Design and Optimization of Structure of Tower-Type Coil in Wireless Charging System for Electric Vehicles

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Abstract—Magnetic resonant wireless power transfer (WPT) is an emerging technology that may create new applications for wireless power charging. However, the output voltage and efficiency fluctuations resulting from lateral misalignments are main obstructing factors for promoting this technology. In this paper, a structure of tower-type coils is proposed. The mathematical model of the proposed structure is built based on equivalent circuit method. The expressions of the output voltage and efficiency are then derived by solving the system equivalent equations. In addition, a method of optimizing the mutual inductance between the transmission coil and intermediate coil and the strong-coupling parameters between the intermediate coil and receiving coil is proposed. The mutual inductance between the transmission coil and intermediate coil can be kept nearly constant with lateral misalignments, and the optimum strong-coupling parameter between the intermediate coil and the receiving coil can be obtained by the proposed method. Therefore, the output voltage and efficiency can be kept nearly constant with different lateral misalignments. The WPT system based on tower-type coils via magnetic resonance coupling is designed. Simulated and experimental results validating the proposed method are given.

1. INTRODUCTION

Electric vehicles (EVs) are receiving increasing attention in the international research community due to tougher regulations triggered by environment and energy security concerns. There are two charging modes for electric vehicles, including wired charging mode and wireless charging mode [1–4]. Compared to the wired charging mode of EVs, the convenience of wireless charging using magnetic resonance can make EVs more acceptable to drivers because they do not need to handle power plug. At the same time, EVs system using wireless charging mode can be safer [5–7].

Two conditions should be satisfied in a magnetic resonant wireless charging system to maintain the stability of a system [8]. First, the system efficiency is high [9]. Secondly, the output voltage or output current of the system is nearly constant. However, in practice, inevitable lateral and vertical misalignments between the transmission coil and receiving coil lead to variations of the mutual inductance between the transmission coil and receiving coil [10]. The efficiency is decreased, and the output voltage or output current may be changed as the mutual inductance between the transmission coil and receiving coil is changed [11]. The system efficiency was improved by adjusting equivalent load resistance with lateral and vertical misalignments [12]. The constant output voltage was also obtained by adjusting equivalent load resistance. However, the equivalent load resistance at maximum efficiency is not the same as that at constant output voltage for a given mutual inductance [13, 14]. In order to achieve simultaneously high efficiency and constant output voltage for a wireless charging system, a maximum efficiency point tracking control scheme was proposed to maximize system efficiency [15].
When the mutual inductance between the transmission coil and receiving coil is changed, the minimum DC input current can be tracked by real-time changing the duty cycle of the DC-DC converter (The minimum input current is an equivalent condition of the maximum efficiency when the input voltage and output voltage are kept constant). The output voltage is kept constant by changing the duty cycle of another DC-DC converter. However, two DC-DC converters are added to the wireless charging systems, and the system efficiency is decreased inevitably because two DC-DC converters have power losses. At the same time, it is difficult to track input current because the waveform of the input current is not standard.

There are other methods using new coil structures to deal with the adverse effect of misalignments on the efficiency and output voltage: 1) A narrow-width I-type power supply rail and pickups were proposed [16]. The experimental results showed that the output power was reduced and reached nearly 1 kW at the cross-point of the poles as the pickup moved away from the center of the pole along X-direction, and the output power exceeded 20 kW as the pickup laterally moved in Y-direction within 20 cm and became half at 24 cm from the center of the power supply rail. The system efficiency was 74%; 2) A large lateral displacement of 30 cm at an air gap of 20 cm was experimentally obtained by using ultraslim S-type power supply rails [17]. The load power reached the −3 dB point having half of its maximum load power with the lateral tolerance of 30 cm; 3) A new homogeneous WPT technique was proposed and implemented to maintain the output voltage constant for lateral and vertical misalignments systems [18, 19]. The homogeneous magnetic field should be paid with reduction of the quality factor of the transmitter because the transmitter is composed of many small coils (58 mm × 58 mm × 22.5 mm) [19]. The system efficiency is reduced when the quality factor of the transmitter is decreased [18]; 4) Reference [20] proposed an extremely asymmetric coil structure, including a big power supply coil set (110 cm × 80 cm) and a small pick-up coil set. When the pick-up coil laterally deviated from the center of the power supply coil by 39 cm, the output voltage was reduced by about 29% from the maximum output voltage 150 V. In conclusion, it is necessary to further reduce output voltage pulsations and improve the efficiency for electric vehicles. In this paper, the structure of tower-type coils is proposed to reduce output voltage pulsations and improve the efficiency.

