Study on High Efficient Electric Vehicle Wireless Charging System

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Abstract. Electric and unmanned is a new trend in the development of automobile, cable charging pile can not meet the demand of unmanned electric vehicle. Wireless charging system for electric vehicle has a high level of automation, which can be realized by unmanned operation, and the wireless charging technology has been paid more and more attention. This paper first analyses the differences in S-S (series-series) and S-P (series-parallel) type resonant wireless power supply system, combined with the load characteristics of electric vehicle, S-S type resonant structure was used in this system. This paper analyses the coupling coefficient of several common coil structure changes with the moving distance of Maxwell Ansys software, the performance of disc type coil structure is better. Then the simulation model is established by Simulink toolbox in Matlab, to analyse the power and efficiency characteristics of the whole system. Finally, the experiment platform is set up to verify the feasibility of the whole system and optimize the system. Based on the theoretical and simulation analysis, the higher charging efficiency is obtained by optimizing the magnetic coupling mechanism.

1. Introduction
At present, China's car ownership exceeded the 163million, ranking second in the world. In recent years, a wide range of concerns about the issue of haze have a greater relationship with car exhaust emissions, promotion of pure electric vehicles is an effective way to alleviate the shortage of energy and environmental pollution. Limited by the capacity of the battery, the current driving range of electric vehicles is relatively short, the construction of battery charging station has become the biggest bottleneck restricting the application and development of electric vehicles [1]. Wireless charging technology allows the moving car to achieve charging, can significantly reduce the requirements of EV battery energy density, and helps to promote the large-scale application of pure electric vehicles. Wireless charging technology has low charging efficiency [2-4], which restricts the development of wireless charging technology, it also brings a great challenge for the adaptation of the electric vehicle manufacturers.

2. Theoretical analysis
The wireless power supply technology is mainly divided into three types: RF or microwave wireless power supply technology, electromagnetic induction type wireless power supply technology and...
electromagnetic resonant wireless power supply technology. Microwave power transmission is a kind of far field radiation energy transmission mode, because of its low transmission efficiency, and harmful to the human body, so it is not suitable for the electric vehicle wireless charging system [5]. Due to the short transmission distance of electromagnetic induction type wireless power supply technology, so its application in the electric vehicle wireless charging is still relatively small, but electromagnetic induction type wireless power supply technology has a high efficiency, in the field of wireless charging electric vehicles have good prospects [5,6]. Electromagnetic resonance wireless power supply technology has the advantages of long transmission distance and high coupling coefficient, at present, this technology is widely used in the field of electric vehicle wireless charging.

Electromagnetic resonance wireless power supply system has two basic coil structures, namely, two coil structure and four coil structure. Two coil structure is the most convenient way to realize electromagnetic resonance wireless power supply, the four coil structure is based on the 2 resonant coils, and the 2 induction coils are added, so that the power supply is isolated from the transmitting coil, and the load is isolated from the receiving coil [7-9]. This paper takes the two coil electromagnetic resonance wireless power supply system as an example to analyze.

2.1. Circuit structure selection

Electromagnetic resonant wireless power supply system has four common topology structure [11], namely: transmitting coil series resonant, receiving coil series resonant(S-S); transmitting coil series resonant, receiving coil parallel resonant(S-P); transmitting coil parallel resonant, receiving coil series resonant(P-S); transmitting coil parallel resonant, receiving coil parallel resonance(P-P) [12-13]. Each resonant structure is shown in figure 1.

![Circuit Structures](image)

**Figure 1.** Four resonant structures

The advantages and disadvantages of four kinds of resonance structures are summarized in the literature [14], according to the load characteristics of electric vehicle, we are using more S-S and S-P type resonant structure. The formula of the power and efficiency of the S-S and S-P resonant structures is derived in the literature [15].

S-S type resonant structure:

\[
P_{ss} = \frac{(\omega M)^2 R_L}{[\tau_1 R_L^2 + \tau_2^2 + (\omega M)^2]^2} U^2
\]

\[
\eta_{ss} = \frac{(\omega M)^2}{\tau_1 (\tau_2 + R_L) + (\omega M)^2} \frac{R_L}{\tau_2 + R_L}
\]

S-P type resonant structure:
The relationship between the coupling coefficient \( K \) and the mutual inductance value \( M \):

\[
P_{tr} = \frac{(\omega M)^2 R_L}{[(1 + j\omega R_L C_2)((\omega M)^2 + \eta_1^2) + j\omega L_2 \eta_1]^2} U^2 \tag{3}
\]

\[
\eta_{tr} = \frac{(\omega M)^2 R_L}{(1 + j\omega R_L C_2)((\omega M)^2 + \eta_2^2) + j\omega L_2 \eta_2} \times \frac{1}{\sqrt{\eta_1^2 + \eta_2^2 + j\omega R_L R_1 C_2}} \tag{4}
\]

The relationship between the coupling coefficient \( K \) and the mutual inductance value \( M \):

\[
M = k \sqrt{L_1 L_2} \tag{5}
\]

In the above formula, \( M \) indicates the mutual inductance between the transmitting coil and the receiving coil, \( R_L \) indicates the load resistance, \( \eta_1 \) and \( \eta_2 \) indicates the resistance value of the transmitting and receiving coils, \( L_1 \) and \( L_2 \) indicates inductance value of transmitting coil and receiving coil, \( C_1 \) and \( C_2 \) indicates resonant capacitor at transmitter and receiver. According to the equation (2) and the equation (4), using Matlab to draw the curve of the S-S and the S-P type resonant structure system efficiency with the change of the equivalent load is shown in figure 2.

