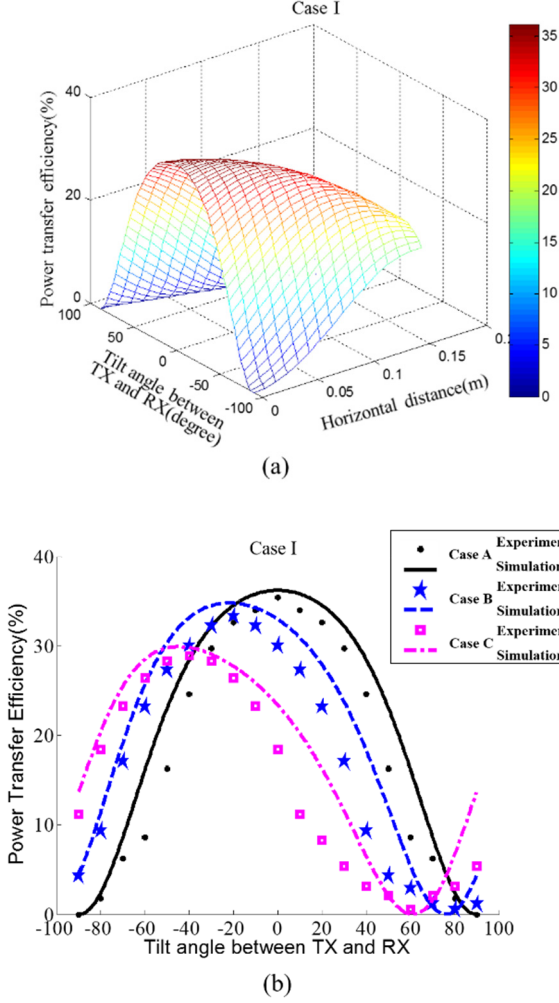


Fig. 6. (a) Simulated transmission efficiency for case I with various tilt angles and horizontal distances. (b) Transmission efficiency with various tilt angles and some special horizontal distance in Fig. 6(a) and the experimental results.

To verify the simulated results, we measure the PTE for the WPT system listed in Table 1 by changing the tilt angle for the three different horizontal offset positions (case A, $y=0$ m; case B, $y=0.05$ m; and case C, $y=0.1$ m). The measured PTE is acquired using the following equation:

$$\eta_p = \frac{P_{RX}}{P_{TX}} = \frac{V_L I_L \cos \gamma_L}{V_{TX} I_{TX} \cos \gamma_{TX}}, \quad (15)$$

where η_p is the ratio of the real power dissipated in the load, P_{RX} , to the power provided by the source driving the TX coil, P_{TX} . V_{TX} , I_{TX} , V_L , and I_L are the voltage and current amplitudes of the source and the load; and γ_{TX} and γ_L are the phase difference between the voltage and the current signals in the source and the load. The measured results are plotted in Figs. 6(b), 7(b), and 8(b) for cases I, II, and III, respectively. Fig. 6(b) shows the simulated transmission efficiency with various tilt angles and a number of special horizontal distances from Fig.

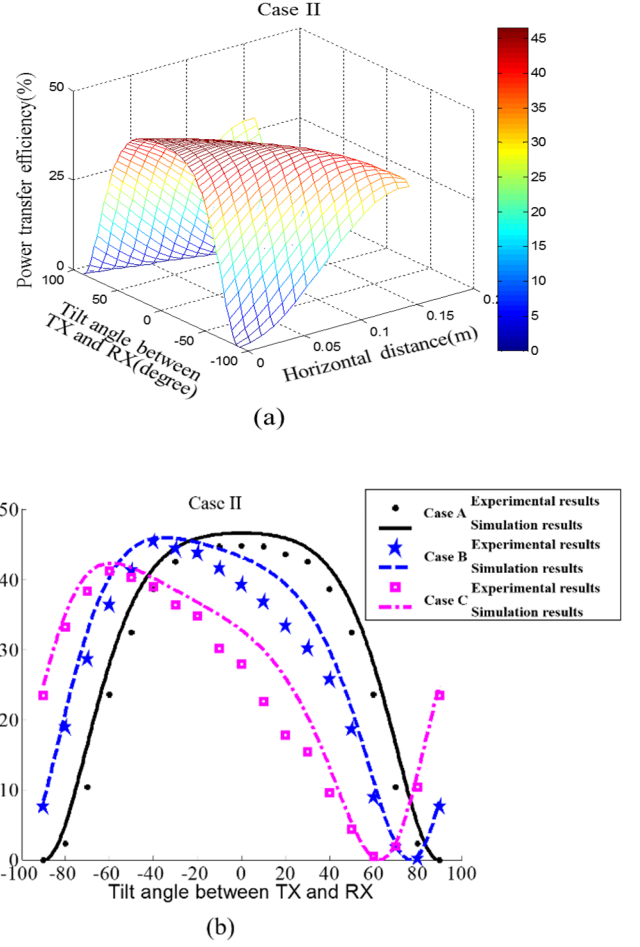


Fig. 7. (a) Simulated transmission efficiency for case II with various tilt angles and horizontal distances. (b) Transmission efficiency with various tilt angles and a special horizontal distance from Fig. 7(a) and the experimental results.

6(a). The experimental results are presented in Fig. 6(b). Fig. 7 shows the simulated and experimental results when the radius of RX is 0.1 m. In Fig. 7(b), when the position of the RX coil is 0.05 m in the positive y -axis and the angle between the RX coil and the TX coil is -34.7667° , the maximum transmission efficiency is obtained. The simulation and experimental results are given in Fig. 8, where the radius of RX is the same as that of TX. In Fig. 8(b), the bifurcation phenomenon occurs when the RX coil is 0.1 m or 0.15 m in the positive y -axis. In this study, the bifurcation phenomenon is not considered. Fig. 8(b) shows that when the radii of the two coils are equal, a special angle and a special horizontal distance are given to ensure the maximum transmission efficiency. In this experiment, the maximum transmission efficiency is reached when the angle between TX and RX is about -56.4247° and the RX coil is located at 0.05 m in the positive y -axis.

