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Electromagnetic Optimization of the Coils of Magnetic Coupling Resonant Wireless Energy Transmission System

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To develop and study the electromagnetic optimization of the coils of magnetic coupling resonant wireless energy transmission system. Compared with the traditional technology, this paper adopts magnetic coupling resonant WPT technology to optimize the traditional technology. In this paper, the finite-element analysis software Maxwell is used to perform the electromagnetic simulation analysis of the coupling coils and then the comparison and research are conducted on the traditional specification to confirm whether the design can achieve the goal. The results of the analysis show that the designed magnetic leakage flux is reduced within the safety limit and achieve the optimization goal.

1. Introduction

Under the development of modern society, the technology of wireless energy transmission has received extensive attention. Under this premise, how to deepen the development of this technology is a key research issue in related academic circles in current stage. Based on the results of modern researches, it is known that the main development direction of wireless energy transmission technology is the magnetic coupling resonant WPT technology. This technology can effectively achieve the long-distance transmission of wireless energy transmission and has the advantages of high efficiency, low radiation and small impact. However, the research on this technology is still in its infancy. Although it has obtained some technical results that can be applied, there is still a lot of research space to be developed, such as the electromagnetic analysis and optimization design of the coils of magnetic coupling resonant WPT system in the moving state.

In this paper, electromagnetic analysis and optimization design of the coils of magnetic coupling resonant WPT system in the moving state are studied. Because the design of magnetic coupling coils will affect the performance of WPT, which is one of the core contents of the WPT system. Therefore, this paper first analyzes the structure and power transmission process of magnetic coupling resonant WPT system by taking electric vehicles as an example. Then, the theory of mutual inductance model is used to establish the equivalent circuit model and the electromagnetic analysis is performed by Maxwell simulation. Finally, the optimization design of the coils is conducted with the goal of improving system efficiency, enhancing anti-offset capability and reducing system radiation.

2. Literature review

In November 2006, at the Forum on Industrial Physics of the American Physical Society, the Marin Soljacic research group at the Massachusetts Institute of Technology (MIT) proposed the theory of magnetic coupling resonant WPT technology for the first time. This technology makes up the inherent defects of the wireless charging technology and can achieve high power and high efficiency transmission. It has successfully set up a new direction of wireless charging technology. In July 2007, by using a radius 300mm, two copper wire rings (line diameter 3mm, 5.25 turns), Gric was used as a resonator to light a 60 W bulb with 2.13m distance through the principle of magnetic coupling resonance. The space distance of energy transfer was four times the device size of WPT, the whole system was 40%. When the distance of the bulb was 0.75m, the rate could reach 96% (Gric, 2016).

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The energy principle of magnetic coupling resonant technology is studied by the Oak Ridge National Laboratory in the United States. Scholars Guerry and others have studied and explored the coupling coils, using a planar spiral coil structure and adding the magnetic core to improve the coupling performance (Guerry et al., 2017). The road is connected in series with two coils as the launcher. The receiving coil is installed inside the chassis of the electric vehicle, and the transmission of electric energy is realized while the vehicle is moving. In the process of dynamic moving of electric vehicles, the transmission efficiency of the system can be improved by adjusting the working frequency of the system.

Scholars Killner and others applied WPT technology to the practical engineering of electric vehicles. It mainly focuses on the system modelling method, the topology structure of electric energy transformation, the optimization design of electromagnetic coupling mechanism and the electromagnetic technology (Killner et al., 2017). In 2009, the first generation OLEV used the launch guide of E core, the transmission distance was only LCM, the efficiency was 80%. The second-generation wireless power supply system using the U core launching guide greatly increased the transmission distance to 17cm, but the efficiency was reduced to 72%. The third generation introduced the skeleton type W type end guide, making the original side with a wider magnetic field of the core length, the transmission distance is 20cm, the output power is 20kW, the efficiency is up to 83%. Scholars Liu and others put forward the fourth generation I core track and the five generation S type orbit, making the efficiency higher. This new type of orbit changes the characteristics that the flux path is perpendicular to the direction of the moving direction, but the magnetic flux along the direction of the vehicle effectively reduces the electromagnetic radiation to the surrounding environment and enhances the transmission performance (Liu et al., 2017).

The research status of other forms of radio transmission abroad is as follows: scholars Man and others have made electric power transmission device based on electric field mismatch mode to realize 1~10W (Man et al., 2016); scholars Messaoudi and others verified a laser charging system, which successfully extended the continuous flight time of Stalker UAV system to more than 48h (Messaoudi et al., 2016); Space solar power plant (SPS) can transmit energy through the microwave transmission module to the ground, and other applications of WPT in different ways and fields, such as radio frequency, superconductor and supermaterial.

