Design and Analysis of Electric Vehicle Wireless Charging System

Zicheng Fang*

The Sino-British College, University of Shanghai for Science and Technology, Shanghai, China

* Corresponding Author Email: sbc-23-8032@sbc.usst.edu.cn

Abstract. As the market for electric vehicles grows, More attention has been paid to wireless charging of electric vehicles because of its higher safety, convenience and flexibility than traditional wired charging. Studying the power transmission theory of the wireless charging system and improving the essential components is a significant way to increase its performance. This essay first outlines the present state of research in this field and highlights its primary issues. It then goes on to discuss the various forms of wireless power transmission also called WPT, the elements that make up a magnetic coupling resonant circuit, and its compensation structure based on the theory. Through theoretical derivation and the summary of the analysis of the design optimization scheme, it is concluded that the planar circular coil is better, and the optimization design process is explained to increase this system's efficiency even further. The results show that S-S topology is more suitable and then provides a scheme for the optimization of coil parameters.

Keywords: Wireless charging, magnetic coupling resonance, optimization of coupling coil.

1. Introduction

With the increasingly serious global environmental pollution, electric cars have become a key component of low-carbon transportation. In 2021, the Ministry of Industry put forward the development plan for the new energy automobile industry, which further indicates the future path for the development of new energy vehicles. The electric vehicle market has been promoted by electric vehicles, which are currently the most important direction for new energy vehicles with the goal of achieving green environmental sustainability [1].

Compared with traditional vehicles, electric vehicles with many advantages such as no pollution, simple structure and better intelligent driving system are undoubtedly more cost-effective. However, the high investment cost in the early stage, as well as the problems such as battery life, charging time and supporting facilities that consumers are concerned about, have hindered its introduction to the market. A big part of these problems comes from charging problems, especially when there are often multiple cars waiting to be charged during rush hours. It shows that the traditional wired charging of electric vehicles has some limitations in the practical application process. So the wireless charging technology has attracted wide attention due to its simple operation, good safety, flexibility and convenience, so the study of wireless charging in the field of electric vehicles has high practical significance. Among them, magnetic coupling resonant wireless charging offers many advantages, including large transmission power, high efficiency, moderate transmission distance, and other advantages, making it a popular choice for electric vehicle wireless charging systems. The coupling coil is the main component and its efficiency is determined by the quality factor. This factor is positively correlated with the mutual inductance and internal resistance ratio of the coil, and the coil parameters also need to be changed in order to make the coil quality factor higher.

The field of wireless power transmission was first explored by foreign researchers. Nikola Tesla was the first to use electromagnetic induction to light a light bulb at the end of the 19th century. Thanks to the advancement of science and technology, the research team of the University of Auckland put forward the design scheme for the coupling system and the method for controlling the system stability, and enhanced the transmission power and migration adaptability through the design of circular coils, DD coils and other coils [2]. In 2018, BMW designed a wireless charging car, the transmitter is connected to the ground AC, the full charge only takes 3.5 hours, and the charging efficiency reaches more than 90% [3]. Oak Ridge National Laboratory in the United States has gradually achieved high-power wireless charging for electric vehicles by increasing the output power of their wireless charging system from 6kW in 2013 to 120kW in 2018. [1]. Domestic research on wireless charging technology started late. A proposal has been made to optimize and design coils at specific frequencies and transmission distances by the research team of Southeast University to design coils for electric vehicles wireless charging systems and address the mutual constraints between various parameters. They also successfully designed the first wireless charging electric vehicle in China and a wireless charging system that uses magnetic coupling and resonance with an output power of 3kW was constructed, with a transmission efficiency of 90%.[4]. Then in 2014, ZTE Automobile Company achieved a maximum of 60kW high-power wireless charging, and the transmission efficiency can reach 90% when the working air gap is 200mm.

In sum, the wireless charging system has been designed and optimized by both domestic and foreign universities and scientific research teams, with a particular emphasis on improving transmission efficiency by optimizing the coupling coil structure and parameters. However, up to now, there is still no mature design scheme that is widely used, which shows that the realization of efficient and safe wireless charging still faces many challenges.

This essay mainly analyzes the theory of wireless charging systems with magnetic coupling resonance, and summarizes some schemes to improve transmission efficiency by optimizing the design of the compensation circuit and coupling coil. In the beginning, the background and significance of electric vehicle wireless charging systems, along with their research status at home and abroad, are presented. Secondly, the types of WPT, the composition and principle of magnetic coupling resonant system, as well as the selection of compensation circuit are introduced. Finally, the optimal design and research results of the magnetic coupling coil are reviewed, as well as the prospect for the future.

2. Principle Analysis Behind Wireless Charging System

2.1. Basic Theory of Wireless Power Transmission Technology

At present, electric vehicles can be charged through wired charging, wireless charging, and battery replacement. Among them, the traditional wired charging method occupies the main market at present, which has advantages such as fast charging speed and strong stability, but it also has disadvantages such as the charging port is not suitable, and the line aging. The battery change method is to charge the car battery by replacing it, and its advantage is that there is no charging time, but this method is difficult to operate, requires professionals to operate, and there are certain safety risks. In contrast, wireless charging has many advantages: no charging pile and its line, no need to consider the adaptation problem, no manual operation, safe and convenient [3]. To sum up, and from table 1, we know that wireless charging has great potential for development.