The remainder of the paper is outlined as follows. Section 2 gives the method of parameters calculated. Section 3 describes the two-coil WPT system. Section 4 proposes the structure of tower-type coils and builds the model of the proposed structure. Section 5 proposes a method of optimization parameters. Section 6 presents the experimental setup and the measurement results with lateral misalignments between the transmission coil and receiving coil. Section 7 draws the conclusion.

2. PARAMETERS CALCULATED

2.1. Calculated Mutual Inductance and Self-Inductance

Figure 1 shows two loops with lateral misalignments between loop 1 and loop 2. D is the transmission distance, a the radius of loop 1, b the radius of loop 2, and Δ the lateral misalignments between loop 1 and loop 2.

The mutual inductance and self-inductance of two loops whose axes are parallel can be expressed by the single integral [21–23]

\[ M_u(a, b, \Delta, D) = \pi \mu_0 \sqrt{ab} \int_0^{\infty} J_1 \left( x \sqrt{a/b} \right) J_1 \left( x \sqrt{a/b} \right) \times J_0 \left( \frac{x \Delta}{\sqrt{ab}} \right) \exp \left( -x \frac{D}{\sqrt{ab}} \right) dx \]  

\[ L(a, r) = \mu_0 a \left( \ln \left( \frac{8a}{r} \right) - 2 \right) \]

where \( J_0 \) and \( J_1 \) are the Bessel functions of zeroth-order and first-order, respectively. \( r \) is the radius of the copper. \( \mu_0 \) is the magnetic conductivity.

For a coil composed of multi-turn, the mutual inductance between the transmission coil and receiving coil can be calculated using

\[ M_{ab} = \sum_{i=1}^{N_A} \sum_{j=1}^{N_B} M_u(a_i, b_j, D, \Delta) \]
where $N_A$ and $a_i$ are the number of turns of the transmission coil and the radius of the transmission coil, respectively. $N_B$ and $b_j$ are the number of turns of the receiving coil and the radius of the receiving coil, respectively.

A multi-turn planar spiral coil can be approximately equivalent to the sum of a plurality of coaxial single-turn coils. Self-inductance of each coil can be calculated by Eq. (4).

$$L_a = \sum_{i=1}^{N_A} L(a_i, r) + \sum_{i=1}^{N_A} \sum_{j=1}^{N_A} M u(a_i, a_j, D = 0, \Delta = 0) \left(1 - \delta_{i,j}\right)$$

where $\delta_{i,j} = 1$ with $i = j$ or $\delta_{i,j} = 0$ with $i \neq j$.

The coupling coefficient between each coil is defined as follows:

$$k_{ab} = \frac{M_{ab}}{\sqrt{L_a L_b}}, \quad 0 \leq k_{ab} \leq 1$$

As shown in Eqs. (1) and (3), it can be seen that mutual inductance is dependent on $a, b, D$, and $\Delta$. When $a, b, and D$ are fixed, mutual inductance is only related to $\Delta$. The bigger the value of $\Delta$ is, the smaller the mutual inductance becomes, and the coupling coefficient $k_{ab}$ is decreased according to Eq. (5).

### 2.2. Calculated Resistance

The resistance of each coil is calculated as follows [24]:

$$R = R_{dc, strand} + R_{ac, strand} / n_s - R_{dc, strand} \frac{\beta \gamma_s \text{ber}^2(\gamma_s) \text{ber}'(\gamma_s) + \text{bei}^2(\gamma_s) \text{bei}'(\gamma_s)}{2 \text{ber}^2(\gamma_s) + \text{bei}^2(\gamma_s)}$$

$$+ \sum_{i=1}^{N} n_s S_{avg, strand} h_{ext, i}^2$$

where

$$R_{ac, strand} = R_{dc, strand} \frac{\gamma_s \text{ber}(\gamma_s) \text{bei}'(\gamma_s) - \text{bei}(\gamma_s) \text{ber}'(\gamma_s)}{2 \text{ber}^2(\gamma_s) + \text{bei}^2(\gamma_s)}$$

$$G_{strand} = -2\pi \frac{\gamma_s \text{ber}^2(\gamma_s) \text{ber}'(\gamma_s) + \text{bei}^2(\gamma_s) \text{bei}'(\gamma_s)}{\text{ber}^2(\gamma_s) + \text{bei}^2(\gamma_s)}$$
$h_{\text{ext,i}}$ is the magnetic field generated over the $i$th-turn of the coil when an RMS current of 1 A is in it. \( \gamma_s = 1.414 r_s / \delta \), \( \delta \) is the skin depth, \( r_s \) the Litz-wire strand radius, and \( R_{\text{dc, strand}} \) the DC resistance of the strand. \( \text{ber}, \text{bei}, \text{ber}', \text{bei}' \) are the Kelvin functions, and \( \text{ber}_2, \text{bei}_2 \) are the second order of Kelvin functions. \( S_{\text{av}} \) is the average length of the coil. \( n_s \) is the number of strands of the Litz-wire.

