Simulation and Optimal Design of Magnetic Coupler and its Shielding for EV Wireless Charger

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Abstract. This paper is focus on the coupler design of wireless power transfer (WPT) system for Electric Vehicle (EV). The author describes the coupler circuit model, design principles and steps, calibration methods and magnetic shielding methods for the coupler. Four shielding methods are simulated and compared in this paper. Through simulation, the author believes that aluminium plate shielding is the best for magnetic shielding, but it will cause more losses. Therefore, we need to do a more optimal design in the next study.

1. Introduction

In last decade, energy supply mode has been changed with the development of energy structure. Wireless power transfer (WPT) is widely used in transportation, lighting, medical instruments, electronic products, rail transportation, electric vehicle (EV), and so on due to the excellent advantages such as safety, reliability and convenience [1-3]. A WPT charger always consists of an AC/DC rectifier and a high frequency DC/AC inverter in the primary side, a high frequency AC/DC rectifier and a DC/DC converter in the secondary side, and a magnetic coupler between the two sides. Several requirements should be met to design a high performance WPT charger system: (a) Large coupling coefficient; (b) High energy transfer efficiency; (c) High power density; (d) Good tolerance to misalignment of coupler’s coils [4]. The publication researches of WPT charging system can be mainly divided into several categories: (1) modelling and theoretical analysing [5], (2) designing of magnetic coupler [6], (3) improving the tolerance to coupler’s misalignment [7], (4) optimization of compensation network’s topology [8-10], (4) designing of impedance matching method [11], (5) power regulation scheme [12,13].

Since 1990, John T. Boys has done a lot reaches on WPT charging systems and proposed circular non-polarized single-coil, Double-D polarized coils, multiple coils, et.al [6], achieving excellent performances. Korea institute of science and technology (KAIST) made a lot reaches on the 2nd and 3rd generation of WPT on-line charging systems for EV. In order to improve the transmission efficiency, KAIST went into more detail on the structures of coupling coils, analysed the influences of U and W coil and obtained an optimized magnetic path of WPT [14, 15]. The shielding design of WPT
was expressed in [16] to reduce the radiation, increase the coupling coefficient and improve the transfer efficiency. The requirement of magnetic flux leakage design was proposed in [17] and [18]. The standard of magnetic flux leakage was given in 2010 by ICNIRP, which required the magnetic flux leakage should be lower than 27 μ T.

Although the abovementioned research have given some design methods of magnetic coupler and its shielding, a good complete solution cannot be found in literatures so far. In this paper, magnetic coupler’s circuit modelling and its design principles are described in detail, and then four shielding methods are simulated and compared. Finally, the coupler’s performance was verified by experiments.

2. Analysis of magnetic coupler

The topology of a WPT system is given in Fig. 1. $i_p$ and $i_s$ are resonant current of primary and secondary coil. $C_p$ and $C_s$ are series compensation capacitors of primary and secondary coils. $M$ is the mutual inductance of magnetic coupler and $R_{load}$ is the load resistor of secondary side.

![Figure. 1. Basic components and topology of wireless power transfer system.](image1)

The topology of WPT in Fig. 1 (b) can be simplified to the circuit in Fig. 2. $L_p$ and $L_s$ are the self-inductance of primary and secondary coil which meet $L_p = L_s$. $r_p$ and $r_s$ are the loss resistors of primary and secondary coil. $R_{ac}$ is the equal resistor of load at AC side of secondary rectifier. $R_{ref}$ is the equal resistor of secondary circuit at primary side. $P_{in}$ and $P_{out}$ are the input and output power of magnetic coupler.

