IOP Conf. Series: Earth and Environmental Science **40** (2016) 012010 doi:10.1088/1755-1315/40/1/012010

Optimization of unipolar magnetic couplers for EV wireless power chargers

H Zeng[1, 2], Z Z Liu[1], H X Chen[1], B Zhou[1] and T Hei[1]

[1]School of Electrical Engineering, Shandong University, Jinan, 250061, China

E-mail: zenghaohust@163.com

Abstract. In order to improve the coupling coefficient of EV wireless power chargers, it's important to optimize the magnetic couplers. To improve the coupling coefficient, the relationship between coupling coefficient and efficiency is derived, and the expression of coupling coefficient based on magnetic circuit is deduced, which provide the basis for optimizing the couplers. By 3D FEM simulation, the optimal core structure and coils are designed for unipolar circular couplers. Experiments are designed to verify the correctness of the optimization results, and compared with previous coupler, the transmission efficiency is improved and weight is reduced.

1. Introduction

EV (Electric vehicle, EV) wireless charging (shown in figure 1) is an emerging technology in recent years. Compared to wired charging system, wireless charging technology can reduce aboveground space, apply to the harsh environment and have no risk of touch spark [1, 2]. Besides, it is expected to be used for mobile power supply for solving the problem that battery energy density is hard to be improved. Therefore, the research and application of wireless charging technology has been getting more and more attention. Generally, EV chargers are required to equip high transfer efficiency and high power output capability, but output power and efficiency is the key factor restricting the development of wireless charging technology.

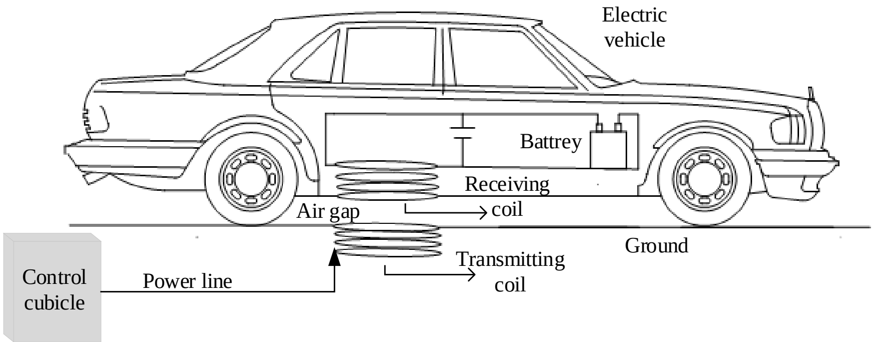


Figure 1. EV wireless charging diagram

[2] Address for correspondence: H Zeng, School of Electrical Engineering, Shandong University, Jinan, 250061, China. E-mail: zenghaohust@163.com.

To improve the efficiency and output power of wireless chargers, the design of magnetic couplers play a key role. In EV wireless charging systems, the air gap (shown in figure 1) between transmitting and receiving coils always changes from 150mm to 250mm. In this situation, leakage inductances of the coils are much larger than the mutual inductance, resulting that coupling coefficient is very small, which is always lower than 0.2. To improve the output power and efficiency, the key is to improve the coupling coefficient of loosely coupled coils.

At present, one of the common way to improve the coupling coefficient is changing the structure of coil, another is add more magnetic cores, and there are many papers have done some relevant research in designing the magnetic coupler. On the basis of assurance on the coupling coefficient, paper [3] optimized the core structure by finite element analysis and experiments, reducing the weight of the magnetic couplers. Paper [4] explored the impact of the number of cores on the coupling coefficient for DD (Double-D, DD) coils and unipolar coils, aiming at finding the maximum coupling coefficient. Paper [5] proposed a form of DLDD (Double Layer Double D-type, DLDD) coil structure, improving the transmission distance and the scope of the charge. But the above papers did not construct a theory to illustrate the number and the shape of magnetic cores how to influence coupling coefficient, so they always lack of direction of optimization. Besides, the above papers designed transmitting and receiving coils in same size, but in practice receiving coil is generally small.

