Edge Effect and Coil Optimization of Wireless Power Transmission System for Electric Vehicle Charging

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Abstract—In order to prevent the leakage of the electromagnetic field and control the electromagnetic field within the limit of the safety limit, the electromagnetic shielding device will be installed in the coupling mechanism of the wireless power energy transmission system. The edge effect will be produced in the back of the primary equipment and the secondary side equipment. This paper mainly introduces the edge effect of the wireless power energy transmission shielding machine and the reasons for it. The consequences are analyzed, and the coupling mechanism is optimized to reduce the edge effect. In this paper, a new shielding structure is designed, which not only reduces the edge effect, but also ensures the security of the system.

Keywords—wireless power transmission; edge effect; electromagnetic shielding

I. INTRODUCTION

Wireless power transmission is a near-field technology based on the transmission of energy from a transmitter to a receiver through an oscillating magnetic field. In case of the convenience[1], Wireless charging for electric vehicle has become one of the most popular research fields. Electromagnetic shielding are added to the coupling mechanism of WPT system to reduce leakage of magnetic field[2]. Because of the existence of electromagnetic shielding, magnetic line of force will gather at edge of shielding mechanism and produce a strong magnetic field at edge[3, 4]. It defines magnetic field aggregation caused by the existence of the shielding mechanism as the edge effect. Edge effect will increase electromagnetic field intensity at the edge of coupling mechanisms[5, 6]. If the electromagnetic field is too high, electromagnetic security problem will be caused. At the same time, eddy current in the shielding mechanism is generated by the electromagnetic field, and the eddy will produce heat in the non-metallic shielding and cause the loss of energy[7, 8].

In 2013, Jiseong Kim of KAIST studied the effect of electric shielding on the magnetic field around the coupling mechanism. The coupling mechanism is a circular ring. They measured the magnetic field intensity at different distances from the coupling mechanism[9]. In 2015, Yoshiki Yashima, a team from the Department of Electrical and Electronic Systems Engineering, Osaka Institute of Technology, studied the effect of electrical shielding on the transmission efficiency of the system. The experimental results showed that the transmission efficiency of the system was improved by 1% and the magnetic field was reduced by 20 μT with the addition of electrical shielding. However, if no magnetic shielding was added to the system, only the shielding was applied. The rate is reduced by 4%[10]. In 2016, Katharina Knaisch’s team at Karlsruhe Institute of Technology studied the effects of electrical shielding on the main parameters of wireless charging systems. The self-inductance and mutual inductance of electric shielding decreased, the coupling coefficient increased, and the internal magnetic induction of electric vehicles decreased by 9μT[7].

Although the influence of electric shielding on the spatial magnetic field around the coupling mechanism of the WPT system is analyzed in the above literature, most of them are only simulated and analyzed. In the experiment, the magnetic field intensity of some points is only measured[11, 12], and the distribution and size of the whole surface magnetic field is not shown completely. Due to the simplification of the simulation model, the simulation results may differ from the actual magnetic field distribution. Therefore, it is important to measure the magnitude and distribution of magnetic field around the coupling mechanism accurately for the research of wireless power transmission[13].

This paper explains the cause of edge effect and analyzes the harm of edge effect. In order to weaken this effect, a new shielding structure is designed, which can not only weaken the diffusion of magnetic field, but also weaken the influence of edge effect. As the same time, the distribution of space magnetic field is simulated by finite element software, and the influence of electric shielding on the magnetic field distribution around the coupling structure is calculated. A three-dimensional magnetic field measurement system for wireless power transmission is built, and the spatial magnetic field distribution is measured and plotted.