The measured results are compared with those of the simulated ones. As the horizontal offset increases, the tilt angle of the RX coil for the maximum PTE also increases. The simula-

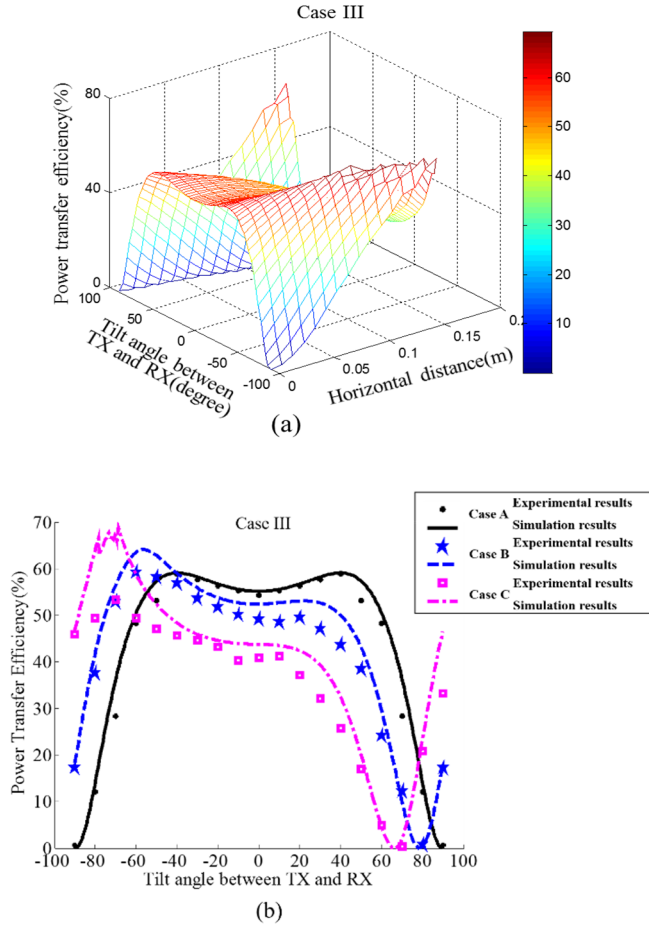


Fig. 8. (a) Simulated transmission efficiency for case III with various tilt angles and horizontal distances. (b) Transmission efficiency with various tilt angles and some special horizontal distance in Fig. 8(a) and the experimental results.

Table 2. Position of the coil and tilt angle for the maximum PTE

	r_2 (m)	O_2 for η_{\max}	Optimum θ ($^\circ$)	η_{\max} (%)
Case I	0.075	$O_2(0,0,0.15)$	0	36.2213
Case II	0.1	$O_2(0,0.05,0.15)$	-34.7669	45.9719
Case III	0.15	$O_2(0,0.05,0.15)$	-56.4247	64.1415

Table 3. Simulated and measured values of PTE for each case

	Case A ($y=0$ m)				Case B ($y=0.05$ m)				Case C ($y=0.1$ m)			
	Simulation		Experiment		Simulation		Experiment		Simulation		Experiment	
	θ	η_{\max}	θ	η_{\max}	θ	η_{\max}	θ	η_{\max}	θ	η_{\max}	θ	η_{\max}
Case I	-0.05	33.5	0	35.4	-21.8	32.2	-20	33.4	-44.7	27.6	-40	28.9
Case II	-0.04	46.6	0	44.8	-35.0	46.0	-40	45.4	-59.1	42.3	-60	41.2
Case III	± 40.2	59.1	40	58.9	-56.2	64.1	-60	59.2	-69.4	66.6	-70	53.3

Table 4. Comparison of accuracy between the simulated results and the experimental results

	Case A ($y=0$ m)	Case B ($y=0.05$ m)	Case C ($y=0.1$ m)
Case I	3.8505	3.9162	4.1944
Case II	3.3371	3.3221	3.5365
Case III	3.1352	3.7635	6.7635

ted PTEs agree well with the measured results as shown in Figs. 6(b), 7(b), and 8(b). The results show that the predicted maximum tilt angle for each case is accurate. The simulated and measured values of PTE for each case are presented in Table 3. Table 4 shows the accuracy between the simulated results and the experimental results using root mean square errors for the WPT system with one TX and one RX. As shown in Table 4, the experimental results agree with the measured ones.

IV. CONCLUSION

We analyze the effect of the tilt angle of the coil on the PTE of the WPT system. Based on our analysis results, the PTE of a WPT with two circular coils can be optimized by changing the tilt angle, relative position, and radii of coils. To archive the optimized PTE, we propose a method to calculate the mutual inductance between the two coils with the tilt angle located at an arbitrary position in a 3D coordinate through the Neumann equation. Using the extracted mutual inductance and the equivalent circuit model of the WPT system, the coupling coefficient and the PTE depending on the tilt angle are extracted. We propose an analytical scheme to extract the optimal tilt angle that maximizes efficiency. To demonstrate our proposed theoretical method, we design experiments using a WPT with two circular coils. By changing the position, radius, and the tilt angle of the RX coils, we compare the transmission efficiency of the different cases. The suggested analysis effectively predicts the optimum tilt angle of the RX coil and the PTE for the various cases.

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