Unipolar magnetic coupler is studied in this paper, which is one of the most popular couplers at present. Firstly, the paper establish relevant theoretical models of electric and magnetic circuits, providing the guidance for the design of the core structure of unipolar coils. Secondly, in order to achieve the desired maximum coupling coefficient with minimal use of materials, the core structure is designed and optimized by 3D finite element simulation. Finally, experiments are designed to verify the theoretical and simulation results. All the receiving coil in this paper is smaller than the transmitting coil.

2. Analysis of electric and magnetic circuits

Analysis of electric circuit is more common than magnetic circuits' analysis. Therefore, in this section a brief explanation is given about circuit analysis, but giving a more detailed description of the magnetic circuit analysis.

2.1. Circuit analysis

In EV wireless charging systems, depending on the connection type of capacitances and coils, resulting in four compensation ways, which are SS, SP, PS and PP. Figure 2 shows an equivalent circuit diagram of SS topology. Studies have shown that, circuit using SS topology may be equivalent to a voltage source to external circuit, and easy to achieve a large output power in a smaller coupling coefficient [6], which is more suitable for wireless charging of EV. This is why the paper selects SS topology as an object of study for EV wireless charging.

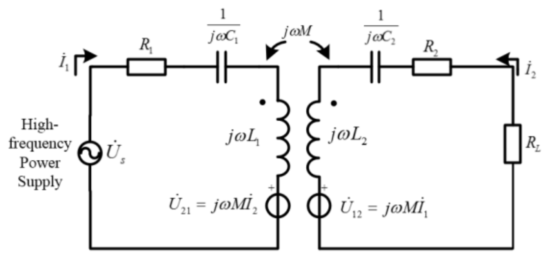


Figure 2. An equivalent circuit diagram of SS topology

From analysis of the circuit, the output power P_{out} can be derived as

$$P_{out} = I_2^2 R_L = \left(\frac{\omega M I_1}{R_2 + R_L} \right)^2 R_L \tag{1}$$

If coupling coefficient is represented by k, equation (1) can be written in another form:

$$P_{out} = \left(\frac{\omega k \sqrt{L_1 L_2} I_1}{R_2 + R_L} \right)^2 R_L \tag{2}$$

From the equation (1), we can get to a conclusion: in the condition that the primary current I_1 is constant, the output power is being large as the coupling coefficient increases.

The input power can be derived as

$$P_{in} = I_1^2 R_1 + I_2^2 (R_2 + R_L) \tag{3}$$

If the quality factors of transmitting and receiving coils are represented by Q_1 and Q_2, where

$$Q_1 = \frac{\omega L_1}{R_1}, Q_2 = \frac{\omega L_2}{R_2} \tag{4}$$

Then, the transmission efficiency η can be derived as

$$\eta = \frac{P_{out}}{P_{in}} = \frac{R_L}{\frac{(R_2 + R_L)^2}{k^2 Q_1 Q_2 R_2} + R_2 + R_L} \tag{5}$$

Equation (5) illustrates that in the case of the transmitting and receiving coils are determined, the transmission efficiency is only related with the coupling coefficient, and the bigger coupling coefficient, the higher the efficiency.

2.2. Magnetic circuit analysis

The magnetic circuit is path that flux go through. Because there is a big gap between the two coils, which are loosely coupled, so the flux path between the two coils can be basically divided into two parts: the first is the flux in magnetic cores near the coils, the second is that in the air gap. Analysis of magnetic circuits of the EV wireless charging systems can reduce flux path's reluctance in a clear direction, which plays a guiding role in optimization of coils and core.

Currently the unipolar magnetic couplers have many kind of shapes, like circular coils, rectangular coils and rectangular coils with rounded corners. But the magnetic field distribution of these couplers is approximately the same, in condition that in one coupler transmitting and receiving coils have only one coil respectively.

