An Optimized Design of an Electric Vehicle Wireless Charging Coupling Coil

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Abstract: With the development of electric vehicle wireless charging technology, the transmission power and transmission efficiency of electric vehicle wireless charging system have become the focus of current research. The transmission power and efficiency of wireless charging system largely depend on the energy loss of two resonant coupling coils. The energy loss is mainly related to the structural parameters of the coupling coil and the coupling coefficient of the two coils. On this basis, the structure of the coupling coil is designed and optimized by using the finite element analysis software Maxwell, and a new combined transmitting coil structure is designed. Experiments and verification show that the coil design meets the requirements of transmission efficiency, which can provide a reference for the design of wireless charging coil of electric vehicle in the future.

1. Introduction
Environmental pollution is a very important topic in today's world. In order to solve the problem of air pollution, many countries have introduced many measures, especially the development of new energy automobile industry. However, there are many factors restricting the development of new energy vehicle industry, one of which is the charging mode of electric vehicles; Wireless charging technology of electric vehicle is a feasible method. Compared with wired plug-in charging, wireless charging is more secure, less vulnerable to climate, less physical space and convenient charging. Considering many factors, the application of wireless charging technology has become a development trend \cite{1}. In fact, as early as the 19th century, scientist Nicolas Tesla began to study wireless power transfer (WPT). Later, it has been ignored by people for a period of time. After MIT realized meter level transmission of radio energy in the early 20th century, resonant radio power transmission technology has gradually become the focus of people's attention \cite{2}.

With the development of magnetic coupling theory and industrial technology, it is possible for electric vehicles to realize high power and high efficiency wireless charging; In order to achieve high power and high efficiency power transmission, the resonant coupling coil is the core part of the whole electric vehicle wireless charging system \cite{3}; At present, the electromagnetic coupler has been designed as a flat plate, the transmitting plate is directly buried in the ground or kept level with the ground, and the power receiving plate is installed on the vehicle chassis. The basic principle of this new design method is to obtain the maximum coupling coefficient and horizontal offset resistance by using the least magnetic cores. The electromagnetic coupling coil is similar to the separation transformer, and the loss...
of the coil is large during energy transmission. This determines that the transmission distance of electromagnetic coupling coil is very small and the anti offset ability is poor. It can not meet the actual charging needs of electric vehicles. Therefore, it is very important to select an appropriate resonant coupling coil [4].

This paper first introduces the working principle of electric vehicle wireless charging, and analyzes the expression of transmission power and efficiency of the system; Finally, a transmitting coil structure with octagonal periphery and circular interior is designed. The feasibility of the design is verified by experiments.

2. A wireless transmission model of resonance coupled electric energy

2.1 Resonance coupling principle

There are many kinds of contactless radio energy transmission modes based on Faraday electromagnetic induction principle, and resonance wireless charging system is a special case of contactless radio energy transmission, which is also a near-field charging transmission; A typical static wireless charging system structure of electric vehicle is shown in Figure 1 [5]. The electric vehicle wireless charging system mainly includes: power factor compensation, rectifier, high frequency inverter, contactless resonance coupler, rectifier filter. The power frequency municipal power becomes high voltage DC after compensation of rectifier power, and the inverter makes DC power into alternating current, AC is a high-frequency AC at this time. High frequency AC makes the resonance circuit on the original side vibrate at high frequency. The high frequency resonance on the original side is composed of transmitting coil and vibration compensation circuit. When the system has high frequency resonance, the impedance of the original side transmission circuit is the minimum value at this time. At this time, the circuit energy is transmitted to the side of the resonance pair [6]. WPT system coil model structure, See Figure 1 and 4 coil type for two coil types as shown in Figure 2; The two coil type is shown in Figure 1. The model is simple in design, simple in circuit model and easy to analyze [7]. The four coil structure is that one excitation coil is added to the generator coil and the front end of load. The excitation coil and load coil are generally set as single turns, which can make the coupling coefficient between the receiving coil and the load coil stable and ensure the optimal impedance matching of the system, To some extent, the transmission efficiency can be improved [8]. In the modeling and analysis of the system equivalent circuit, generally, two coil structure is selected, because the excitation and load circuits of four coils are regarded as pure resistance. Modeling according to the structure of two coils can simplify the analysis process.