At home, a lot of institutions of higher learning and scientific research institutions have carried out a series of scientific research work, mainly in the Harbin Institute of Technology, Southeast University, Tianjin University of Technology, the Electrotechnical Institute of the Chinese Academy of Sciences, Chongqing University and other institutions of higher learning and research institutes. The establishment of the WPT Technology Committee in 2014 has promoted the commercialization of wireless transmission technology.

The research group of Professor Zhu Chunbo of Harbin Institute of Technology has studied the mechanism, power characteristic, distance characteristic, high frequency current measurement technology and system loss of magnetic coupling resonant WPT. The resonator is composed of spiral copper coil connecting capacitor, and the power of their magnetic resonance device reaches SOW, and the transmission distance is 30cm. The efficiency is 60%. Cooperation with Haier company to develop a study of the power of 700W tailless electrical appliances, the device launches and receives the coil using a planar spiral structure, increasing the plane magnetic core to increase the coupling coefficient of the system.

In the study of magnetic coupling resonance WPT system, scholars Washburn and others discuss the relationship between the coupling coil parameters and the transmission characteristics. Under the premise of the system design load and the certain distance, the optimal design of the transmission efficiency or output power can be obtained by the coils that determine the number and the radius of the coil (Washburn et al., 2017). And it has increased the distance of wireless transmission to about 50cm, which can achieve wireless transmission of kilowatt class power over half a meter. By optimizing the planar spiral coils, a coil with high quality factor is designed. Combining two kinds of two tuning ways, the optimal problem of transmission efficiency is transformed to find the optimal ratio of mutual inductance and internal resistance. In the case of the final number of online circle turns five, the output power is 200W and the maximum transmission efficiency is 90.9%.

The researchers of Huazhong University of Science and Technology analysed the relationship between the energy transmission efficiency of the magnetic coupling resonant transmission system and the distance and the coil parameters from the circuit point of view. On this basis, the frequency tracking system was added to solve the problem of low transmission efficiency due to frequency detuning in the transmission process.

In January 2010, Haier launched the world's first "tailless TV" on Haier at the forty-third International Consumer Electronics Exhibition (CES). Scholars Zhang and Nah use the principle of "magnetic coupling resonance" to realize the world's first "tailless TV" without power lines, signal lines and network lines (Zhang and Nah, 2016). At present, the research and Development Department of Haier group has begun to apply this technology to various household appliances in daily life. The product is serialized and commercialized to form a "tailless home" solution for Haier group.

The Marin Soljacic research team at the Massachusetts Institute of Technology (MIT) set up WiTricity, which is developing the EV wireless charging system with companies like MITSUBISHI and Delphi. Now WiTricity technology can transmit up to 3.3KW power at more than 90% efficiency. This efficiency corresponds to the transmission distance of 20cm, which is the EV wireless charging system developed by WiTricity.
In August 2013, the South Korean Institute of higher science and Technology (KAIST) developed OLEV electric vehicles, using more than 400 meters long transmission belts for wireless charging, and the other 400 meters of distance to rely on rechargeable batteries.

3. Method

The characteristics of the coils before the optimization are shown in Figure 1. The existing coil model of the laboratory is a spiral coil structure with a hollow plane. The coupling coils with the same specification are placed coaxially to each other, realizing a magnetic coupling resonant WPT with a load of 100 watts, whose efficiency can reach 78%. As the low-power electronic devices and high-power electric vehicles will inevitably shift or move during the wireless charging process, the design of the coils before the optimization only considers the high-efficiency power transmission in the static state, while not considering the offset effect of coupling coils in the charging device. In this study, the relative offset between the coupling coils is considered in the design process and the optimization is conducted on the coil spacing and transmission distance.