II. FINITE ELEMENT SIMULATION ANALYSIS

In this paper, the relationship between the back magnetic flux density of the coupling mechanism and the electromagnetic shielding materials is established through the formula deduction, so as to optimize the design.
Ferrite material is chosen as magnetic shielding material. Because its conductivity is far lower than that of conductor, the influence of conductivity on magnetic field is ignored. Conductor is chosen as shielding material, and the conductivity is not 0. Therefore, according to Maxwell equation, the field source relation of the system in the working area is decomposed in the x and y directions. Components Ex and Hx form a group of plane waves, and components Ez and Hz form a group of plane waves. The two groups of component waves are independent of each other. The propagation law is similar, so we only need to analyze a set of them. In this paper, the first component Ex and Hx are analyzed, and the corresponding wave equation in the case of passive sinusoidal electromagnetic field is as follows:

\begin{align}
\frac{d^2 \mathbf{H}_x}{dz^2} + \alpha \frac{\omega}{\mu} \mathbf{H}_x - \frac{j \omega}{\mu} \mathbf{E}_x &= 0 \\
\frac{d^2 \mathbf{E}_z}{dz^2} + \alpha \frac{\omega}{\mu} \mathbf{E}_z - \frac{j \omega}{\mu} \mathbf{H}_z &= 0
\end{align}

The equation of electric field intensity in the above formula is the same as that of magnetic field intensity. In the passive ideal medium ($\gamma = 0$), the homogeneous Helmholtz equation of sinusoidal uniform plane electromagnetic wave is one-dimensional second-order homogeneous differential equation:

\begin{equation}
\frac{d^2 \mathbf{E}_z}{dz^2} + \alpha \frac{\omega}{\mu} \mathbf{E}_z = 0
\end{equation}

The propagation function of ideal medium is defined as:

\begin{equation}
k = \omega \sqrt{\frac{\mu}{\epsilon}}
\end{equation}

The general solution of differential equation 2-35 is:

\begin{equation}
\mathbf{E}_z = C_1 e^{kz} + C_2 e^{-kz}
\end{equation}

In the formula C1 and C2 are undetermined coefficients. If the space is infinite, only the electromagnetic field in a single direction exists. If set in the + X direction, the coefficients C2 = 0. The physical meaning of the undetermined coefficient C1 should be the initial vector of the electric field intensity of the incident wave. If the initial phase is not considered as the effective value, $C_1 = E_0$ is recorded. The superscript plus sign indicates that the electromagnetic field propagates along the positive direction. The complex vector of the electric field intensity and the instantaneous value are written respectively:

\begin{equation}
\mathbf{E}(z,t) = E_0 e^{j(kz - \omega t)}
\end{equation}

The general solution of magnetic field intensity can bring the obtained complex vector of electric field intensity into Maxwell's second equation and obtain as follows:

\begin{equation}
\mathbf{H}_x = \mathbf{E}_y \times \frac{1}{\omega \mu} \frac{\partial}{\partial z} e_y = \frac{k}{\omega \mu} E_0 e^{j(kz - \omega t)} e_y = \frac{k}{\omega \mu} \mathbf{E}_z e_y
\end{equation}
The coupling coil is wound by a diameter of 2.5mm Liz line with a total of 14 turns. The transmission distance is 16cm. The system frequency is 85kHz and the primary side current is 22A. Magnetic shielding covers the rear of the coupling mechanism. PC95 square plate ferrite is selected as the material. Electrical shielding material is attached to the rear of the ferrite, the thickness is 5mm. Because the shielding effect in the case of little difference, the circular shielding occupies more space, weight will also increase, so the shielding is used square shielding.

A simulation model is built by finite element simulation software. The finite element simulation and analysis of the magnetic field and electric field on the back side of the primary equipment and side equipment are carried out. A rectangular aluminum plate with 1.5 × 1.2 m and a thickness of 3 mm is used at the receiving end to simulate the chassis of an electric vehicle.