**Figure 2.** The relationship between system efficiency and equivalent load

From figure 2, when equivalent load resistance is small, the efficiency of S-S type resonant structures is higher than that of the S-P type resonant structures, when equivalent load resistance is large, the efficiency of S-S type resonant structures is lower than that of the S-P type resonant structures. The voltage of the electric vehicle in this system is 74V, if the charging power is 3Kw, the equivalent load is less than 1 ohm, S-S type resonant structure has a high system efficiency.

According to the power equation and efficiency equation of the S-S type resonant structure and the relationship between the coupling coefficient and the mutual inductance, the curve of the system efficiency and the coupling coefficient and the relationship between the transmission power and the coupling coefficient can be drawn. As shown in figure 3.

According to the curve in figure 3 shows: with the increase of coupling coefficient, the system efficiency first increased rapidly, and then gradually stabilized at around 93%, transmission power of the system is the first sharp increase, after a sharp decrease, the peak appears in the coupling coefficient of about 0.5. The system efficiency and transmission power should be considered when match the coupling coefficient between the receiving and transmitting coils. According to the curve shown in Figure 3, when the coupling coefficient is 0.15, the system efficiency is more than 91%, and the system transmission power is more than 7Kw. The system is suitable for high power electric vehicle wireless charging.
2.2. Optimization of coil structure

The design of coil structure is one of the key points of the design of wireless charging system for electric vehicle [16-17]. A good coil structure should have the characteristics of high level of freedom, moderate coupling coefficient, moderate distance between receiving and transmitting coils, less leakage, and no heating of the coil. At present, most of the research institutions in China and abroad on the coil part of the research are mostly the same as the literature [18], Tending to have a higher coupling coefficient structure in order to obtain a higher system efficiency. But in practical application, different coupling coefficients should be chosen according to different working conditions. Use Ansys Maxwell software to model the common coil structure as shown in figure 4.

In figure 4, the black section represents the core of ferrite material, the yellow part represents the power coil. The diameter of the disc type transmitting coil is 600mm, and the diameter of the receiving coil is 400mm, the most outer coil diameter of the wheel transmission coil is 600mm, and the coil diameter of the receiving coil is 400mm, DD type transmitting part and the receiving part are two coils, the transmitting coil length was 600mm, the receiving coil length was 400mm. When the car parking, there will be a certain deviation, causing the transmission coil and the receiving coil has a certain distance. In this paper, under the premise of the vertical distance between the transmitter coil and the receiving coil is 200mm, horizontal migration experiment of three kinds of coils is carried out. Due to the asymmetry of the DD coil structure, the horizontal migration experiment of X and Y direction is required for three kinds of coils, the experimental results are shown in figure 5.

Combination of figure 5 and figure 3, in the X direction, the coupling coefficient of the DD type coil structure is maintained between 0.14 and 0.165, and the system efficiency is higher, in the Y
direction, the coupling coefficient of the DD coil structure is maintained between 0.06 and 0.165, system efficiency decreased from 92% to about 70%. In the X (Y) direction, the coupling coefficient of the Disc type coil structure is maintained between 0.095 and 0.155, system efficiency is maintained at more than 85%. In the X (Y) direction, the coupling coefficient of the Wheel type coil structure is maintained between 0.04 and 0.14, system efficiency is gradually reduced to 65%. When the electric vehicle wireless charging, receiving coil and the transmitting coil will inevitably be some offset. Due to the symmetry of the disc structure, the efficiency in each direction of the shift will not be reduced sharply, the system has been in the state of high efficiency, so the disc type is more suitable for the actual electric vehicle wireless charging system.

![Figure 5. (a) X direction](image1)

![Figure 5. (b) Y direction](image2)

**Figure 5.** Relationship between offset distance and coupling coefficient

### 3. System simulation

According to the previous section, the simulation system with S-S resonator, coupling coil-coupling coefficient is set to 0.15, input transceiver coil inductance and resistance values, through the Simulink toolbox to build electric vehicle wireless charging simulation system as shown in figure 6.

![Figure 6. Wireless charging simulation system for electric vehicle](image3)

In order to ensure the system has a good applicability, this simulation system uses single-phase 220V AC power supply as the input power, after power frequency rectifier, DC chopper, and full bridge inverter and then input coupling coil part, the energy is transmitted from the transmitting coil to the receiving coil, after high frequency rectifier to charge the electric vehicle. In the simulation, due to the load characteristics of the battery are greatly changed, simulation using a resistor instead of a
battery has a big difference between the actual situations. Through several experimental results found that the combination of DC source to represent the battery voltage and resistor represents the internal resistance of the battery closer to the battery load characteristics.

