Magnetic Shielding Design for Coupler of Wireless Electric Vehicle Charging Using Finite Element Analysis

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Abstract. Inductive power transfer (IPT) is a practical and preferable method for wireless electric vehicle (EV) charging which proved to be safe, convenient and reliable. Due to the air gap between the magnetic coupler, the magnetic field coupling decreases and the magnetic leakage increases significantly compared to traditional transformer, and this may lead to the magnetic flux density around the coupler more than the safety limit for human. So magnetic shielding should be adding to the winding made from litz wire to enhance the magnetic field coupling effect in the working area and reduce magnetic field strength in non-working area. Magnetic shielding can be achieved by adding high-permeability material or high-conductivity material. For high-permeability material its magnetic reluctance is much lower than the surrounding air medium so most of the magnetic line goes through the high-permeability material rather than surrounding air. For high-conductivity material the eddy current in the material can produce reverse magnetic field to achieve magnetic shielding. This paper studies the effect of the two types of shielding material on coupler for wireless EV charging and designs combination shielding made from high-permeability material and high-conductivity material. The investigation of the paper is done with the help of finite element analysis.

1. Introduction
As a new charging way wireless power transmission has attracted attention of all the world. Electric vehicle based on wireless power transmission technology has advantages of security, waterproof, dust-proof and easy to maintain, ensuring safely charging even in cold and damp environment. Inductive power transfer (IPT) is one of the most widely used wireless power transmission method and has an increasing demand in many applications, such as many medical implants, consumer electronics chargers. Compared with plug-in charging, wireless EV charging has several characteristics. In wireless charging system, power is transmitted through magnetic coupler with air gap and the distance of air gap depends on applications. For wireless EV charging, the receive coil pad is usually fixed in the car chassis while the transfer coil pad is on the ground. So the vertical distance of air gap may be 100-400 mm [1]. On the other hand, the output power for EV charging should be several kW depending on the EV types [2]. To achieve this
high output power, wireless EV charging works in high frequency. Due to the air gap between the magnetic coupler, the magnetic field coupling decreases and the magnetic leakage increases significantly compared to traditional transformer, and this may lead to the magnetic flux density around the coil pads more than the safety limit for human. To reduce the operating electromagnetic interference of the wireless charging coupler in the non-working area, magnetic shielding must be considered when designing magnetic coupler. In practice magnetic shielding usually can be achieved by adding high-permeability material or high-conductivity material. For high-permeability material, its magnetic reluctance is much lower than the surrounding air medium because of its high permeability. This will force most of the magnetic line go through the high-permeability material rather than surrounding air. For high-conductivity material, due to the electromagnetic induction effect, the eddy current in the material can produce reverse magnetic field to achieve magnetic shielding.

This paper investigates the characteristics of the two types of shielding material and designs an effective magnetic shielding for coupler of EV charging using finite element analysis. In section II coupler with single kind of material shielding is studied and compared to explore the characteristics of the two kinds of material. In section IV combination shielding composed of high-permeability material and high-conductivity material is designed and investigated.

2. Single kind of material shielding

The coupler design of IPT system is difficult and complex because the magnetic field produced by coupler depends on many factors, such as vertical distance between coupler, geometry, number of turns, shielding material and so on. So the coupler design has to rely on finite element analysis (FEM) software. In this paper, the FEM software JMAG is used to model coupler.

To achieve high transfer power rating and large misalignment tolerance, many different structures of magnetic coupler has been proposed and investigated in [3][4][5]. In this paper square coupler in Fig.1 is chosen as study object to simplify the finite element analysis model. However, the study results and design method also can be applied to other structures.

![Fig.1 The structure of square coupler](image)

The coupler in Fig.1 is composed of two coil pad with one layer shielding plate made from high-permeability material or high-conductivity material. In this paper PC47 ferrite manufactured by TDK company and aluminum are selected as representative of high-permeability material and high-conductivity material. The size of shielding plate is 600 mm×600 mm×4 mm and the vertical distance between the magnetic coupler is 200 mm. The distance between shielding plate and winding is 5 mm. The winding in Fig.1 is made from litz wire whose diameter is 4 mm and the turn of winding is 20. The internal length of winding is 400 mm while the external length of winding is 560 mm. The amplitude of current in the transfer winding is set to 20 A and its frequency is 20 kHz which is consistent with the existing experimental platform.

For wireless EV charging the region between the transfer coil pad and the receive coil pad is the working area contributing to output power and the surrounding air region is non-working area. So it is expected that the magnetic field strength in the working area is strong while in the non-working area magnetic field strength is weak so that high output power and the safety of human standing around the car can be ensured at the same time. To evaluate the magnetic field around the coupler, measurement line along z-axis is selected. The magnetic field strength along the measurement line is shown in Fig.2 and Fig.3. For Fig.2 the simulation model consists of only the transfer coil pad and the measurement line is along z-axis with origin in the center of the transfer coil pad. Fig.3 shows the magnetic
field strength of coupler composed of the transfer coil pad and the receive coil pad. The measurement line for Fig.3 is along z-axis with origin in the center of coupler.

It can be seen that after adding high-permeability or high-conductivity plate back the winding the magnetic field strength in non-working area is reduced to a low level. Furthermore the shielding effect of high-conductivity material is better than high-permeability material. When adding high-permeability shielding to the winding, the magnetic field strength in non-working area is much lower while the magnetic field strength in the working region above is much higher compared to coil pad without any shielding. This means that high-permeability material can help enhance magnetic field strength in the working area and weaken magnetic field strength in non-working area. But after adding high-conductivity shielding the magnetic field strength is very low in both working area and non-working area. This is because the reverse magnetic field produced by the eddy current in the high-conductivity material counteracts the original magnetic field in the whole area.