The input and output power equations can be derived based on circuit principle.

$$P_{in} = \left| I_p \right|^2 \frac{1}{j\omega C_p} + j\omega L_p r_p + R_{ref}$$  \hspace{1cm} (1)

$$P_{out} = \left| I_s \right|^2 + R_{ac}$$  \hspace{1cm} (2)

![Figure.2 Mutual inductance equivalent model:](image2)

(a) Primary equivalent circuit (b) Secondary equivalent circuit

Where, $I_p$ and $I_s$ are respectively the current phasors of primary and secondary coils in magnetic coupler. $\omega = 2\pi f_c$ is the angle frequency and $f_c$ is the operation frequency which is also the resonant frequency of the magnetic coupler. $R_{ref} = (\omega M)^2/(1/j\omega MC_s + j\omega L_s + r_s + R_{ac})$ represents the equal impedance of magnetic coupler secondary side at primary side.

Then the mutual inductance model of magnetic coupler can be obtained as follow.

$$\left| I_s \right| = \frac{1}{j\omega C_s} \frac{\left| I_p \right|}{j\omega L_p + r_s + R_{ac}}$$  \hspace{1cm} (3)

Combine equations (1), (2) and (3). The energy transfer efficiency of magnetic coupler can be rewritten as follows.
3. Design of magnetic coupler

In order to meet the requirements of system, the parameters of magnetic coupler are usually achieved by combining the simulation and calculation.

The design process is shown in Fig. 3. Firstly, calculate the system parameters based on theoretical analysis. The self-inductance and mutual inductance are designed based on the system requirements. Then build a simulation model using the calculated parameters and modify the parameters based on the engineering experience. Moreover, the parameters are verified and modified based on the simulation results. Finally, the optimized parameters are achieved.

3.1. Parameter calculation

In order to simplify the analysis, the inner resistors of magnetic coupler primary and secondary coils are ignored and \( L_p = L_s = L \). Then the delivered power from source to load can be derived as follow.

\[
\eta = \frac{1}{\frac{r_p}{R_{ac}} \left( \frac{r_p + R_{RL}}{\omega M} \right)^2 + \left( 1 + \frac{r_s}{R_{ac}} \right)}
\]

(4)

\[
P_{in} = \frac{(oM)_p}{Z_c} R_{ac} = \left( \frac{\omega M L_{ac}}{R_{ac}} \right) = V_{oc} I_{in} Q_{RL} = \frac{\omega M I_p^2}{L} Q_{RL} = k Q_{RL} (oM) I_p^2
\]

(5)

Where, \( Q_{RL} = L/R_{ac} \). \( V_{oc} \) is the open voltage of magnetic coupler secondary coil. \( I_{in} \) is the short current of magnetic coupler secondary coil. \( k \) is coupling coefficient of magnetic coupler, which is \( k = M/(L_{ac})^{0.5} = M/L \).

Roman Bosshard simplified the output power equation in [19], which thought \( k Q_{RL} = 1 \) when the load is matched for optimal efficiency at secondary system. Thus the simplified power equation can be obtained as follow.

\[
P = k Q_{RL} (oM) I_p^2 = (oM) I_p^2
\]

(6)

And

\[
P = k Q_{RL} (oM) I_p^2 = k Q_{RL} \left( \frac{k}{R_{ac}} \right) R_{ac} I_p^2 = (k Q_{RL})^2 R_{ac} I_p^2 = R_{ac} I_p^2
\]

(7)

Then the calculation results can be verified by the simulation results.

3.2. Simulation results

As shown in Fig. 4, the outer diameter is set as 20cm and inner diameter is set as 8cm to reduce the coil area. The inductance of the coil can be estimated based on the design experience. The coil inductance equation can be derived as follow.
\[ L = \frac{\mu_0 N^2 d \psi}{8\pi} \quad (8) \]

Where, \( d = (d_{in} + d_{out})/2 \) which is the average value of inner and outer diameter. When the coil inner diameter is small, the follow equation can be achieved.

\[
\psi = \frac{(1+\rho)^3}{\rho^2} \left[ 1.7424 + 3.29\gamma^5 \ln \gamma - 2.27\gamma^3 + 0.3702\gamma^5 + 0.0826\gamma^7 + 0.0312\gamma^9 \right]
\]

\[ (9) \]

Where, \( \rho = r/d \) is the ratio between the radial direction and average diameter, and \( \gamma=(1-\rho)/(1+\rho) \).

