Study on distribution characteristics of wireless charging system coupling mechanism

Zhaohui Wang*, Xin Huang*, Chuan Li*, Jin Li* and Baoqiang Zhang*
CATARC Automotive Test Center (Tianjin) Co, Ltd., Tianjin, China

*Corresponding author e-mail: wangzhaohui@catarc.ac.cn, huangxin@catarc.ac.cn, lichuan@catarc.ac.cn, lijing@catarc.ac.cn, zhangbaoqiang@catarc.ac.cn

Abstract. Coupling mechanism is one of the key issues in the research of electric vehicle wireless charging system. Single D and DD are two kinds of coupling mechanism commonly used in wireless charging system, and spatial magnetic field distribution are different depending on the coupling mechanism. In this paper, the expressions of magnetic flux density at any point in a single D and DD were derived. A 3D magnetic field measurement platform was built and the magnetic field distribution was drawn. The experimental results show that in the primary test, single D type magnetic induction intensity is 1.18 times of DD type, with the increase of the transmission distance, DD type coupling mechanism of magnetic induction intensity attenuation is slow, and on the secondary side of DD type magnetic induction intensity is 1.12 times of D type.

1. Introduction

The electric vehicle wireless charging system generally includes a wireless charging power source for achieving high frequency inversion, a primary side device and a secondary side device for spatially coupling electric energy, and a vehicle power component for rectified and regulated output [1]. The core to complete the power transmission process is the power coupling mechanism [2], which causes the difference in the spatial electromagnetic field distribution between the primary and secondary equipment, and directly affects the energy efficiency characteristics of the entire system transmission [3-4].

There are many types of electric energy coupling mechanisms in electric vehicle wireless charging technology, which are mainly divided into three types: scattered or densely wound hollow coil structures, flat disc coils with magnetic shielding structures, and linear reciprocating coil rail structures [5]. In 2011, the Oak Ridge National Laboratory in the United States developed a new wireless charging system for electric vehicles. The coupling mechanism uses multiple sets of closely wound copper tubes [6]. This system can achieve 4kW energy transmission at 254mm air interval, and the transmission efficiency is 95%. For the planar disc coil and magnetic shielding structure, the University of Auckland proposed a DD-shaped mechanism composed of rectangular coils in 2013. The magnetic field distribution is similar to that in a single-phase loosely coupled transformer, but only the spatial magnetic field is simulated and analyzed in this article. The true magnetic field distribution [7].

In this paper, the analytical model of single D-type and DD coil space magnetic induction strength is firstly established analytically. In order to accurately measure the spatial magnetic field distribution characteristics, this paper builds a three-dimensional electromagnetic field measurement platform dedicated to wireless energy transmission systems, measures and plots the spatial magnetic field...
distribution map of the two coupling mechanisms at the same number of turns, maximum outer diameter, and the same current. The magnetic induction intensity of the single D-type coupling structure is 1.18 times that of the DD-type coupling mechanism. As the distance between the primary device and the secondary device increases, the attenuation rate of the DD type is slower than that of the single D type. On the secondary side, the magnetic induction intensity of the single D-type coupling structure is 1.12 times that of the DD-type coupling mechanism.

2. Mathematical model analysis of electric energy coupling mechanism of wireless charging system for electric vehicles

2.1. Mathematical model of single D coil with magnetic shield

In the practical application of wireless charging devices for electric vehicles, in order to increase the coupling of the coil, improve the efficiency of electric energy transmission, and at the same time reduce the influence of the wireless energy transmission system on the electromagnetic environment in the non-working area, high permeability materials are generally used to make the magnetic shielding mechanism.

In order to study the spatial magnetic field distribution of a single D-type coil with magnetic shielding, the mirror image method is used to simplify based on the coupling analysis of the air-core coil [25].

![Diagram](image)

**Figure 1.** Field-circuit structure diagram of wireless power transmission system

Figure 1(a) is a schematic diagram of the current interface between two media. Among them, the magnetic permeability of the two media are \( \mu_{\text{air}} \) and \( \mu_{\text{fer.}} \). A piece of finite length straight current-carrying wire is placed in the air, the current is \( I \), and it is parallel to the interface of the two media. According to the equivalent principle of the mirror image method, the magnetic field at any point \( P \) in the air is synthesized by the magnetic field generated by the current \( I \) and the image current \( I' \), as shown in Figure 1(b), and the image current is:

\[
I' = \frac{\mu_{\text{fer.}} - \mu_{\text{air}}}{\mu_{\text{fer.}} + \mu_{\text{air}}} I
\]

The direction of the image current is determined by the sign of \( \mu_{\text{fer.}} \mu_{\text{air}} \), and its value is positive. The direction of the image current is the same as the direction of the current; the value is negative, the opposite. Because the magnetic permeability of the electromagnetic shielding device \( \mu_{\text{fer.}} \) is close to infinity, and \( \mu_{\text{air}} = \mu_0 \), the image current size and direction corresponding to the single D-type coil with magnetic shielding device and the current passed by the coil Consistent. Therefore, the magnetic induction intensity of the single D-type coil with magnetic shield is:
\[ B = \sum_i [f_B(x, y, z, I, L) + f_B'(x, y, z, I, L, R)] \]  

(2)

\( f_B \) and \( f_B' \) are the magnetic induction intensity generated by the current passed by the coil and its image current, respectively. Among them: \( x, y, z \) are spatial coordinates, \( R \) is the distance between the current in the coil and the surface of the magnetic shielding device, which is generally regarded as the radius of the wire used for winding the coil.