In addition, WPT system can be summarized as four basic resonance systems according to different ways of connecting the original and auxiliary compensation capacitor to the loop, including series series resonance system (SS), series parallel resonance system (SP), parallel series resonance system (PS) and parallel parallel resonance system (PP); Among these four systems, SS resonance system has the best effect and is widely used at present [9]. Here, the main purpose is to design a new coupling coil model structure for reference for the future design of electric vehicle wireless charger. The following work selects SS mcr-wpt system for modeling and analysis.
2.2 Equivalent resonant coupled circuit model

The two hollow coils are $L_s$ and $L_D$ are used for wireless transmission of energy. The inductance $L_s$ of the transmitting coil and the loop resistance are equivalent to the resistance $R_s$; $R_d$, $L_D$ and $R_W$ are the equivalent resistance of the receiving circuit, the inductance value of the receiving coil and the equivalent load resistance value. $C_S$ and $C_D$ are respectively the compensation capacitance of the original and secondary resonance circuits. When the system works normally and the system working frequency is the same as the resonance frequency, the system will undergo resonance coupling. At this time, the load circuit can be considered as a pure resistance circuit [10]. In order to simplify the analysis, the load circuit is considered as a pure resistance circuit [10], Select SS resonance system as the analysis object, and the system equivalent resonance coupling circuit diagram is shown in Figure 4.
The working frequency of the transmission system is $\omega$. The self impedances of the two coils are:

$$Z_S = R_S + j\omega L_S + \frac{1}{j\omega C_S}Z_D = R_D + R_W + j\omega L_D + \frac{1}{j\omega C_D},$$

$M$ is the mutual inductance of two coils, and the KVL loop equation is given

$$\begin{bmatrix} U_{in} \\ 0 \end{bmatrix} = \begin{bmatrix} R_S + j\omega L_S + \frac{1}{j\omega C_S} & -j\omega M \\ -j\omega M & R_D + R_W + j\omega L_D + \frac{1}{j\omega C_D} \end{bmatrix} \begin{bmatrix} i_s \\ i_d \end{bmatrix}$$

(1)

The equivalent loop current of $L_S$ and $L_D$ can be obtained:

$$i_s = \frac{Z_D U_{in}}{Z_S Z_D + (\omega M)^2}$$

(2)

$$i_d = -\frac{j\omega M U_{in}}{Z_S Z_D + (\omega M)^2}$$

(3)

It can be seen from the results of equations (2) and (3) that the impedance values of the transmitting coil circuit and the receiving coil circuit have changed. The impedance reflected from the primary side to the secondary side is set as $Z_{DS}$, and the impedance reflected from the secondary side to the primary side is set as $Z_{SD}$. $Z_{DS} = \frac{(\omega M)^2}{Z_S}$, $Z_{SD} = \frac{(\omega M)^2}{Z_D}$. When the mutual inductance $M$ is larger, the reflection impedance will be larger [11]. In order to reduce the influence of the reflected reactance on the resonant frequency, the system must work in the resonant state, so that the reactance of both circuits is 0, and the reflected reactance can be written as $Z_{DS} = \frac{(\omega M)^2}{R_S}$, $Z_{SD} = \frac{(\omega M)^2}{Z_D}$. After resonant coupling, the primary side circuit and secondary side circuit of the system become pure resistance circuit, and the equivalent impedance of the two circuits can be written as [12]:

$$Z_{Seq} = R_S + \frac{(\omega M)^2}{R_D + R_W}$$

(4)

$$Z_{Deq} = R_D + R_W + \frac{(\omega M)^2}{R_S}$$

(5)

3. Maximum transmission efficiency of the system

3.1 Power and efficiency expressions

It can be seen from (1), (2), (3) that the input power of the coupling coil and the output power of the load resistor $R_W$ under normal operation are expressed as follows:

$$P_{in} = \frac{U_{in}^2 Z_D}{Z_S Z_D + (\omega M)^2}$$

(6)
\[ P_{\text{out}} = \frac{U_{\text{in}}^2 (\omega M)^2 R_W}{[Z_S Z_D + (\omega M)^2]^2} \] (7)

Then the transmission efficiency between the two coils is:

\[ \eta = \frac{(\omega M)^2 R_W}{Z_D [Z_S Z_D + (\omega M)^2]} \times 100\% \] (8)

When \( L_S \) and \( L_D \) self resonate at the same time, that is, the two coils are resonant coupled, \( Z_S = R_S, Z_D = R_D + R_W \), the wireless transmission efficiency of resonant coupling energy is as follows:

\[ \eta = \frac{(\omega M)^2 R_W}{(R_D + R_W) [R_S (R_D + R_W) + (\omega M)^2]} \times 100\% \] (9)

When the resonant coupling occurs in the system, the impedance of the resonant circuit is pure resistance, and the current in the resonant circuit is the largest. At this time, the output power of the system is the largest, and the transmission efficiency is the highest.