The above calculation results are achieved based on the assumption that the coil is close winding, which is hard to be realized. Thus, the calculation results are usually larger than the real value. Then the parameters should be modified by the simulation. A 7kW magnetic coupler is designed in this paper. Based on the analysis in section 3.1, \( kQ_{RL} \) is set to 1 to achieve the optimal matched load. Then the coil turns and coil spacing are modified based on the simulation results achieving the optimal parameters.

The WPT system in this paper is designed with the operation frequency near 85 kHz, the output power about 7kW and the rated output voltage at 400V. The coupling coefficient is set to 0.18 in this system and the DC/DC converter is ignored. Then the equal resistor is achieved.

\[ R_e = \frac{U^2}{P} = \frac{8}{\pi} \left( \frac{400^2}{7000} \right) \times \frac{8}{\pi} \Omega = 18.53\Omega \quad (10) \]

Combine equation (8), (9) and (12), the currents can be derived. \( I_p = 19.44A \) and \( \omega M = 18.53 \).

Then the self-inductance of primary and secondary coil can be achieved: \( L_p = L_q = L = 192.75\mu H \). Based on the design principle in section 2.2, the design parameters of the magnetic coupler can be obtained as shown in Table 1 (the next page). The simulation results are expressed in Fig. 5 (the next page).

The calculated current is achieved under the condition of \( k=0.18 \). When the coefficient \( k \) is small, the current should be increased to maintain the secondary voltage. When \( k=0.09 \), the primary current is maximum and \( I_p = 19.44 \times 0.18/0.09 = 38.88A \). Thus, the wire diameter is designed based on the maximum current of 38.88A. The current density is limited to \( J=6A/mm^2 \). Then the required cross-sections of the wire can be derived.

\[ S = \frac{I}{J} = \frac{38.88A}{6A/mm^2} = 6.48mm^2 \quad (11) \]

The Litz wires of 0.1mm \( \times \) 1500 are chosen. The cross-sections are given as follow.

\[ S = \pi (d_{nom}/2)^2 \times 1500 = \pi \times (0.1/2)^2 \times 1500 = 11.78mm^2 > 6.44mm^2 \quad (12) \]

Therefore, the design parameters can meet the requirements of the system.

| Table 1 | The design parameters for simulation |
|---------|------------------------------------|
| Outer diameter (mm) | 200 |
| Inner diameter (mm) | 80 |
| Turns | 27 |
| Wire diameter (mm) | 0.1mmx1500 |
| Coil spacing (mm) | 0.8 |
| Distance (mm) | 150 |
| Self-inductance (\( \mu H \)) | 197.00 |
| Mutual-inductance (\( \mu H \)) | 35.12 |
| Coupling Coefficient | 0.18 |
4. Shield of magnetic coupler

The shield of the magnetic coupler is very important for the WPT system, which should achieve perfect shielding performance and reduce the transfer power loss. As shown in Fig. 6, several shield methods are expressed [20]. This section will give the simulation results of these four shielding method.

Table 2 The simulation parameters for magnetic shielding

| Parameter          | Aluminum plate shielding | Value | Parameter          | Aluminum ring shielding | Value |
|--------------------|--------------------------|-------|--------------------|--------------------------|-------|
| Outer diameter/mm  |                          | 200   | Outer diameter/mm  |                          | 200   |
| Inner diameter/mm  |                          | 80    | Inner diameter/mm  |                          | 80    |
| Turns N            |                          | 27    | Turns N            |                          | 27    |
| Thickness /mm      |                          | 1     | Thickness /mm      |                          | 1     |
| Distance /mm       |                          | 5     | Distance /mm       |                          | 5     |
| Radius /mm         |                          | 230   | Radius /mm         |                          | 230   |
| Current /A         |                          | 20    | Current /A         |                          | 20    |