### 2.2. Magnetic field distribution of single D-type and DD-type coupling mechanism with magnetic shield

The magnetic field in the electric energy coupling mechanism is formed by the superposition of the magnetic fields generated by the two coils. Based on the conclusion drawn in Section 2.1, the magnetic field distribution can be obtained. In order to facilitate the study of the characteristics of the magnetic field distribution, this paper selects the axial cross between the two coils as the research object and draws a three-dimensional surface diagram. The schematic diagram of the selected surface is shown in Figure 2.

**Figure 2.** Schematic diagram of magnetic field selection surface

In order to facilitate the observation of the magnetic field distribution of the selected surface, an electric energy coupling mechanism with the parameters shown in Table 1 is established.

**Table 1.** Parameters of electric energy coupling mechanism.

| Parameter             | Value |
|-----------------------|-------|
| Primary coil current/A| 7     |
| Secondary coil current/A| 5     |
| Coil outer diameter/cm | 28    |
| Coil spacing/cm       | 17    |
| Coil turns/turn        | 10    |

After MATLAB simulation, a three-dimensional distribution map of the selected surface magnetic induction intensity can be obtained, as shown in Figures 3 and 4.

**Figure 3** is a schematic diagram of the spatial distribution of the magnetic induction intensity of the single D-type electric energy coupling mechanism on the XOY plane. It can be seen from Figure 3 that...
the maximum value of the magnetic induction intensity in the XOY plane is $5.7 \times 10^{-4}$ T, and it is located in the central part of the plane.

![Figure 3. XOY surface magnetic induction intensity distribution diagram of Type D](image)

Figure 4 is the magnetic induction intensity distribution of the double D-type electric energy coupling mechanism on the XOY plane. Comparing Figure 3, it can be seen that the double D-type electric energy coupling mechanism produces two distributed troughs with the same size and shape on the surface, and the single distributed trough is the same as the single D-type electric energy coupling mechanism in the magnetic induction intensity distribution. The intensity is the largest, and its value decreases continuously as it extends outward. And the maximum magnetic induction intensity of the double D-type electric energy coupling mechanism is the same as that of the single D-type electric energy coupling mechanism, both of which are 6.7 mT.

![Figure 4. XOY surface magnetic induction intensity distribution diagram of Type DD](image)

3. Experimental results and analysis
When winding the single D and DD type coupling mechanism, ensure that the maximum outer diameter, transmission distance and number of turns are consistent, as shown in Figure 5. The material of the coil is a litz wire with a diameter of 2.5 mm, a maximum outer diameter of 28 cm, a transmission distance of 17 cm, and a number of turns of 10 turns. The ferrite shield is attached to the rear of the coupling mechanism. The resonance frequency of the entire system is 80 kHz. The current flowing into the primary coupling mechanism is 7 A.

![Figure 5. Coupling mechanism](image)
Figure 6(a) shows the distribution of single D-type XOY magnetic flux density, where two valley peaks appear in $B_x$ and $B_y$, and there is only one valley peak in $B_z$ and $|B|$. The magnetic flux density in the center is the largest, and the maximum value is 0.54mT. From the center to the surroundings, the magnetic flux density gradually decreases. The magnetic induction intensity distribution of the XOY surfaces of the DD type coupling mechanism is shown in Figure 6(b). In Figure 6(b), due to the superposition of the magnetic field in the central part of the DD type coil, the central magnetic induction intensity is greater than that on both sides, and its maximum value is 0.31mT.

4. Conclusion
By comparing the relationship between the magnetic induction intensity of the single D-type coupling mechanism and the DD type coupling mechanism and the transmission distance, on the primary side, the single D-type magnetic induction intensity is 1.18 times that of the DD type. As the transmission distance increases, the magnetic induction intensity of the DD type coupling mechanism The decay speed is slow, and the magnetic induction intensity of the DD type on the secondary side is 1.12 times that of the single D type. The magnetic induction strength of the two coupling mechanisms in the X-axis direction increases first and then decreases. The coupling structure of the DD type is always larger than that of the single D type, the maximum value of the DD type is 0.64mT, and the single D type is 0.59mT.

Acknowledgments
This work was financially supported by Major State Research and Development Program(2018YFB0106304) fund.

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