Analysis and optimization of coil structure of magnetic circuit mechanism for electric vehicle wireless charging system

Songcen Wang¹, Chong Xu¹, Bin Wei¹, Jinxing Xu¹, Jiacheng Yin² and Chenyang Xia²,³

¹ Electrical Engineering and New Material Department, China Electric Power Research Institute, Beijing 100192, China
² School of Electrical and Power Engineering, China University of Mining and Technology, 221116 Xuzhou, Jiangsu
³ Corresponding author’s e-mail: 18260722082@163.com

Abstract. To improve the efficiency of the electric vehicle wireless charging system, an optimization design method for the number of coil layers is proposed and studied, which effectively improves the coupling coefficient of the magnetic circuit mechanism. This article first analyzes the energy efficiency characteristics of the wireless charging system for electric vehicles. Then, it analyzes the inductance value changes and magnetic field distribution characteristics of fixed turns coils under different layers. The finite element simulation results performed by MAXWELL show that inducing the number of primary coil layers and increasing the number of secondary coil layers are conducive to the improvement of the coupling coefficient between the coils. Then, based on the theoretical analysis results, the number of coil turns of each layer of the multilayer coil is analyzed and optimized, and a bowl-shaped pair multilayer coil winding method is proposed.

1. Introduction

Compared with the traditional contacted wired power transmission method, Wireless Power Transfer (WPT) technology has the advantages of no wear, no electric spark, no need for manual plugging because there is no direct electrical contact [1-3], is conducive to adapting the equipment to harsh extreme environments, has received extensive attention and research in the fields of electric vehicles [4], medical implants [5], and consumer electronics [6].

As a key part of energy transmission, the magnetic coupling mechanism directly affects the performance of the entire wireless charging system [7]. To improve the performance of electric vehicle wireless charging systems, research institutions have done a lot of research from the aspects of design and optimization of magnetic circuit mechanisms, electromagnetic shielding technology, etc., and achieved good results. In terms of magnetic circuit design, the anti offset performance and coupling coefficient of the magnetic coupling mechanism is improved by optimizing the core structure of the magnetic circuit mechanism [8-9]. John T. Boys of the University of Auckland, New Zealand, and his research team optimized the distribution of single-coil cores [10-11] to achieve wireless charging of 2 to 5 kW; Besides, the team proposed a DD-type coil as an energy transmitting coil and an electromagnetic coupling mechanism composed of a DDQ coil as an energy pickup coil [12], it has been widely used; Zaheer A. proposed a BPP coil structure instead of the DDQ coil as a pickup coil. Reduced the amount of wire used by 1/4 [13-14]. A Taiji type coil structure is proposed, which is
based on DD type coil and changes the straight line wire of DD type coil into a curved wire. In the offset state, a higher coupling coefficient and magnetic flux can be obtained and higher transmission efficiency can be achieved [15]. In terms of coils structure optimization, the asymmetric magnetic coupling mechanism is designed by using circular coil, and the influences of various parameters such as turns and internal and external diameters on the migration performance are analyzed [16]. Yang Qingxin's team at Tianjin University of Technology optimized the receiver coils at the transmitting end of the system based on the direct field coupling algorithm model [17].

Throughout the existing research, it is found that the optimization of the coil mainly includes size, number of turns, shape, winding method, etc., but these optimizations are performed on a single layer coil, and the three-dimensional optimization potential of the coil is not fully utilized. One conceivable way of optimizing is to optimize the number of layers of the coil.

2. Analysis of structure and energy efficiency of the wireless charging system

A typical electric vehicle wireless charging system is shown in Figure 1.

![Figure 1. Structure of an electric vehicle wireless charging system.](image)

In Figure 1, the electric vehicle wireless charging system consists of electrical energy input $V_{in}$, primary AC-DC rectifier and DC-AC inverter, primary resonance compensation, magnetic circuit mechanism, secondary resonance compensation, secondary AC-DC rectifier, and DC-DC converter and other parts.

The equivalent circuit of the electric vehicle wireless charging system shown in Figure 1 is shown in Figure 2.