| Parameter                        | Litz ring shielding | Value | Parameter                        | Litz reverse shielding | Value |
|----------------------------------|--------------------|-------|----------------------------------|------------------------|-------|
| Outer diameter/mm                | 200                |       | Outer diameter/mm                | 200                    |       |
| Inner diameter/mm                | 80                 |       | Inner diameter/mm                | 80                     |       |
| Turns                            | 27                 |       | Turns                            | 27                     |       |
| Distance /mm                     | 10                 |       | Distance /mm                     | 10                     |       |
| Shielding turns                  | 4                  |       | Shielding turns                  | 4                      |       |
| Equal shielding current /A       | -20                |       | Equal shielding current /A       | -20                    |       |
| Current /A                       | 20                 |       | Current /A                       | 20                     |       |

4.1. Simulation results of shield

ICNIRP, IEEE, IEC et. al all give the standards of electromagnetic radiation, especially for EMC and EMI of equipment. In 2010, ICNIRP give the radiation standards, which rule that under the condition of variable electric field and magnetic field with operation frequency of 3 kHz ~ 10MHz[21], the electric field intensity should be smaller than 0.083kV/m and magnetic field intensity should be smaller than 21A/m, magnetic flux density should be smaller than 27μT. Then the simulation results of the four shield methods are given as follows.

The simulation parameters are given in Table 2. Based on the above design parameters, the shielding performances are given in Fig. 7. The aluminium plate shielding has the best shielding performance.
4.2. Comparison of shielding performance

4.2.1 Comparison of stray magnetic field at side face. As shown in Fig. 8 (the next page), the stray magnetic field varying with the offset value of four shielding methods are given.

From the figure, the aluminium plate shielding method has the best shielding performance. The magnetic flux density falls to 27μT when the distance is 300mm. The other three shielding methods have similar shielding performances, magnetic flux density of which fall to 27μT when the distance is 400mm.

4.2.2 Comparison of magnetic flux. As shown in Fig. 9, the magnetic flux density varying with the offset value of four shielding methods are given. From the figure, the aluminium plate shielding method has the best shielding performance. The stray magnetic field is almost zero beyond the aluminium plate. Litz ring shielding method has the worst performance.

4.2.3 Comparison of magnetic field. As shown in Fig. 10 and Fig. 11, the magnetic field above and below coil 50mm varying with the offset value of four shielding methods are given. From the figures, the four shielding methods have similar shielding performances, only the peak values are different.

In conclusion, the aluminium plate has the best shielding performances and other shielding methods can’t meet the requirements of the system. Thus the aluminium plate shielding can be used in WPT system.
4.3. Comparison of marginal stray magnetic flux density

In 2015, IEC gave the standards of EMF[22]. As shown in Fig. 12, the standard requires to record the measurements when the maximum appeal position beyond 10s.

Then the stray magnetic flux density in section 4.2 are discussed. Due to the limitation of the sample data in the simulation, we only analyse the shielding performance with the distance of 300mm.

4.3.1 Comparison of stray magnetic field at side face. As shown in Fig. 13, the stray magnetic flux density at side face with shield is reduced to 100μT meeting the requirement of ICNIRP. The aluminium plate shielding has the best performance and Litz reverse shielding method performance is worst.

4.3.2 Comparison of stray magnetic field with 50mm below and above coil. As shown in Fig. 14, the aluminium plate shielding has best performance. In conclusion, the four shielding methods all can meet the requirements of ICNIRP. Considering the influences on self-inductance and mutual inductance of primary and secondary magnetic coupler and efficiency of different shielding methods, the four methods can be combined to achieve the best shielding performance.
5. Conclusion
This paper analyzes the circuit of magnetic coupler in WPT system achieving the key factors of transfer efficiency. Then the design process of the coupling coils is expressed. Finally, four shielding methods are simulated achieving the shielding performance of each method, which can guide the magnetic coupler design in WPT system.

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