3. PROPOSED STRUCTURE

3.1. Structure of Tower-Type Coils

In this section, a structure of tower-type coils is proposed to deal with the effect of lateral misalignments on mutual inductance. The proposed structure contains three coils, which are transmission coil, intermediate coil, and receiving coil, labeled as Tx, Im, and Rx, as shown in Fig. 2(a). Im and Rx can be placed on the same plane, or Rx can be placed on the plane staying away from Tx. \( D \) is the transmission distance between the Tx and Im. \( k_{ij} \) is the coupling coefficient between \( i \)-th coil and \( j \)-th coil \((i \neq j; \ i, j = 1, 2, 3)\). Subscript 1 denotes Tx; subscript 2 denotes Im; subscript 3 denotes Rx. The transmission coil is bigger than the intermediate coil in size, and the intermediate coil is bigger than the receiving coil. \( k_{13} \) is smaller than \( k_{12} \) because the intermediate coil is bigger than the receiving coil. Therefore, \( k_{13} \) may be neglected in the next analysis.

Figure 2. The proposed structure. (a) Structure of tower-type coils. (b) Structure of tower-type coils with misalignment.

Figure 2(b) shows the proposed structure with misalignments. \( \Delta \) is the lateral misalignments between Tx and Im. In general, the variations of \( \Delta \) may result in the changes of mutual inductance or the coupling coefficient. However, the variations of the mutual inductances between the Tx and Im are very smooth with misalignments when the proposed structure is used. The system can maintain high efficiency and constant output voltage because mutual inductances between the Tx and Im are nearly constant with misalignments. In Section 3, how to maintain the mutual inductance constant will be further discussed. The overall structure of the proposed structure is shown in Fig. 3. It is composed of a power, Tx, Im, Rx, and Load. \( C_i \) is the resonance capacitor \((i = 1, 2, 3)\). The main flow of power is as follows: First, the power source via the compensation capacitor \( C_1 \) is connected in series to the transmission coil Tx. Secondly, the power is transferred from Tx to Im using magnetic fields. And the power is transferred from Im to Rx. Finally, the power is transferred from Rx to the Load.

The proposed WPT system can be represented in terms of lumped circuit elements \((L, C, M, \text{and} \ R)\), as shown in Fig. 4. \( R_1 \) is the parasitic resistance of Tx, \( R_2 \) the parasitic resistance of Im, \( R_3 \) the parasitic resistance of Rx, \( R_s \) the internal resistance of the power source, \( R_L \) the load resistance, \( L_1 \) the inductance of Tx, \( L_2 \) the inductance of Im, \( L_3 \) the inductance of Rx, \( C_1 \) the external compensating
capacitance of Tx, $C_2$ the external compensating capacitance of Im, $C_3$ the external compensating capacitance of Rx, $M_{12}$ the mutual inductance between Tx and Im, $M_{13}$ the mutual inductance between Tx and Rx, $M_{23}$ the mutual inductance between Im and Rx, $V_s$ the voltage of the power, and $V_{out}$ the voltage of the load.

3.2. Mathematical Model of Proposed Structure

By applying Kirchhoff’s voltage law (KVL), the proposed WPT system is presented as follows:

\[
\begin{align*}
Z_1 I_1 + j\omega M_{12} I_2 + j\omega M_{13} I_3 &= V_s \\
-j\omega M_{12} I_1 + Z_2 I_2 + j\omega M_{23} I_3 &= 0 \\
-j\omega M_{13} I_1 + j\omega M_{23} I_2 + Z_3 I_3 &= 0
\end{align*}
\]  
\tag{7}

\[
\begin{align*}
Z_1 &= R_1 + R_s + j\omega L_1 + 1/(j\omega C_1) \\
Z_2 &= R_2 + j\omega L_2 + 1/(j\omega C_2) \\
Z_3 &= R_3 + R_L + j\omega L_3 + 1/(j\omega C_3)
\end{align*}
\]  
\tag{8}
The current expressions of each coil can be obtained by solving Eqs. (7) and (8)

\[
\begin{align*}
I_1 &= \frac{M_{13}^2 \omega^2 V_s + Z_2 Z_3 V_s}{\omega^2 M_{13}^2 Z_3 + \omega^2 M_{13} Z_2 + \omega^2 M_{13} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}} \\
I_2 &= -\frac{\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}}{\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}} \\
I_3 &= -\frac{\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}}{\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}} \\
\end{align*}
\]

where \( I_1 \) is the current of Tx, \( I_2 \) the current of Im, and \( I_3 \) the current of Rx.