The paper below chooses a circular coil coupler with plate cores as an illustration, which is shown in figure 3, then establishes the model of equivalent magnetic circuit and derives the expression of coupling coefficient. Thus, according to the flux path and the expression of coupling coefficient, we can conclude the method that makes the coupling coefficient be larger.

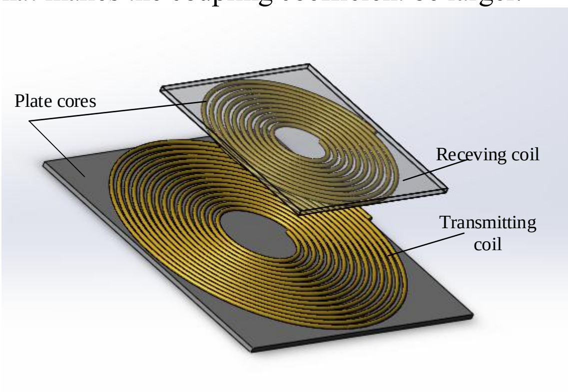


Figure 3. Structure diagram of circular coil coupler with plate cores

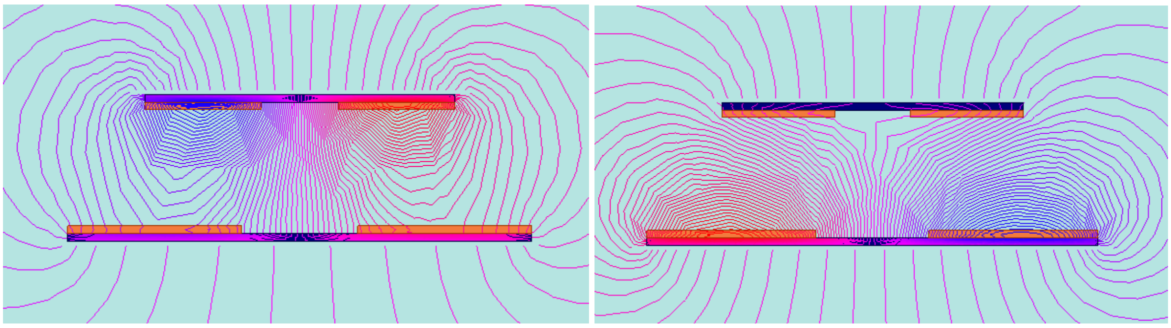


Figure 4. The magnetic field distribution at different times

Figure 4 shows the magnetic field of distribution of a circular coil coupler with plate cores at different times in a cross section. From the two pictures above, the magnetic field distribution of this type of couplers is very clear. Thus, a magnetic partition model is come up with and shown in figure 5.

From figure 5, the magnetic circuit can be deduced by expressing the mutual coupling areas' reluctance with R_m and expressing the self-coupling areas' reluctance with R_s, which is shown in figure 6.

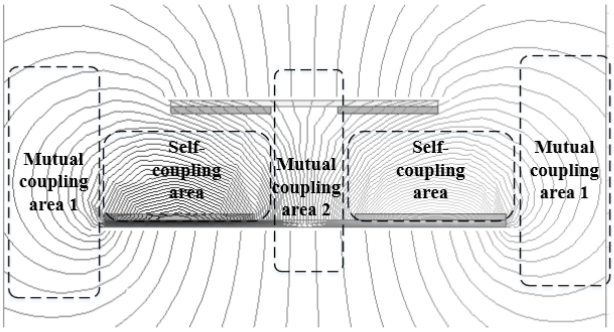


Figure 5. The approximate distribution of self-coupling areas and mutual coupling areas