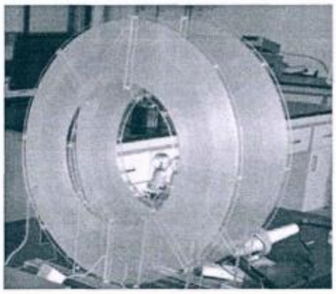

Figure 1: Optimize the structure of the front coil

The selection principle is that the output power should be large enough, the current at the source end should be low enough under the premise of meeting the power output conditions, and the transmission efficiency should be high. In order to facilitate laboratory research, the power of hectowatt scale is selected and the efficiency is above 70%. The self-inductance design of the coupling coil is performed according to the current range 0~10A of the power the power amplifier in the laboratory.
Internationally, the frequency fluctuation range of non-contact charging system for electric vehicles is determined to be 81.38 to 90.00 kHz. In accordance with this standard, the system sets the operating frequency of the dynamic charging system for electric vehicles to 85 kHz. The system frequency and the natural frequency f2 of the resonator are both f, that is, the natural frequency of the system is assumed to be the same as that of the resonator. At this time, the resonator is in a resonance state and the system impedance of the series resonance compensation presents the resistive characteristics. In this design, the small-scale electric vehicles are taken as an example and the equivalent resistance of the battery during charging is 2.7~20Ω. The load impedance selected in this paper is 20 and the simulation value of the parameter variable is shown in Table 1

Table 1: parameter variable simulation value

Parameter variable	Simulation set value	describe
U	40V	End voltage of transmitting coil
F	85kHz	System working frequency
F1	85kHz	Emitter coil frequency
F2	85kHz	Receiving end loop frequency

The inductance of the coupling coil is determined by the size and number of turns of the coil itself, which plays a decisive role in the target parameters such as magnetic coupling resonant WPT power, transmission distance and efficiency. Therefore, the self-inductance of the coupling coil is the key parameter to the link of WPT characteristics and the coupling coil entity.

Figures 2, 3, 4 and 5 are three-dimensional graphs of transmission characteristics. When the self-inductance value of the transmitting and receiving coils are equivalent, parameters such as transmission efficiency and power are larger than the self-inductance value. Therefore, in order to ensure that when the resonator parameters are matched, the transmitting end and the receiving end are in the same resonance point. The designed coupling coil adopts uniform transmitting and receiving coil parameters. Therefore, the relationship between the inductance value and the transmission characteristics can be clearly seen from the two-dimensional figure.

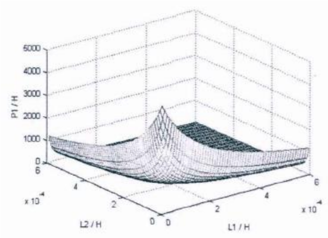

Figure 2: input power characteristics

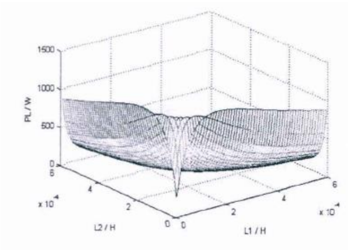

Figure 3: load power characteristics

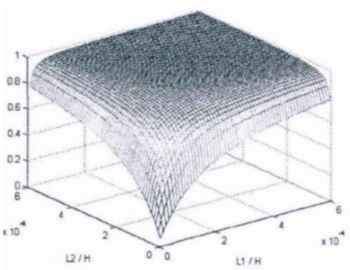

Figure 4: transmission efficiency characteristics

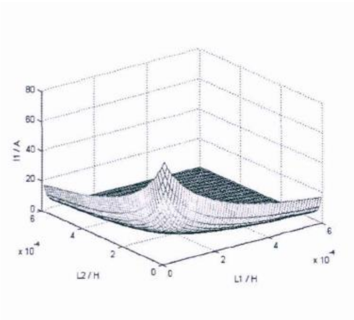

Figure 5: current characteristics of source end

In the magnetic coupling resonant wireless WPT process, high-frequency alternating current flows go through the coil and the conductor surface current is unevenly distributed under the action of induction. And the current density at the conductor surface is greater, resulting in the increase of equivalent resistance of the coupling coil. The occurrence of skin effect will not only increase the power loss of the system and reduce the efficiency, but also lead to the rise in temperature of the conductor surface, bringing potential safety hazards. In order to weaken the skin effect, a plurality of mutually insulated fine wires are used to form a bundle in a high-frequency circuit to replace the thick wire of the same cross-sectional area. In the current WPT research, the Litz wire is usually used to weaken the skin effect and reduce the resistance in the coupling coil, thereby improving the power transmission efficiency of the system.
Based on the research of magnetic coupling resonant WPT system, the magnetic coupling resonant coils have many different structural designs for different research objectives. The common shapes include: cylindrical solenoid type, circular planar spiral structure and rectangular planar spiral structure, which is shown in Figure 3-6 and it can be understood through the comparison.