![FIGURE II. SYSTEM GEOMETRY DIAGRAM](image)

Table I is simulation results of self inductance and mutual inductance of coil after adding electromagnetic shielding. It can be seen from table II that magnetic shielding increases the self inductance and mutual inductance of the coil. The introduction of chassis reduces self inductance and mutual inductance, thus reducing the coupling coefficient. Because the high frequency alternating magnetic field can cause a large eddy current on the chassis plate, and then through the eddy current demagnetization, the magnetic field on the chassis plate weakens, so that the high frequency alternating magnetic field can not be penetrated from the chassis.

|                  | core coil | Ferrite | Ferrite and chassis |
|------------------|-----------|---------|---------------------|
| L/μH             | 128       | 189     | 181                 |
| M/μH             | 27.1      | 50.2    | 44.5                |
| k                | 0.21      | 0.26    | 0.24                |

Generally speaking, magnetic field generated by the charging system has been well limited by the shielding method of fully covered aluminum plate, but the magnetic field at the edge is still very large. In order to reduce the edge effect, a shielding method is proposed to replace the whole aluminum plate by installing shielding strips only on the outer edge of the secondary side, as show in Fig. 3.

Fig. 4 shows the distribution of magnetic field in the x-z plane of the original side and the x-z plane of the chassis back after adding electrical shielding. The flux density of the original side and the secondary side decreases, and the maximum value of the original side is 0.22mT. The magnetic flux density on the x-y surface of the original side is smaller in the middle from Fig. 4(a), and the closer to the edge, the greater the flux density. From the results of Fig. 4(b), it can be seen that the flux density in the center of the secondary side is also very small. The addition of electrical shielding weakens the edge effect, and the magnetic field converge on the corner of the back side of the ferrite material.

![FIGURE IV. SIMULATION RESULTS OF MAGNETIC FIELD DISTRIBUTION IN X-Z SURFACE WITH ALUMINUM STRIP](image)

In Figure 5, the change of magnetic induction intensity in horizontal direction under three installation modes of shielding at transmitter, receiver and both ends. From the graph, the attenuation trend of magnetic induction intensity is similar only when shielding is installed at transmitter and shielding is installed at both ends, and the safe distances satisfying the limits are 21cm and 14cm respectively. The safety distance is 35cm only when the receiving end is equipped with electric shield. The installation method of electric shielding only needs to select the electrical shielding material at the transmitter, which not only keeps the system high efficiency, but also improves the economy.
The case of magnetic induction intensity of 40 cm vertical measurement line above the receiving coil as shown in figure 6(a). It can be seen from the figure that when the thickness of the aluminum plate is 1 mm, the maximum value above the receiving end is 0.85 μT, which is far less than the standard limit. With the increase of the thickness, the maximum value gradually decreases. The shielding effect of electromagnetic field above aluminum terminal is small. When the horizontal direction is 22 cm away from the edge of the coil, the magnetic induction intensity satisfies the limit value. Compared with the case of adding only ferrite shielding material, the safety distance increases by 8 cm respectively. It can be seen that the shielding effect of aluminum shielding belt on the electromagnetic field in the safety protection area is higher than that of only adding magnetic shielding. Based on the above analysis, it can be concluded that when the electrical shielding thickness is 3mm, the economy type and safety type are the highest.

Figure 7 shows the change of magnetic flux density at edge of the receiving coil in the direction of x extension. The magnetic flux density at edge of the coil is 250 μT with electrical shielding at receiver. The magnetic flux density at the distance of 27 cm from edge of the coil meets the ICNIRP limit. After installing the shielding electrical shielding at transmitter, the magnetic induction intensity at the edge of the coil is 189 μT, and the magnetic induction intensity at the distance of 16cm from the edge of the coil meets the ICNIRP limit.

This paper explains the edge effect of wireless power energy transmission shielding mechanism, expounds the
influence of the edge effect, and optimizes the coupling mechanism according to the effect. The simulation results show that increasing the area of the non-metallic shielding of the coupling mechanism can effectively reduce the influence of the edge effect. In this paper, a new type of electric shielding structure with electric shielding aluminium plate installed at the transmitter is designed. This structure not only ensures the high efficiency of the system operation, but also reduces the electromagnetic field intensity in the safe area and ensures the safety of the system.

ACKNOWLEDGMENT

This paper was supported by Major State Research and Development Program (2018YFB0106304).

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