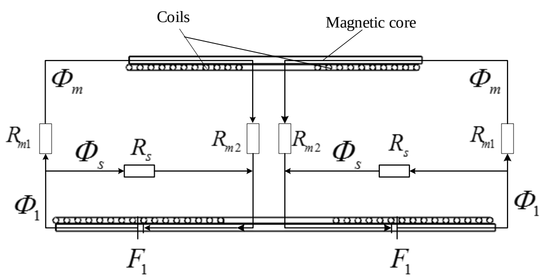


Figure 6. The equivalent magnetic circuit

From figure 3, 4 and 5, the circular coil coupler with plate cores is axial symmetry, so in a cross section its magnetic field distribution should be bilateral symmetry. Because of which that in figure 5 and 6, magnetic partition and equivalent magnetic circuit are modelled bilateral symmetry. In figure 5 and 6, R_{m1} represents the reluctance of mutual coupling area 1, and R_{m2} represents the reluctance of mutual coupling area 2. In figure 6, F_1 represents the MMF (Magnetomotive force, MMF), and Φ_s represents magnetic flux that is self-coupling, and Φ_m represents flux that is mutual coupling. Then, from the equivalent magnetic circuit, we can get

$$\Phi_1 = \Phi_s + \Phi_m \tag{6}$$

Φ_1 is the total flux of one side. Thus, the coupling coefficient can be express as

$$k = \frac{\Phi_m}{\Phi_1} = \frac{R_s // (R_{m1} + R_{m2})}{R_{m1} + R_{m2}} = \frac{1}{1 + \frac{R_{m1} + R_{m2}}{R_s}} \tag{7}$$

From equation (7), the method to increase k is to reduce the R_s and magnify ($R_{m1} + R_{m2}$). Then, according to figure 5 and 6, we can change parameters of coils and cores in the direction above-mentioned to increase k.

3. Optimization and simulation of circular coil coupler

3.1. Optimization of magnetic cores

At present the most widely used core structures for circular coil is the plate cores (shown in figure 3) or strip cores which are radial under the coils (shown in figure 7(a)). But the question is we don't know how many strip cores should be used, so firstly using plate cores as a reference, then designing the core structures of the circular coils.

Parameters of the transmitting and receiving coils used in this section are shown in table 1:

Table 1. Coil and core parameters of unipolar circular couplers

	Outer diameter(mm)	Inside diameter(mm)	The thickness of the magnetic cores(mm)	The thickness of the coils(mm)
Transmitting coils	600	200	10	6
Receiving coils	400	150	10	6

Besides, the gap between transmitting and receiving coils is 200mm, and the width of strip cores is 20mm.

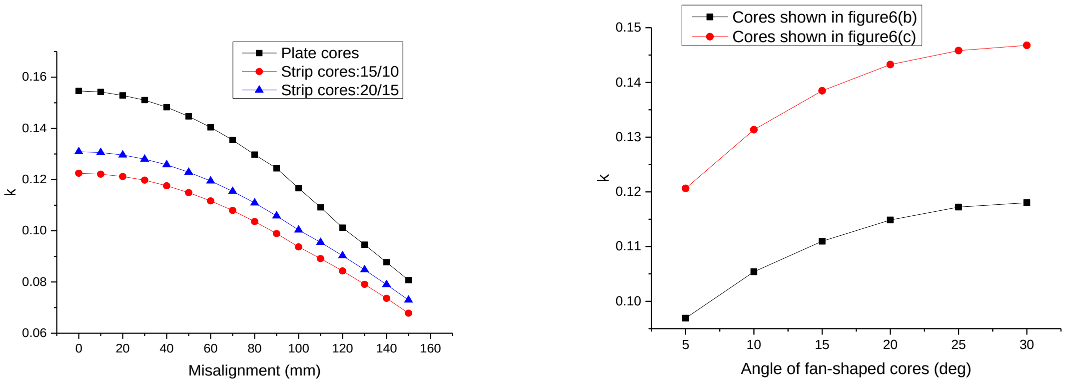
3.1.1 Optimization of the number of cores.

At first, three different kind of cores with the same coils are simulated, which are coils with plate cores, coils with less strip cores (15/10, 15/10 means there are 15 strip cores under the transmitting coils and 10 strip cores on the receiving coils, the same below), and coils with more strip cores (20/15), and recording each coupling coefficient between the two coils when the receiving coil is misaligned from the transmitting coil by 10mm every time.