The output power of the system can be adjusted by adjusting the output voltage of the DC-DC, the output power and efficiency of the system under different input voltage can be calculated according to the power of the input side and the output side, as shown in figure 7.

According to the simulation curve of output power and efficiency of the system under different input voltage, it can be known that the output power of the electric vehicle wireless charging system can be more than 3Kw, the efficiency of the electric vehicle wireless charging system can be more than 90%, meet the demand of electric vehicle charging system for high power and high efficiency.

![Figure 7. Simulation curve of output power and system efficiency](image)

**4. Experiment and conclusion**

According to the analysis of the above chapters, this system chooses the S-S type resonant structure, and the disk type coil coupling structure to build the experimental system and carries on the loading experiment. The experimental platform is shown in figure 8.

![Figure 8. (a) Battery pack experiment](image)

![Figure 8. (b) Installation experiments](image)

**Figure 8.** Experiment platform
The battery voltage of the experimental vehicle is 74V, the vertical distance between the receiving and transmitting coils is 200mm, and the coupling coefficient K is 0.15. When the receiving coil horizontal offset 0 cm, 5 cm, 10 cm, the experimental results are shown in figure 9.
Due to the limitation of the duty cycle of the DCDC circuit, the maximum input voltage of the experiment is 250V. It can be known from Figure 9 that when horizontal offset 0 cm, the input voltage is 250V, the system efficiency reaches 89%, and the output power exceeds 2200W; when horizontal offset 5 cm, the system efficiency and output power are increased slightly compared to the horizontal offset 0 cm; when horizontal offset 10 cm, the output power is reduced to about 2000W, and the system efficiency is reduced to about 85%. Thus, the electric vehicle wireless charging system designed in this paper can obtain higher system efficiency and output power in a large degree of freedom. The experimental results are very consistent with the simulation results; the system has reached the design requirements. But the input voltage is low and the battery voltage of the experimental car is too low, which results in the low output power of the system, in the following experiments, it is also needed to find a way to get more power and more efficient.

References
[1] Chen Z Z and Wu Z J 2008 Construction of EV charging station Popular Utilization of Electricity 6 34-6
[2] Wang J H et al. 2008 Research on detachable transformer for contactless energy transmission system Transformer 45 26-9
[3] Fernandez C et al. 2008 Overview of different alternatives for the contact-less transmission of energy Proc. the IEEE Annual Conference of the Industrial Electronics Society 1318-23
[4] Wang S, Covic G A and Stielau O H 2004 Power transfer capability and bifurcation phenoemena of loosely coupled inductive power transfer systems IEEE Transactions on Industrial Electronics 51 148-57
[5] Wang Z Y et al. 2014 Advances of wireless charging technology in electric vehicle J. Power Supply 3 27-32
[6] Boys J T, Covic G A and Green A W 2000 Stability and control of inductively coupled power transfer systems IEEE Proc Electrical Power Application 147 37-43
[7] Zhao Z M, Zhang Y M and Chen K N 2013 New progress of magnetically-coupled resonant wireless power transfer technology Proc. the Chinese Society for Electrical Engineering 33
[8] Lu W C et al. 2015 Comparison of Series Series Model and Series Parallel Model of Wireless Power Transmission Via Magnetic Resonance Power Electronics 49 73-5

[9] Kurs A et al. 2017 Wireless power transfer via strongly coupled magnetic resonances Science 317 83-6

[10] Moon S C et al. 2014 Analysis and design of a wireless power transfer system with an intermediate coil for high efficiency IEEE Transactions on Industrial Electronics 61 5861-70

[11] Tan L et al. 2010 Study of wireless power transfer system through strongly coupled resonances International Conference on Electrical and Control Engineering 4275-78

[12] Li Y et al. 2012 Influence factors analysis on power and efficiency in wireless power transfer system Advanced Technology of Electrical Engineering and Energy 31 31-4

[13] Chunbo Z et al. 2008 Simulation and experimental analysis on wireless energy transfer based on magnetic resonances Proc. the Vehicle Power and Propulsion Conf. 1-4

[14] Cheng L M and Cui Y L 2012 Magnetic Coupling Resonant Type Wireless Power Transmission Technology Study Progress Electrotechnics Electric 12 1-5

[15] Ren X F 2014 Desing and Performance Optimization of the Wireless Charging System in Electric Vehicles (Harbin: Harbin Institute of Technology)

[16] Yu C L, Lu R G, Mao Y H, Zhu C 2009 Research on the model of magnetic resonance based wireless energy transfer system Proc. the Vehicle Power and Propulsion Conf. 414-8

[17] Zhang X et al. 2010 The Application of Non-contact Power Transmission Technology (NPT) in the Modern Transport System Proc. the 2010 IEEE International Conf. on Mechatronics and Automation 345-9

[18] Budhia M et al. 2011 Development and evaluation of single sided flux couplers for contactless electric vehicle charging IEEE Energy Conversion Congress and Exposition 614-21