### 3.2 Maximum efficiency analysis

The system works at high frequency, the coil mainly produces ohmic loss \( R_O \) and radiation loss \( R_s \), and its value is:

\[ R_O = \frac{\omega \mu_0 l}{2 \sigma 2 \pi a} = \frac{\omega \mu_0 n r}{2 \sigma a} \] (10)

\[ R_r = \frac{\mu_0}{\varepsilon_0} \left[ \frac{\pi}{12} n^2 \left( \frac{\omega r}{C} \right)^4 + \frac{2}{3 \pi^3} \left( \frac{\omega h}{C} \right)^2 \right] \] (11)

Among them, \( \mu_0 \) is the vacuum permeability; \( A \) is the radius of coil wire; \( R \) is the radius of resonant coupling coil; \( N \) is the number of coil turns; \( \sigma \) is the conductivity of the conductor; \( L \) is the total length of conductor; \( \varepsilon_0 \) is the dielectric constant of air; \( H \) is the coil width; \( C \) is the speed of light. The approximate value of \( R_S = R_D \approx R \). The efficiency expression is further expressed as:

\[ \eta = \frac{R_D + R_W}{R_S (R_D + R_W) + (\omega M)^2} \times 100\% \] (12)

For the convenience of experimental verification, the parameters of \( L_S \) and \( L_D \) are consistent to ensure the same self resonant frequency, that is, \( n_s = n_d = n; R_s = R_d = R \), then the mutual inductance \( M \) and coupling coefficient \( k \) between them are calculated as follows:

\[ M = \frac{\pi \mu_0 r^4 n}{2 D^3} \] (13)

\[ k = \frac{M}{\sqrt{L_S L_D}} \] (14)

By substituting (9), (10), (11) into (12), the transmission power and efficiency of the system can be obtained \( \eta \). With the coil size \( (a, R, n) \), system operating frequency \( \omega_0 \), the relationship between the distance between the two coils and the resistance \( R_W \). From the above derivation process, it can be seen that the expression of the maximum efficiency is mainly related to the parameters of the resonant coupling coil. When the coupling coefficient of the resonant coil is larger, the transmission power and efficiency of the system are larger. Therefore, the shape and structure of the coil have a great influence on the transmission efficiency of the system.
4. The influence of coil shape on coupling coefficient

At present, the commonly used coupling coil structures are circular, square, DD type, etc., but the peripheral structures are mainly circular and square; Square coil has high coupling efficiency when it is laterally offset. In this paper, the electromagnetic simulation tools Ansoft Maxwell and Simplorer circuit simulation software are mainly used to design and optimize the magnetic coupling structure, and analyze and compare the change of coupling coefficient of several common coils when they are laterally offset and longitudinally offset [9].

In this paper, the idea of control variable is adopted, and the actual charging scenario of electric vehicle is considered. Form round, square coil and octagonal conductor, and select ordinary Leeds conductor. The total length of conductor shall be controlled at about 20000 mm, and the spacing between conductors shall be 2 mm. The inner diameter, outer diameter and turns of circular coil are 60mm, 160mm and 20 turns respectively, and the inner diameter, outer diameter and turns of square coil are 50mm, 180mm and 21 turns respectively; The physical simulation model is established by Maxwell, and various coil models are drawn in turn, as shown in Figure 5.

1) Modeling

![Figure 5 Structure diagram of three coils with different shapes.](image)

2) In the electromagnetic simulation software Maxwell, when the center of the receiving and transmitting coils is aligned, the coupling coefficient of the circular, square and octagonal coils is analyzed with the change of the longitudinal distance between the coils. The simulation results are shown in Figure 6.

![Figure 6 Variation of coupling coefficient with longitudinal offset distance](image)

3) When the coil position is set at the longitudinal distance of 40mm, the coupling coefficients of circular, square and octagonal coils are simulated with the transverse offset of the coil. The simulation results are shown in Figure 7.

![Figure 7 Variation of coupling coefficient with lateral offset distance](image)
The experimental results in the above two tables show that the coupling coefficient of square coil and octagonal coil is almost the same, and the coupling efficiency is higher than that of square coil; The results show that the coupling coefficient of circular coil decreases sharply when it is laterally offset, while the coupling coefficient of square coil and octagon coil decreases when it is laterally offset. When the offset exceeds 20 mm, the coupling coefficient of both coils is larger than that of circular coil and decreases slowly. Therefore, in general, the circular coil has strong longitudinal anti offset ability, the square coil has strong transverse anti offset ability, and the octagonal coil has both advantages of transverse and longitudinal anti offset ability.