According to Eq. (9), the output voltage \( V_L \) is as follows:

\[
V_L = I_3 R_L = -\frac{j \omega M_{13} Z_3 V_s + j \omega M_{13} Z_2 V_s}{\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13}} R_L 
\]

According to Eqs. (7)–(10), the efficiency and output voltage are dependent on \( \eta \) and \( V_L \).

\[
\eta = \frac{\left( \frac{I_3^2 R_L}{V_s I_1} \right)}{\left( \frac{I_3^2 R_L}{V_s I_1} \right)} = \frac{(\omega^2 M_{12}^2 M_{23} + j \omega M_{13} Z_2)^2 R_L}{(\omega^2 M_{12}^2 Z_3 + \omega^2 M_{12} Z_2 + \omega^2 M_{23} Z_1 + \omega M_{12} M_{23} M_{13} - 2 j \omega^3 M_{12} M_{23} M_{13})} 
\]

When the \( M_{12} \) is changed, according to Eq. (10) the output voltage can be obtained, and the transmission efficiency can be obtained according to Eq. (11).

Assuming the frequency of each coil is the same, the efficiency expression (11) and output voltage expression (10) can be simplified as follows:

\[
\eta = \frac{(U_1 U_2 + j U_3)^2 U_L}{(U_2^2 + U_L + 1)(U_1^2 + 1 + U_L) + U_2^2 (1 + U_L) + U_3^2 (1 + U_L) + (1 + U_3)(1 + U_L) - 2 j U_1 U_2 U_3} 
\]

\[
V_L = \frac{(U_1 U_2 + j U_3) V_s U_L}{(U_2^2 + U_L + 1)(U_1^2 + 1 + U_L) + U_2^2 (1 + U_L) + U_3^2 (1 + U_L) + (1 + U_3)(1 + U_L) - 2 j U_1 U_2 U_3} \sqrt{R_3/R_1} 
\]

where the source matching factor is defined as \( U_s = R_s/R_1 \), the load matching factor defined as \( U_L = R_L/R_3 \), the strong-coupling parameter between Tx and Im defined as \( U_1 = k_{12} Q_1 Q_2 \), the strong-coupling parameter between Im and Rx defined as \( U_2 = k_{23} Q_2 Q_3 \), the strong-coupling parameter between Tx and Rx defined as \( U_3 = k_{13} Q_1 Q_3 \), the unload quality factor of the Tx coil defined as \( Q_1 = \omega L_1/R_1 \), and the unload quality factor of the Rx coil defined as \( Q_2 = \omega L_2/R_2 \), and the unload quality factor of the Rx coil defined as \( Q_3 = \omega L_3/R_3 \).

When the coupling coefficient \( k_{13} \) is neglected, the efficiency expression (12) and output expression (13) can be simplified as follows:

\[
\eta = \frac{(U_1 U_2)^2 U_L}{(U_2^2 + U_L + 1)(U_1^2 + 1 + U_L) + U_2^2 (1 + U_L) + (1 + U_3)(1 + U_L)} 
\]

\[
V_L = \frac{U_1 U_2 U_3 V_s}{(U_2^2 + U_L + 1)(U_1^2 + 1 + U_L) + U_2^2 (1 + U_L) + (1 + U_3)(1 + U_L)} \sqrt{R_3/R_1} 
\]

According to Eqs. (14) and (15), the efficiency and output voltage are dependent on \( U_1, U_2, U_3, \) and \( U_L \). In general, \( U_s, U_L, \) and \( U_L \) are nearly constant for a given load resistance and parameters of Tx, Im, and Rx coil; therefore, \( U_1 \) and \( U_2 \) are key parameters to obtain high efficiency and maintain output voltage constant.

By differentiating \( \eta \) with respect to \( U_2 \) and equating the differential function to zero

\[
\frac{\partial \eta}{\partial U_2} = 0 
\]

The optimum strong-coupling parameter between Im and Rx for the optimum efficiency can be obtained as follows:

\[
U_{2,\text{opt}} = \left( \frac{2 U_L + U_s + 2 U_L U + 2 U_1^2 U_L + U_2^2 U_s + U_2^2 + U_2^2 U_2^2 + 1}{U_s + 1} \right)^{1/4} 
\]

For a given \( U_1, U_L, \) and \( U_s, \) the value of \( U_{2,\text{opt}} \) can be obtained according to Eq. (17).
4. METHOD OF PARAMETER OPTIMIZATION

In this section, a method of optimizing $M_{12}$ and $U_2$ is proposed in order to obtain high efficiency and maintain output voltage constant. The process of the method of optimizing $M_{12}$ ($U_1$) and $U_2$ is shown in Fig. 5.