(a) Coils with strip cores (b) Coils with fan-shaped cores (c) Coils with long fan-shaped cores

Figure 7. Three shapes of cores

Then three different curves about coupling coefficient can be sketched, which are shown in figure 8(a).



(a) Coupling coefficient with different number of strip cores

(b) Coupling coefficient with different angle of fan-shaped cores

Figure 8. The variation tendency of coupling coefficient with different cores

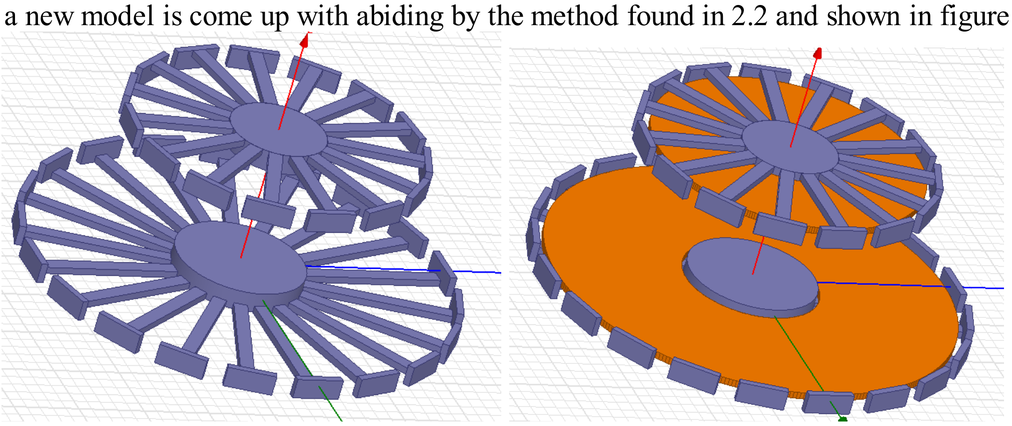
From figure 8(a), the number of strip cores has a great influence in coupling coefficient. Thus, models shown in figure 7(b) and figure 7(c) are used to study the impact. Model shown in figure 7(b) adopts 12 fan-shaped cores which are equivalent to strip cores, by the reason that it is convenience in simulation. In FEM simulation, coupling coefficient is calculated every 5 °extension of the fan-shaped cores, then the curves shown in figure 8(b) is obtained.

From figure 8(b), the slope of the curve is slowing as the angle of fan-shaped cores increases, almost unchanged from 25 degree to 30 degree. This means, it is unnecessary to cover the coils with a whole core, and the equivalent area of the core is suitable that designed to cover two-thirds of the area of the coil.

3.1.2 Optimization of the position of cores.

From figure 8(b), not only can we find the regulations of how many cores should be placed, but also we can notice that coupling coefficient of coils with long fan-shaped cores(shown in figure 7(b)) is much larger than coils with short fan-shaped cores(shown in figure 7(c)). It means that the extension of the core will significantly increase coupling coefficient. This is because, as shown in figure 5, extended core reduces the reluctance of mutual coupling area 1, and appropriately increase the reluctance of the self-coupling area, thereby increasing the coupling coefficient.

Thus, a new model is come up with abiding by the method found in 2.2 and shown in figure 9.



(a) A new model of the cores

(b) The model in application

Figure 9. A kind of new model of the cores

From figure 9, many short but high strip cores are placed around the coils, and a cylindrical core is placed in the hole of the coil. From figure 5, the short strip cores and the cylindrical cores greatly reduce the reluctance of mutual coupling area, and the coupling coefficient is shown in figure 10.