5. Coil design
Considering that the above experiments verify that the vertical coupling efficiency of the circular coil is higher, and the lateral anti offset ability of the square coil is stronger, based on the above, a coil structure design combining the octagonal coil and the circular coil is proposed. The outer design of the coupling coil is octagonal coil, and the inner design is circular coil. The inner and outer coils are wound by a copper wire. As shown in Figure 8 and Figure 9.

The coil size design considers the practical application scenario of electric vehicle wireless charging. The inner circular coil size is set as the inner radius of 200 mm, the outer radius of 350 mm, the coil section radius of 1.5 mm, and the number of coils is 50. The starting position of the outer octagonal spiral coil is 350 mm from the origin, and the end point is 400 mm from the origin. The number of coils is 20. The three-dimensional diagram and plane diagram of the designed coil structure are shown in Figure and Figure 9. At the same time, in order to enhance the coupling coefficient, the iron core coil is added in the coil design, and the aluminum material is used in the bottom tray to reduce the magnetic flux leakage phenomenon [13], as shown in Figure 10.
6. Simulation platform construction

6.1. Co-simulation of Maxwell and Simplorer
The copper material is selected according to the actual cost of coil material. The modeling is carried out in Maxwell software, and the material is allocated. For the convenience of analysis and according to the actual application scenario, the distance between the two coils is selected as d = 200 mm. In Maxwell software:

1) Firstly, the excitation source is set in the static magnetic field as the current value of 10a, the inductance matrix is calculated, and the self inductance L1, L2 and mutual inductance m of coil 1 and coil 2 are obtained.

2) The resistances R1 and R2 of the two coils are calculated in the eddy current field, and the designed coil parameters are solved. The coupling cloud diagram is shown in Figure 11.

3) For transient field simulation, external excitation should be set. The external excitation is the simulation resonant circuit, and the external resonant circuit is the capacitor series resonant circuit. The simulation circuit is shown in Figure 12 below. The working frequency is set to 85kHz, \(f\) is 85kHz, and the amplitude is 400V. According to the resonance conditions, the series capacitance values that meet the resonance conditions are \(C_1\) and \(C_2\). In order to meet the above maximum transmission efficiency requirements, the resistance value of the load can be calculated as \(R_W\).

4) Maxwell and Simplorer co simulation, observe the voltage and current phase difference between the two ends of the primary side resistance \(R_1\), and determine the circuit the resonance of the system; The load \(R_W\) power and system transmission efficiency are calculated to verify whether the results meet the theoretical design requirements.

![Figure 12 Maxwell and Simplorer co simulation diagr](image)

6.2. Pspice system simulation
The radio energy transmission system is simulated in PSPICE. The whole system simulation is shown in Figure 13. The whole system includes boost circuit, rectifier circuit, filter circuit, inverter circuit and so on; The coupling coefficient K of coupling coil is 0.169701, which is the coupling value calculated by Maxwell
7. Experimental result

1) As shown in Figure 14, the current and voltage phases at both ends of the equivalent resistance Rs on the primary side are the same, indicating that the resonance circuit on the primary side is resonant, and the primary side resonance circuit is equivalent to a pure resistance circuit;

2) As can be seen from Figure 15, the output from the inverter circuit on the primary side is a square wave voltage with a voltage amplitude of 360V, which is transmitted to the load after passing through the coupling coil, and the voltage amplitude at both ends of the load is 345v. As can be seen from Figure 16, the output current value of the inverter is 9.8a and the value flowing through the load circuit on the secondary side is 9.5a. The maximum transmission power of the system is 3277.5w, and the transmission efficiency is more than 92.90%.
Figure 15 Output voltage and load voltage of primary side inverter

Figure 16 Output current value and current value of the inverter circuit

8. Conclusion
1) This paper mainly designs and optimizes the structure of magnetic coupling coil in the resonator of electric vehicle wireless charging, and puts forward a new type of coil with octagonal outer periphery and circular inner circumference.

2) The simulation results show that the energy transmission efficiency of the new coil can reach 92.9%, and the coupling strength is high. It has certain engineering practical significance. It can be used as a new type selection structure of resonant coupler coil for electric vehicle wireless charging system.

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