Table 1. Comparison of three charging methods

Wired charging	Wireless charging	Charging by changing the battery
Manual operation	No operation required	Difficult to operate
Exist security risks	Few safety risks	Exist security risks
Moderate occupation area	No floor space required	Large occupied area

According to the form of power transmission, the following categories can be used to categorize wireless power transmission. Non-radiation form has the characteristics of short effective distance, small transmission loss and high transmission efficiency. Its simple principle is to use the inductive coupling between the wire coils to generate the wireless transfer of energy. The characteristics of radiation form are: long effective distance of transmission, large transmission loss and the transmission direction is difficult to control, which requires the specific receiver to accept.

Wireless power transmission through magnetic field coupling is established on the basis of the Ampere-loop law and Faraday's law of electromagnetic induction. To transmit electric power wirelessly, an alternating magnetic field is used as the energy carrier and the coupling coil completes the "electric-magneto-electric" power conversion process.

Electric field coupled wireless power transmission takes a high-frequency electric field as a power transmission carrier, and comprehensive use of power electronics technology, electrical theory and modern control theory, to achieve power transmission without direct electrical connection.

Microwave wireless power transmission takes microwave as the carrier, and uses antenna or antenna array to transmit and receive microwave power. It has the characteristics of long transmission distance, but its power loss and potential impact on the human body need to be studied.

Laser wireless power transmission uses lasers as the carrier, which boast small transmitting apertures, high energy density, good focusing abilities, and long transmission distances.

Ultrasonic wireless power transmission takes ultrasonic wave as an power carrier. It uses the transducer to complete the mutual conversion of electrical power and sound power in order to achieve wireless transmission of electrical power. An ultrasonic wave is a mechanical wave that can propagate in water, air, metal, and other media. Electromagnetic radiation, electromagnetic interference, or other problems are not caused by this method, and metal substances can be present in the propagation path.

Table 2. Comparison of five wireless transmission

Magnetic field coupled WPT	Electric field coupled WPT	Microwave WPT	Laser WPT	Ultrasonic WPT
more than 90% transmission efficiency	99% close-range transmission efficiency	High-efficiency transmission	Low-efficiency transmission	Low-efficiency transmission
Long-distance transmission (up to several meters)	Short-distance transmission (about 10cm)	Long-distance transmission (up to kilometers)	Long-distance transmission	Long-distance transmission

The five wireless power transmission types mentioned in Table 2 are shown, and it can be concluded that magnetic field coupled WPT is the most appropriate option for electric vehicles.

2.2. Composition and Principle of Magnetic Coupling Resonant Wireless Charging System

A wireless charging system that is magnetically coupled and resonant has the same function as a transformer where it transfers power from one end to the other through a magnetic field. The transmitting terminal comprises a DC power source, an inverter circuit, and a transmitting coil. This setup converts direct current (DC) into alternating current (AC), which is subsequently stored in the magnetic field generated by the transmitting coil as magnetic energy. At the receiving end, there exists a load, coil loss resistance, and a receiving coil. The variation in the magnetic field induces an alternating current within the receiving coil. This AC is then rectified into direct current (DC) by the rectification circuit and stored in a power storage device, as illustrated in Figure 1.

To achieve efficient power transmission, it is essential for both the transmitting coil and the receiving coil to operate at the same frequency, thereby creating a resonance phenomenon. In an ideal resonant state, the system demonstrates pure resistance, resulting in maximum transmission efficiency. Conversely, if the system becomes detuned, inductive or capacitive loads can impede power transfer. Therefore, ensuring frequency consistency between the transmitting and receiving coils is crucial for the overall effectiveness of the system.