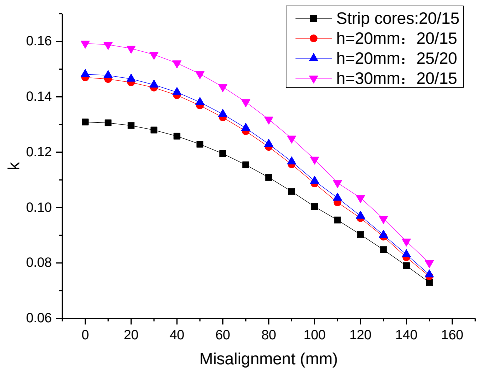
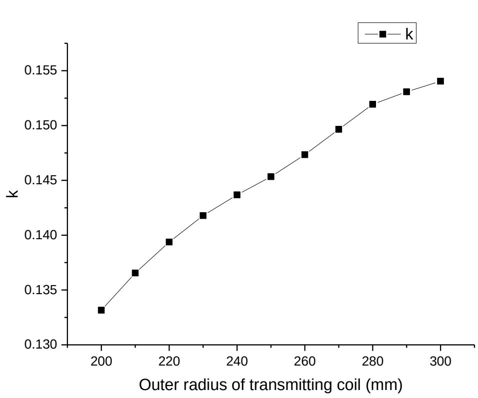


Figure 10. Comparison of coupling coefficient with different cores

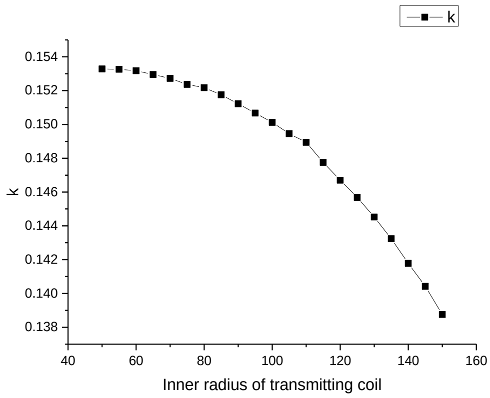
In figure 10, “h=20mm” means the height of short strip cores and cylindrical cores is 20mm. Figure 10 compares the coupling coefficient in case of several cores, changing the number of long strip cores and thickness of short strip cores and cylindrical cores respectively, then the conclusion is that the factor that influence the coupling coefficient is mainly the height of the short strip cores and cylindrical cores, while the number of the long strip cores' influence is not obvious.

Thus, to improve the coupling coefficient, it is necessary to follow the rules that increasing reluctance of the self-coupling area and reducing the reluctance of the self-coupling area, and it is effective to make the strip cores' length is longer than the width of the coil, and to place short strip cores and cylindrical cores in the position which is shown in figure 9.

3.2. Optimization of coils



(a)The change of coupling coefficient by changing of transmitting coil's outer radius



(b) The change of coupling coefficient by changing of transmitting coil's inner radius

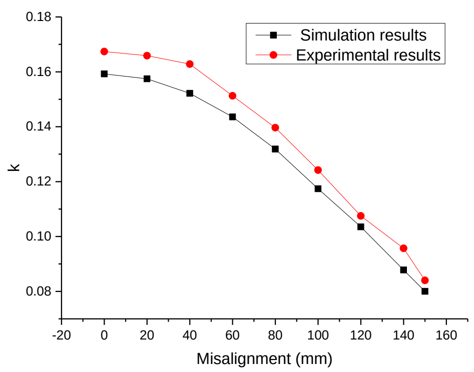
Figure 11. The change of coupling coefficient in different situation

From figure 11, the conclusion is that if the transmitting coil inner diameter remains unchanged, the larger the outer diameter of the transmitting coil, the greater the coupling coefficient; and if the transmitting coil's outer diameter remains unchanged, the larger the inner diameter of the transmitter coil, the coupling coefficient is smaller. The conclusion can be also explained by the figure 5 and 6 and equation (7), which is that the larger the outer diameter of the transmitting coil, the bigger R_s is, so the coupling coefficient is larger; and the larger the inner diameter of the transmitter coil, the smaller R_s is, so the coupling coefficient is smaller. The conclusion is suitable for the receiving coil.