**Figure 5.** The process of the method of optimizing $M_{12}$ and $U_2$.

Step 1. Optimizing $M_{12}$: $M_{12}$ may be constant in the proposed structure to optimize the outer diameters and the numbers of turns of Tx and Im with misalignments. According to the optimum $M_{12}$, parameters of Tx and Im (diameters of Tx and Im, the numbers of turns of Tx and Im) can be obtained.

Step 2. Optimizing $U_2$: $U_1$, $U_L$, and $U_s$ can be obtained according to the optimum $M_{12}$, optimum parameters of Tx and Im (diameters, turns), and the load resistance. The value of $U_{2\text{opt}}$ can be obtained according to Eq. (17). The outer diameter of Rx and the number of turns of Rx are optimized in order to obtain $U_{2\text{opt}}$.

4.1. Optimizing $M_{12}$

It can be seen from Eq. (15) that the output voltage $V_L$ is dependent on $U_1$, $U_2$, $U_L$, $U_s$, and $(R_3/R_1)^{1/2}$. In general, $U_1$, $U_2$, $U_L$, $U_s$, and $(R_3/R_1)^{1/2}$ are nearly constant when the parameters $(R, L, C)$ of each coil and the load are given. However, the mutual inductance $M_{12}$ may be changed with the variations of lateral misalignments (The variations of $M_{12}$ result in the changes of $U_1$ and $U_2$, respectively). Lateral misalignments between Im and Rx may not occur, and $M_{23}$ may be kept constant when both Im and Rx are fixed at the same plane by using the proposed structure. Lateral misalignments between Tx and Im or Rx may occur. Therefore, how to maintain the mutual inductance $M_{12}$ (or $U_1$) constant is a problem. In this section, the method of the mutual inductance optimization is proposed. The mutual inductance $M_{12}$ (or $U_1$) can be kept nearly constant with lateral misalignments by using the proposed method.

The process of the method of mutual inductance optimization is as follows:

1) Parameters setting: the resonant frequency is set to 85 kHz. The mutual inductance between the transmission coil and intermediate coil should be large enough to obtain high efficiency. The mutual inductance is set to 6.0 $\mu$H. The transmission distance is set to 15 cm. The diameter of copper is set to 2.3 mm. The outer diameter of Tx is changed from 0.25 m to 0.30 m in a step of 2.0 mm. The outer diameter of Im is changed from 0.2 m to 0.25 m in a step of 2.0 mm. The number of turns of Tx is changed from 17 to 40 in a step of 1. The number of turns of Im is changed from 6 to 10 in a step of 1.

2) Calculated mutual inductance: According to Eqs. (1) and (2), the mutual inductance between Tx and Im can be obtained with different lateral misalignments. $M_{1210}$ is the mutual inductance between Tx and Im when lateral misalignment equals 10 cm; $M_{120}$ is the mutual inductance between Tx and Im when lateral misalignment equals 0 cm.
Figure 6. The flowchart of the method of the mutual inductance optimization.

3) Compared to $\varepsilon \ (\varepsilon = (M_{120} - M_{1210})/M_{120})$ at a given outer diameter of Tx, outer diameter of Im, the number of turns of Tx, and the number of turns of Im, the optimum $\varepsilon$ is obtained (The smaller $\varepsilon$ is, the smaller the variations of mutual inductance become).
Figure 7. The optimum parameters of each coil. $N_1$ is the number of turns of Tx, $N_2$ is the number of turns of Im, $a_1$ is the out radius of Tx, $a_2$ is the out radius of Im.

Figure 8. The optimum mutual inductance $M_{120}$, $M_{1210}$ and $\varepsilon$.

4) According to the optimum $\varepsilon$, optimum parameters of Tx and Im can be obtained. The detailed optimization process is shown in Fig. 6.

Figure 7 shows optimum parameters of each coil ($N_1$, $N_2$, $a$, $b$). It can be seen that optimum $N_1$ is equal to 17, optimum $N_2$ equal to 10, optimum $a_1$ equal to 0.3 m, and optimum $a_2$ equal to 0.1 m. Fig. 8 shows optimum mutual inductance $M_{120}$, $M_{1210}$, and $\varepsilon$. It is clearly seen that all $\varepsilon$ are smaller than 5%; optimum $\varepsilon$ is 3.1%; all mutual inductances are larger than 6.0 $\mu$H. In the above analysis, it can be seen that the radius of Im should be decreased, and the number of turns of Im should be increased in order to obtain constant mutual inductance.

4.2. Optimizing $U_2$

$U_2$ is also a key parameter to obtain high efficiency, and optimum $U_2$ can be obtained by Eq. (17) with given $U_1$, $U_L$, and $U_s$. Parameters of Rx (the number of turns of Rx $N_3$ and the outer diameter of Rx $a_3$) can be obtained according to optimum $U_2$.