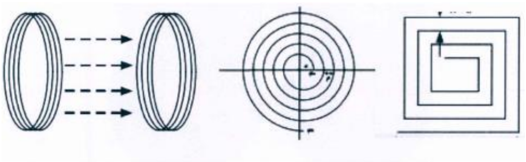

Figure 6: common magnetic coupling resonant co structure

4. Result and analysis

By normalizing the relationship between the voltage a, the detuning factor ξ and the coupling factor η: there is a critical coupling at this point $\eta = 1$; when η >1, there is over coupling. The frequency splitting decreases with the coupling factor and eventually converges at the resonance frequency point; When η <1 is, there is under coupling. The system's energy transfer efficiency drops rapidly. When the frequency splitting phenomenon occurs and the parameter of the transmitting and receiving coils is the same, the splitting is symmetry. According to international standards, the frequency fluctuation range of the wireless charging system for electric vehicles is determined to be from 81.38 to 90.00 kHz. In the process of this study, the frequency is also selected within the scope of international standards, so it cannot be applied to the power supply mode of self-adaptive power supply.
For coaxial coils, the distance will have a great impact on WPT efficiency under the same system parameter. It can be seen from the coupling factor formula $U_1 = z_1 I_1 + j\omega M I_2$ that the larger the axial distance becomes, the smaller the mutual inductance and the larger the coupling factor. It can be known from the normalized voltage frequency response that with the change of the axial distance, under the under coupling state, the load voltage of receiving coil becomes larger with the axial distance; after reaching the over coupling state, the axial distance becomes larger and the load voltage of receiving coil becomes smaller. Therefore, it can be known that the maximum value of the load voltage of the receiving coil can be obtained when the coupling factor reaches the critical point in the axial distance variation process.
Therefore, under the condition that the system parameter remains consistent, the radial offset characteristics of two coaxial coils are studied. Similar to the axial offset, the radial offset, the offset of the radial offset affects the coupling factor 7 through the mutual inductance. When the radial distance becomes larger, the load voltage of the receiving coil becomes smaller. Therefore, it can be seen that the maximum value of the load voltage of the receiving coil can be obtained when the coupling factor reaches the critical coupling point in the radial distance variation process.
In order to verify the correctness of the Maxwell simulation method proposed in this paper for magnetic coupling coils, an equivalent model is established according to the existing coupling coils in the laboratory to perform simulation verification.
Maxwell's simulation analysis mainly consists of determining model parameters, modeling, operation loading and post-processing.
The simulation modeling is conducted on the magnetic coupling coil before the optimization design and the modeling parameter should strictly follow the parameter of magnetic coupling coil. There are certain errors in the physical model due to manual winding. In order to ensure that the transmitting and receiving coils have the same natural frequency, the modeling parameter of the transmitting and receiving coils in the simulation modeling is designed to be models with the same specification and consistent parameter.

According to the modeling data, an equivalent three-dimensional model diagram is created using the Maxwell simulation software. The coil located below serves as the transmitting coil of the WPT system and the coil located above serves as the receiving coil. The two coils are placed coaxially and the transmission distance is 100 mm. Because there is a large amount of calculation in the three-dimensional equivalent model in the simulation software and the three-dimensional equivalent model is a symmetrical structure, this paper designs a two-dimensional simplified model after axisymmetric processing to reduce the calculation under the premise of not affecting the calculation accuracy.

In order to verify the accuracy of the simulation model, the self-inductance value of the transmitting and receiving coils of the circular coil before the optimization is simulated and calculated and the simulated self-inductance value is compared with the actual measured value to verify the correctness of the simulation model. In order to verify the accuracy of the simulation of the coupling coil in the operating circuit of the system before optimization, the voltage value and current value of the load end are measured respectively when the magnetic coupling resonant WPT system works normally,.

5. Conclusion

In this paper, the finite element analysis software Maxwell is used for the electromagnetic simulation analysis of the coupling coils, and then the correctness of the simulation model is verified through the comparison with the simulation analysis of the existing coupling coil working system. The verification at this stage proves that the simulation model has a certain degree of accuracy, thus ensuring the correctness of the subsequent experimental results. Secondly, this paper conducts the stimulation analysis of the power transmission process of the magnetic coupling coil under the overall operating state of the system and analyzes the electromagnetic field through the stimulation of the coils after the optimization. And then, this variation of the offset is used to study the impact of the coil offset, system efficiency and magnetic field distribution. Finally, through the addition of high magnetic permeability, the magnetic core will be analyzed for structural optimization effect. At the same time, the parameterization method is used for the stimulation analysis to obtain the optimal placement position of the magnetic core. The addition of the planar magnetic core on both sides reduces the magnetic flux leakage during the WPT process within the safety limit. In addition, the analysis of this paper is based on the normal operation of the magnetic coupling resonant WPT system and the voltage value and current value of the load is measured respectively.

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