![Figure 2. SS type compensation topology circuit diagram.](image)

In Figure 2, $U_S$ is the equivalent output power of the inverter, $L_P$ and $L_S$ are the inductances of the primary and secondary coils, $R_P$ and $R_S$ are the internal resistances of the primary and secondary coils, respectively, $C_P$ and $C_S$ are resonance compensation capacitors of transmitting coil and receiving coil respectively, $M$ is the mutual inductance between the transmitting and receiving coils.

When the system resonates,

$$\omega = \frac{1}{\sqrt{L_p L_p}} = \frac{1}{\sqrt{C_p C_s}}$$  \hspace{1cm} (1)

Based on the mutual inductance coupling principle, the power and efficiency of the system can be obtained as:

$$P_{out} = P_{DC} Q_S = V_{DC} I_{DC} Q_S = \omega I_p^2 M^2 Q_S = U_p I_p k^2 Q_S$$  \hspace{1cm} (2)

$$\eta = \frac{k^2 Q_S Q_S}{1 + k^2 Q_S Q_S} \times 100\%$$  \hspace{1cm} (3)
In the actual situation, the $Q_S$ value is generally limited to 2~10 due to various factors. It can be seen from (3) that when all $Q$ values are fixed, the transmission efficiency $\eta$ is positively related to the square of the coupling coefficient $k$.

Based on the above analysis, the transmission efficiency $\eta$ of the system can be improved by increasing the coupling coefficient $k$ and the secondary side quality factor $Q_S$. Because there is a limit to the improvement of the $Q_S$ value, in this paper, improving the coupling coefficient is the main optimization goal.

3. Multilayer coil inductance calculation

Analyze the magnetic field distribution characteristics of different layers of coils, to understand the performance characteristics of different layers of coils, and simulate the magnetic field distribution characteristics of different layers of coils. For the circular coil, under the condition of fixed coil turns and coil outer diameter, the magnetic field distribution diagram is as shown in Figure 3.

![Magnetic field distribution of different layers of coils.](image)

When the smaller secondary coil is fixed, the larger primary coil changes from a single layer coil to a multilayer coil. The magnetic field strength near the primary coil is increasing, and the magnetic field strength in the middle of the coil is relatively small. Since the self-induction zone is near the coil and the mutual induction zone is in the middle of the coil, the self-induction will become larger and the mutual induction will become smaller, which means that the coupling coefficient will decrease. In other words, with the increase of the number of secondary coil layers, the coupling coefficient of the coil will decrease.

When the primary coil with a larger size is fixed and the secondary coil with smaller size changes from a single layer to multilayer, the demand of the secondary coil for the vertical magnetic field decreases, in other words, the acceptance of the inclined induction line increases. Generally speaking, in the application of electric vehicle wireless charging, the primary side coil is larger than the secondary side coil, and the inclined induction line generated by the primary side coil is usually distributed around the secondary side coil. The increase of the receptivity of the secondary coil to the inclined induction line will contribute to the magnetic field coupling of the primary and secondary sides.
4. Multilayer coil structure optimization

In section 3, the preliminary conclusions of the optimization of the number of coil layers are obtained by analyzing the characteristics of the different number of coil layers. This section will further verify through simulation.

4.1. Simulation of the multilayer coil with equal number of turns

To analyze the coupling of the primary and secondary coils with the same outer diameter and number of turns, the number of turns in each layer is equal, and the number of layers is changed, the simulation analysis is performed based on the parameters shown in Table 1 using Maxwell software.

Table 1. Simulation parameters.

| Parameter           | Value               |
|---------------------|---------------------|
| Primary coil turns  | 16                  |
| Secondary coil turns| 16                  |
| Primary coil size   | 700*700mm           |
| Secondary coil size | 350*350mm           |
| Line diameter       | 4mm                 |
| Clearance           | 150mm               |

4.1.1. Single-layer of the primary coil, change the number of turns on the secondary coil. The number of turns of the primary coil is maintained at 16 turns and a single layer, and the number of layers of the secondary coil is 1, 2, 4, 8, and 16 turns. Building a magnetic circuit model is shown in Figure 4:

![Figure 4. Simulation of the number of secondary edges.](image)

Based on the structure and parameters shown in Figure 4, simulation and analysis of the coil self-inductance and mutual inductance parameters under different structures are shown in Figure 5. This results in a changing trend of the coupling coefficient $k$ as shown in Figure 5.