The process of the method of optimizing $U_2$ is as follows: 1) Parameters setting: the resonant frequency is set to 85 kHz. The diameter of copper is set to 2.3 mm. Optimum $N_1$ is set to 17, optimum $N_2$ set to 10, optimum $a_1$ set to 0.3 m, and optimum $a_2$ set to 0.1 m. The outer diameter of Rx is changed from 0.01 m to 0.10 m in a step of 2.0 mm. The number of turns of Rx is changed from 5 to 20.
in a step of 1 turn (The diameter of each turn is 2.3 mm).

2) Calculate strong-coupling parameters $U_2$:
   a) According to Eqs. (1)–(3), the mutual inductance between Im and Rx ($M_{12}$) can be obtained.
   b) The self-inductances of Tx, Im, and Rx can be obtained according to Eqs. (3) and (4).
   c) The coupling coefficients ($k_{12}$ and $k_{13}$) can be obtained according to Eq. (5).
   d) The resistances of Tx, Im, and Rx can be obtained according to Eq. (6).
   e) The unload quality factors of Tx, Im, and Rx can be obtained according to $Q_1 = \omega L_1/R_1$, $Q_2 = \omega L_2/R_2$, and $Q_3 = \omega L_3/R_3$.
   f) $U_2$ can be obtained according to $U_2 = k_{23}(Q_2 Q_3)^{1/2}$.

3) Compare $\varepsilon_1$ with $\varepsilon_1^*(\varepsilon_1 = (U_2^* - U_2)/U_2^*)$ at a given outer diameter of Rx and the number of turns of Rx. The optimum $\varepsilon_1$ can be obtained.

4) According to optimum $\varepsilon_1$, optimum parameters of Rx can be obtained. The detailed optimization process is shown in Fig. 9.

Figure 9. The flowchart of the method of optimization $U_2$. 
Figure 10. Experimental setup. (a) DC voltage source. (b) H-bridge inverter. (c) Tx. (d) Im. (e) Rx and Im. (f) The overall setup.
5. EXPERIMENTAL AND SIMULATION RESULTS

5.1. Experimental Setup

To validate the proposed structure and optimization method, the prototype model of the system has been built, as shown in Fig. 10. It is composed of a DC voltage source, a transmission resonant coil, an intermediate coil, a receiving resonant coil, an H-bridge inverter, and the load. The value of the DC voltage source is 36 V. The DC voltage source is shown in Fig. 10(a). H-bridge inverter is used at the transmitter side to provide AC excitation, as shown in Fig. 10(b). It contains four MOSFETs (IRF3207). The transmission resonant coil is shown in Fig. 10(c). The intermediate resonant coil is shown in Fig. 10(d). The intermediate resonant coil and receiving resonant coil are shown in Fig. 10(e). According to the optimization method, the outer diameter of the transmission resonant coil is 0.6 m with a pitch of 0 cm for approximately 17 turns; the outer diameter of intermediate resonant coil is 0.2 m with a pitch of 0 cm for approximately 10 turns; the outer diameter of receiving resonant coil is 0.09 m with a pitch of 0 cm for approximately 16 turns. All coils are made from 300-strand AWG 38Litz-wire.

Table 1. Measured parameters of the resonant coils.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>the inductance of Tx</td>
<td>333.7 μH</td>
</tr>
<tr>
<td>$L_2$</td>
<td>the inductance of Im</td>
<td>30.5 μH</td>
</tr>
<tr>
<td>$L_3$</td>
<td>the inductance of Rx</td>
<td>10.9 μH</td>
</tr>
<tr>
<td>$C_1$</td>
<td>the compensation capacitance of Tx</td>
<td>10.5 nF</td>
</tr>
<tr>
<td>$C_2$</td>
<td>the compensation capacitance of Im</td>
<td>115.0 nF</td>
</tr>
<tr>
<td>$C_3$</td>
<td>the compensation capacitance of Rx</td>
<td>321.6 nF</td>
</tr>
<tr>
<td>$R_1$</td>
<td>the parasitic resistance of Tx</td>
<td>0.402 Ω</td>
</tr>
<tr>
<td>$R_2$</td>
<td>the parasitic resistance of Im</td>
<td>0.067 Ω</td>
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<tr>
<td>$R_3$</td>
<td>the parasitic resistance of Rx</td>
<td>0.04 Ω</td>
</tr>
<tr>
<td>$f_0$</td>
<td>the original resonant frequency</td>
<td>85.0 kHz</td>
</tr>
</tbody>
</table>

Figure 11. Measured and calculated mutual inductance versus misalignments with the proposed structure and the traditional structure. (a) Measured and calculated mutual inductance with proposed structure. (b) Measured and calculated mutual inductance with traditional structure.
An impedance analyzer is used to extract the parameters in Eqs. (7) and (8). The original resonant frequency is set to 85.0 kHz. The load resistance is set to 3.7 Ω with a tower-type coil WPT system. The transmission distance is 15 cm. Parameters of the resonant coils are listed in Table 1. The moving direction of the receiver is noted as $y$-axis, and the coordinates are marked in Fig. 2(b).