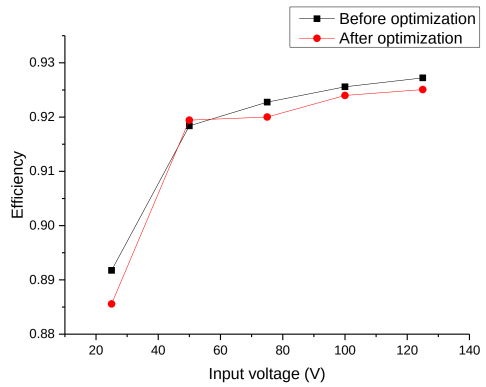
Thus, the bigger the better transmit coil if it is feasible; and the inner diameter of the transmitting coil should be appropriately reduced.

4. Experiment

Based on the above simulation, at first coils are wrapped and cores are placed to test the correctness of the simulation results.



(a) Results comparison of simulation and experiment



(b) Efficiency comparison before and after optimization

Figure 12. Experimental data

From figure 12 (a), the experimental coupling coefficient of the structure shown in figure 9 fits the simulation results. Then, a compare experiment is designed and using the couplers before and after optimization respectively. Parameters of the couplers is shown in table 1, and core structures are plate cores and structure shown in figure 9. And before the experiment, the coupling coefficient of coupler that before optimization is 0.167, and the coupling coefficient of coupler that after optimization is 0.163.

The efficiency in figure 12 (b) refers to DC-in to DC-out. From figure 12(b), the efficiency curves of before and after optimization are basically the same, which proves the availability of structural optimization.

And the transmitting and receiving coil are packaged by aluminium case, which can be used for magnetic field shielding, and assembled on an EV whose model is Cloud 100 manufactured by ZOTYE AUTO. The optimized couplers performed as well as the primary coils, but the weight of the optimized couplers is much lighter than the primary couplers.

Figure 13. Transmitting and receiving coil assembled on an EV in experiments

5. Conclusion

In order to improve the efficiency and output power of EV wireless power chargers, the coupling coefficient needs to be large. In this paper, the unipolar magnetic couplers for EV wireless charging has been optimized. From the circuit of SS topology, the equations of output power and transmission efficiency is derived, illustrating the importance of the coupling coefficient; by means of 2D and 3D FEM simulation, the magnetic circuit of circular unipolar coupler is determined; then, the coupling coefficient's expression based on magnetic circuit is obtained. According to the theory, the parameters that influence the coupling coefficient has been researched and a new kind of core structure has been designed for circular unipolar couplers. Compared to the original couplers, the weight of the optimized couplers is reduced and the coupling coefficient is increased. Finally, the simulation results is verified by the experiment, and the practicability of the optimized coupler has been proved by the efficiency experiment.

References

[1] Mohrehkesh S and Nadeem T 2011 Toward a wireless charging for battery electric vehicles at traffic intersections *2011 14th International IEEE Conference on Intelligent Transportation Systems (Itsc)* 113-8
[2] Zhong W X, Xun L and Hui S Y R 2011 A novel single-layer winding array and receiver coil structure for contactless battery charging systems with free-positioning and localized charging features *IEEE Trans. Ind. Electron* **58** 4136–44
[3] Budhia M, Covic G A and Boys J T 2011 Design and optimization of circular magnetic structures for lumped inductive power transfer systems *IEEE Trans. Power Electron* **26** 3096–108
[4] Zhang W, White J C, Abraham A M and Mi C C 2015 Loosely coupled transformer structure and interoperability study for EV wireless charging systems *IEEE Trans. Power Electron* **30** 6356–8
[5] Wang Z H, Hu C, Sun Y and Dai X 2015 Design of magnetic coupler for inductive power transfer system based on output power and efficiency *Transactions of China Electrotechnical Society* **30** 29-30
[6] Li S Q and Mi C C 2015 Wireless power transfer for electric vehicle applications *IEEE J. Emerging and Selected Topics in Power Electronics* 3 10–1