![Figure 5. Simulation results of the number of secondary coil layers.](image)

As seen in Figure 5, as the number of secondary coil layers increases, the coupling coefficient of the coupling mechanism shows an upward trend.
4.1.2. Single-layer of the secondary coil, change the number of primary coil layers. The number of turns of the original secondary coil remains unchanged at 16 turns. First, the number of layers of the secondary coil is kept as one layer. To keep the number of turns of each layer of the coil equal, the number of layers of the primary coil is 1, 2, 4, 8, and 16 in turn. Similar to the analysis in Section 4.1.1, the simulation results of the mutual inductance coupling coefficient $k$ with the number of primary edge layers can be obtained as shown in Figure 6 under the change of the number of primary edge layers.

![Figure 6](image)

**Figure 6.** Simulation results of changes in the number of primary layers.

From the calculation formula of the coupling coefficient $k$, this leads to a downward trend of the coupling coefficient $k$. This is an unsatisfactory phenomenon in wireless charging systems, so there is no need to optimize the number of layers in the primary coil.

The research results in Figure 5 and Figure 6 are consistent with the analysis results of the magnetic field shape in the third section.

4.2. Simulation of multilayer coil with unequal turns

Section 4.1 analyzes the case where the number of turns of each layer is equal. This section will study the case where the number of turns in each layer is different. Since it has been concluded that the number of layers of the primary coil is not necessary to be optimized, the research focus will be on the optimization of the number of layers of the secondary coil.

When the number of layers is fixed, the cross-sectional shape of the coil will be an optimization method when the number of turns in each layer is different. Due to the complexity of multilayer coils, first, study the primary coil with 16 turns, and the secondary coil with a total of 16 turns.

The number of turns of the second layer coil of the secondary coil is set to $n$, and the number of turns of the first layer coil is 16. The simulation shows that the mutual inductance coupling coefficient $k$ varies with $n$ as shown in Figure 7.

![Figure 7](image)

**Figure 7.** Coupling coefficients of different turns distribution.

As can be seen from Figure 7, the coupling coefficient of the system is highest when $n$ is 6. It is easy to think that when the cross-sectional shape of the secondary coil is optimized to be a bowl shape, it conforms to the above rule, that is, a small number of high-level coils are transferred to the bottom layer, and the diameter is not too small.
Further research, the secondary coil returns to 16 turns, keeping 4 layers to optimize its cross-section to a narrow upper and lower wide shape, as shown in the bowl shape of Figure 8.

![Figure 8. Section optimization of the secondary coil.](image)

The simulation results are shown in the following Table 2:

| shape                      | k          |
|----------------------------|------------|
| 4 layers divided equally   | 0.12863    |
| 4 layers of bowl distribution | 0.13324   |
| Single-layer               | 0.12258    |

It can be seen that under the same number of turns, the coupling coefficient can be further improved by changing the number of layers of the secondary coil into multilayers. By optimizing the cross-section of the secondary coil, the bowl shape is formed, while maintaining the number of layers.

5. Conclusions
For the circular loop coil magnetic circuit mechanism with fixed turns, when the outer diameter is fixed, the increase of the number of layers of the secondary coil can improve the coupling coefficient of the system, thus improving the performance of the system, so it is necessary to optimize the number of layers of the secondary coil when the number of layers of the primary coil increases, the coupling coefficient will be reduced, so there is no need to optimize the number of layers of the primary coil; When the number of turns and layers of the secondary coil is fixed, the coupling coefficient of the system can be improved by changing the section shape of the coil into a bowl shape. In the future, we will further study the core structure suitable for multilayer coils.

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