Figure 11(a) shows the measured and calculated mutual inductances between Tx and Im versus misalignments with the proposed structure. It can be seen that the mutual inductance between Tx and Im ($M_{12}$) is changed from 6.89 $\mu$H to 6.63 $\mu$H as the misalignment is varied from 0 cm to 10 cm. The difference between $M_{120}$ and $M_{1210}$ is 0.26 $\mu$H. $\varepsilon$ is equal to 3.77% according to $\varepsilon = (M_{120} - M_{1210})/M_{120}$. The variations of mutual inductance are very smooth as the misalignment is varied from 0 cm to 10 cm. Fig. 11(b) shows the calculated mutual inductance between the transmission coil and receiving coil versus misalignments with the traditional structure (Both the transmission coil and receiving coil are the same as Im in size). It can be seen that the mutual inductance between the transmission coil and receiving coil is changed from 1.13 $\mu$H to 0.63 $\mu$H as the misalignment is varied from 0 cm to 10 cm. $\varepsilon$ is equal to 44.24%. The variations of mutual inductance with the proposed structure are smaller than those of the traditional structure.

5.2. Two-Coil Structure

In the two-coil WPT system, Tx is the transmission coil, and Im is used as receiving coil. The load resistance is set to 10 Ω in order to obtain the optimum efficiency [11], and the value of the DC voltage source is set to 48 V.

Figure 12 shows the measured and calculated output voltages versus misalignments with the two-coil WPT system. It can be seen that the output voltage is changed from 14.40 V to 14.60 V as the misalignment is varied from 0 cm to 10 cm. The output voltage is nearly constant as misalignment is varied from 0 cm to 10 cm. Fig. 13 shows the measured and calculated efficiencies versus misalignments with the two-coil WPT system. It can be seen that the efficiency is changed from 65.6% to 63.5% as the misalignment is varied from 0 cm to 10 cm. The efficiency is also nearly constant as the misalignment is varied from 0 cm to 10 cm.

5.3. Structure of Tower-Type Coils

All parameters of the tower-type coil system are shown in Table 1 and Fig. 11. The strong-coupling parameter between Im and Rx $U_2$ can be obtained according to $U_2 = k_{23}(Q_2 Q_3)^{1/2}$, and the actual $U_2$ is equal to 34.2. Optimum $U_2$ can also be calculated in terms of Eq. (17), and optimum $U_2$ equals 36.9. The value of actual $U_2$ is very close to the value of optimum $U_2$. 

![Figure 12. Measured and calculated output voltage versus misalignments.](image1)

![Figure 13. Measured and calculated efficiency versus misalignments with two-coil WPT system.](image2)
The effect of $M_{13}$ ($U_{13}$) on the output voltage and efficiency is small in this paper according to the following calculated results. In order to analyse the effect of $M_{13}$ ($U_{13}$) on the output voltage and efficiency, the calculated results can be obtained with the help of MATLAB in terms of Eqs. (12)–(16). Fig. 14(a) shows the calculated output voltage with considering $M_{13}$ and without considering $M_{13}$. The output voltage with considering $M_{13}$ is changed from 14.46 V to 15.79 V as the misalignment is varied from 0 cm to 12 cm. The output voltage without considering $M_{13}$ is changed from 15.13 V to 16.24 V as the misalignment is varied from 0 cm to 12 cm. The value of the output voltage with considering $M_{13}$ is nearly the same as that without considering $M_{13}$. Fig. 14(b) shows the calculated efficiency with considering $M_{13}$ and without considering $M_{13}$. The efficiency with considering $M_{13}$ is changed from 87.5% to 86.8% as the misalignment is varied from 0 cm to 12 cm. The efficiency with considering $M_{13}$ is changed from 87.0% to 86.4% as the misalignment is varied from 0 cm to 12 cm. The value of the efficiency with considering $M_{13}$ is also nearly the same as that without considering $M_{13}$.

Figure 14. Calculated output voltage and efficiency versus misalignments. (a) Calculated output voltage versus misalignments. (b) Calculated efficiency versus misalignments.