Fig.2  Magnetic field strength along z-axis for only the transfer coil pad

Fig.3  Magnetic field strength along z-axis for coupler
According to [3] power output of wireless EV charging can be calculated by (1)

$$P_{out} = V_{oc}I_{sc}Q_2 = P_{uo}Q_2$$  \hspace{1cm} (1)

Here, $V_{oc}$ is the open-circuit voltage of receive coil. $I_{sc}$ is the short-circuit current in receive coil. $P_{uo}$ is the uncompensated power rating and equal to the product of $V_{oc}$ and $I_{sc}$. $Q_2$ is defined as quality factor of resonant circuit in receive side.

To calculate uncompensated power rating of coupler, circuit calculation should be added to the coupler model. Fig.4 (a) shows the circuit to calculate open-circuit voltage of the receive coil and Fig.4 (b) shows the circuit to calculate short-circuit current in the receive coil. In Fig.4 (a) AC working current is flowing in the transfer coil while the receive coil is open circuited. In Fig.4 (b) the same current is flowing in the transfer coil while the receive coil is short circuited. In practical application, power supply is usually a voltage source, which can be converted to current source by adding LCL immittance converter [6][7].

In this paper, the receive coil pad is designed to be identical to the transfer coil pad. To ensure strongest coupling effect, the transfer coil pad and the receive coil pad should be center aligned. But in practice application it is very hard for drivers to keep the receive coil pad fixed in the car chassis center aligned to the transfer coil pad on the ground, so the coupler must have enough misalignment tolerance to ensure EV charging under a certain level of misalignment. Fig.5 shows the uncompensated output power rating of coupler under different misalignment. After adding high-conductivity shielding the uncompensated output power rating of coupler increased significantly because the magnetic field strength in the working area is enhanced. The power rating of coupler with high-conductivity shielding is very low. So single kind of high-conductivity shielding plate is inappropriate in wireless EV charging.
3. Combination shielding of high permeability material and high conductivity material

In section II high-permeability material shielding and high-conductivity material shielding are compared and the result shows the shielding effectiveness of high-conductivity material is better than high-permeability material. But high-conductivity material will weaken the magnetic field in working area and significantly reduce the output power. So just adding high-conductivity material as shielding is inappropriate in wireless EV charging. The high-permeability material can help enhance magnetic field strength in working area and weaken magnetic field in the non-working area. But its shielding effectiveness is lower than high-conductivity material and in some cases just adding high-permeability material may not guarantee the magnetic field strength in the surroundings meet the safety standard. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has developed guidelines for different applications to assure the protection of human [8]. The safety limit for general public exposed to flux density is frequency dependent and the spot limit is $27 \mu T$ in the frequency of 0.8 to 150 kHz [9]. Considering the shielding characteristics of the two kinds of material, combination of high-permeability material and high-conductivity material may be an optimal design. The position of the two kinds of material is essential and the magnetic field strength along the vertical measurement line under different position of the two kinds of material is shown in Fig.6. It can be seen the high-permeability material should be put close to the winding. That is because high-permeability material acts by changing the distribution of magnetic line while high-conductivity material acts as shielding by producing reverse magnetic field.

The magnetic field distribution of coupler before and after adding high-conductivity material is shown in Fig.7. The measurement plane is 20 mm above the receive coil pad. It can be seen that the magnetic field strength in non-working area will significantly decrease by adding another shielding layer made from high-conductivity material.
In IPT system for wireless EV charging, the transfer coil is fixed on the ground and the receive pad is fixed in the vehicle chassis. To evaluate magnetic flux density in non-working area around the magnetic coupler, probe magnetic flux density along x-direction and y-direction when the receive coil and transfer coil is center aligned. Fig.7 (a) shows magnetic flux density along a horizontal line while Fig.7 (b) shows magnetic flux density along a vertical line.

For coupler with high-permeability shielding the magnetic field density in horizontal position is larger than that in vertical position in non-working area. Adding another layer shielding made from high-conductivity material can help reduce magnetic field density in non-working area and magnetic field density in non-working area will drop to a safety level in a short distance which means magnetic radiation has been improved. From Fig.7 it can be seen that the high-conductivity plate back the winding is more effective in improve vertical magnetic radiation. The decrease of magnetic flux density in the horizontal position is very small. In practical high-conductivity shielding ring around the coupler can be added to the coupler to further decrease the magnetic field strength in the horizontal position to ensure human safety.

4. Conclusion

To model and investigate the influence of high-permeability and high-conductivity material shielding coupler of square structure is constructed and simulated using finite element analysis software. This paper compares the shielding effect and analyzes the shielding principle of the two material. The high-permeability material can help enhance magnetic field strength in working area and weaken magnetic field in the non-working area while the high-conductivity material shielding reduces magnetic field strength in both working area and non-working area. So although the shielding effect of high-conductivity material is better than high-permeability material, single kind of high-conductivity shielding is inappropriate in wireless EV charging. To increase the transmission power of the magnetic coupler and further reduce magnetic field strength in the non-working area, combination of the two kinds of material can be used. In practical if the shielding effect is not satisfactory more layer of high-conductivity shielding can be added.
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