The misalignment $\Delta$ is set to 0 cm, 2 cm, 4 cm, 6 cm, 8 cm, 10 cm, and 12 cm, respectively. We test the input voltage, input current, the current of $I_m$, and output voltage, respectively. Fig. 15 shows measured and calculated input currents versus misalignments. It can be seen that the input current is changed from 1.76 A to 1.89 A as the misalignment is varied from 0 cm to 12 cm. The input current of ratio of change is only 6.8%. It is convenient to design the transmission coil because the input current of ratio of change is small.

Figure 16 shows measured and calculated currents of $I_m$ versus misalignments. It can be seen that the current of $I_m$ is changed from 8.62 A to 9.02 A as the misalignment is varied from 0 cm to 12 cm. Compared with the value of the input current, the value of the current of $I_m$ is higher. This is beneficial for increasing the magnetic field strength of the $I_m$ coil. Therefore, the efficiency may be improved. And it is helpful for reducing the MOSFET of current stress.

Figure 17 shows the measured and calculated output voltages versus misalignments. It can be seen that the output voltage is changed from 14.07 V to 14.36 V as the misalignment is varied from 0 cm to 12 cm. The output voltage is nearly constant as the misalignment is varied from 0 cm to 12 cm. Fig. 18 shows the measured and calculated efficiencies versus misalignments. It can be seen that the efficiency is changed from 82.9% to 80.4% as the misalignment is varied from 0 cm to 12 cm. The output voltage and efficiency are nearly constant because the mutual inductance between $T_x$ and $I_m$ ($M_{12}$) is nearly constant as the misalignment is varied from 0 cm to 12 cm. Compared to a two-coil structure, the efficiency of the structure of tower-type coils is higher because the magnetic field strength is increased when $I_m$ coil is added into the WPT system. The validity of the proposed method is verified by simulated and experimental results. Performance comparison between other references and our paper is shown in Table 2. Compared with lateral misalignments in references [14, 15, 18], lateral
Figure 15. Measured and calculated input current versus misalignments.

Figure 16. Measured and calculated current of Im versus misalignments.

Figure 17. Measured and calculated output voltage versus misalignments.

Figure 18. Measured and calculated efficiency versus misalignments.

Table 2. Performance comparison.

<table>
<thead>
<tr>
<th>References</th>
<th>Size of Tx (Length × width)</th>
<th>Size of Rx (Length × width)</th>
<th>Lateral misalignments (cm)</th>
<th>Ratio of output power (%)</th>
<th>Ratio of efficiency (%)</th>
<th>Maximum efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[14]</td>
<td>30 cm × 20 cm</td>
<td>100 cm × 80 cm</td>
<td>X-direction: 24</td>
<td>50.0</td>
<td>30.0</td>
<td>74.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y-direction: /</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[15]</td>
<td>20 cm × 10 cm</td>
<td>100 cm × 80 cm</td>
<td>X-direction: 30</td>
<td>50.0</td>
<td>30.1</td>
<td>71.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y-direction: 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[18]</td>
<td>110 cm × 90 cm</td>
<td>70 cm × 20 cm</td>
<td>X-direction: 39</td>
<td>29</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y-direction: 18</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Our work]</td>
<td>Radius: 30 cm</td>
<td>Radius: 4.5 cm</td>
<td>X-direction: 12</td>
<td>2.0</td>
<td>3.0</td>
<td>82.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Y-direction: 12</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

'/' denotes that the value is not given in reference.
misalignment is not the largest in this paper. However, the sizes of Tx and Rx are the smallest; the change rates of efficiency and power are the smallest; the misalignment of X-direction is the same as that of Y-direction; and the output voltage is kept nearly constant without the voltage regulator with misalignments. According to SAE J2954 standard, the misalignment in X direction is 10 cm, and the misalignment in Y direction is 7.5 cm. Therefore, the misalignments in both X and Y directions meet SAE J2954 standard by using the structure of tower-type coils.

6. CONCLUSION

In this paper, a structure of tower-type coils is proposed. The mathematical model of the proposed structure with lateral misalignments is built based on equivalent circuit method. The mutual inductance between the transmission coil and intermediate coil is kept nearly constant as the misalignment is varied from 0 cm to 12 cm, and the optimum strong-coupling parameter $U_2$ is also obtained according to the proposed optimization method. Both the output voltage and efficiency are nearly constant with different lateral misalignments by using the proposed structure and method. Experimental results show that the mutual inductance of the transmission coil and intermediate coil is changed from 6.88 $\mu$H to 6.63 $\mu$H, the output voltage ranged from 14.07 V to 14.36 V, and the efficiency changed from 82.9% to 80.4% as the misalignment is varied from 0 cm to 12 cm in the tower-type coil WPT system. We will further increase the lateral misalignments to meet the needs of the dynamic wireless power transfer system.

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