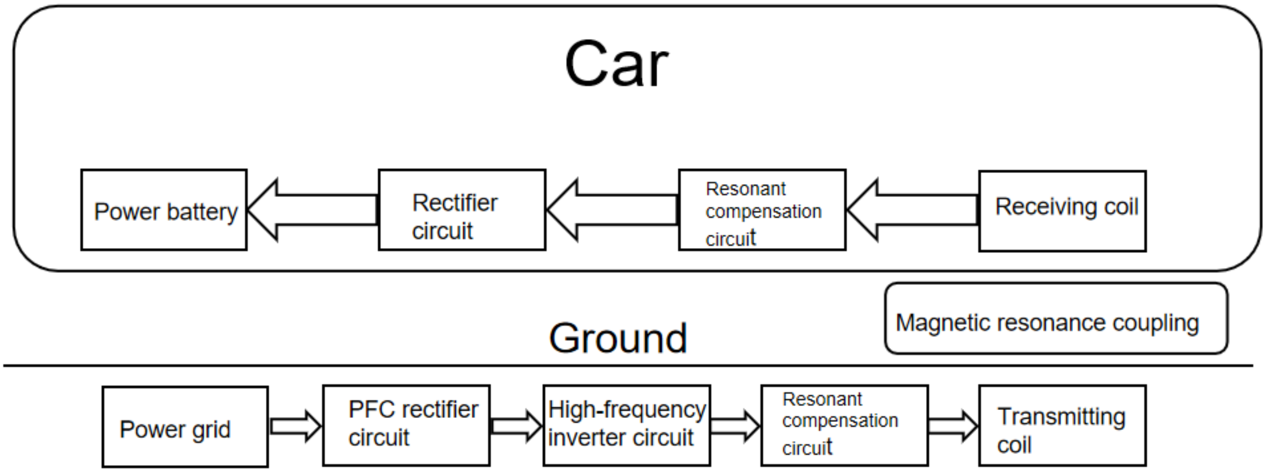

Figure 1. The basic structure figure of the magnetically coupled resonant wireless charging system

2.3. Analysis of the Coupling Model

Figure 2 illustrates the theoretical circuit model of the magnetically coupled resonant system. To ensure that the frequencies of the primary and secondary resonant loops align which means the transmitting and receiving coils operate at the same frequency, a resonant compensation structure must be implemented. This structure is primarily composed of two components: primary resonant compensation and secondary resonant compensation.

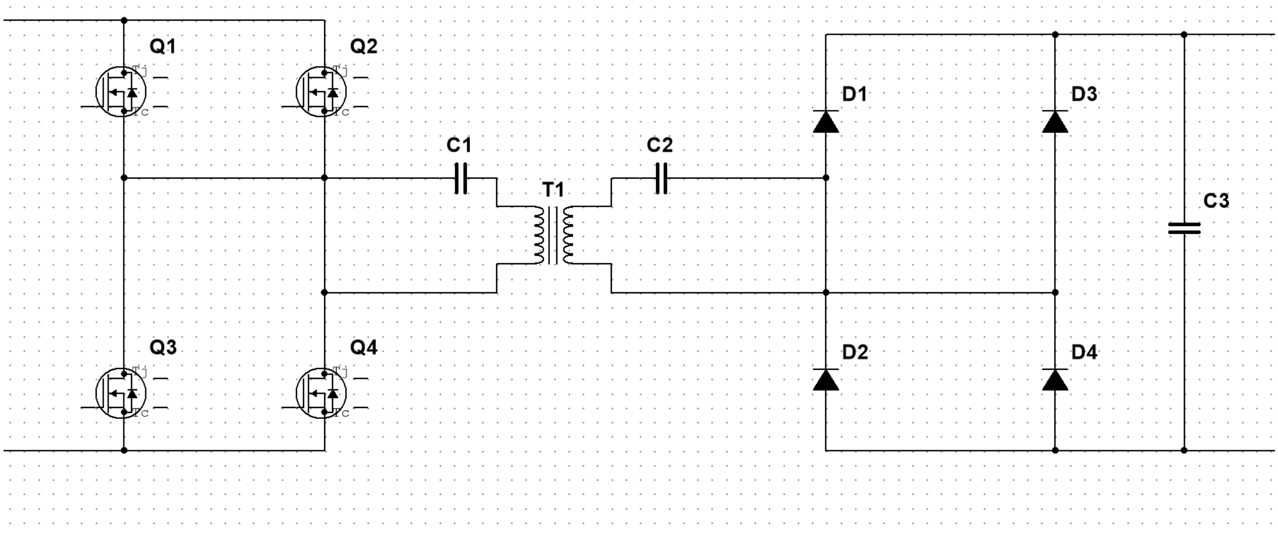

Figure 2. The theoretical circuit model for the magnetically coupled resonant system

The two fundamental resonant compensation structures are series compensation and parallel compensation. The four most common topologies include series-series (S-S), series-parallel (S-P), parallel-parallel (P-P), and parallel-series (P-S), as illustrated in Figure 3.[5].

To select the appropriate compensation structure, we can derive the circuit equation based on Kirchhoff's law. Using this equation, we can calculate the system's input and output power, allowing us to determine the transmission efficiency. Subsequently, we can utilize simulation software such as Simulink to model and analyze the four resonant compensation structures. This enables us to compare the output power and transmission efficiency under identical conditions. [1]. The S-S compensation can make the system transmission efficiency greater than 85% in a relatively wide frequency range [1], compared with the S-P compensation topology, whose effective operating frequency range is small, and the output power of P-S and P-P compensation topology is low. The maximum output power of the four compensation topologies is as follows: S-P >S-S >>P-S >P-P; The maximum transmission efficiency is as follows: S-S =P-S >S-P =P-P; The operating frequency range which makes the transmission efficiency greater than 85% is as follows : S-S >P-S >>S-P =P-P. Moreover, In wireless charging systems for electric vehicles, the primary and secondary coils are loosely coupled, resulting in a small coupling coefficient. Under these conditions, the output power of the series-series (S-S) and series-parallel (S-P) compensation topologies is significantly greater than that of the parallel-series (P-S) and parallel-parallel (P-P) topologies. Therefore, the S-S topology emerges as the most suitable option for electric vehicle wireless charging systems.

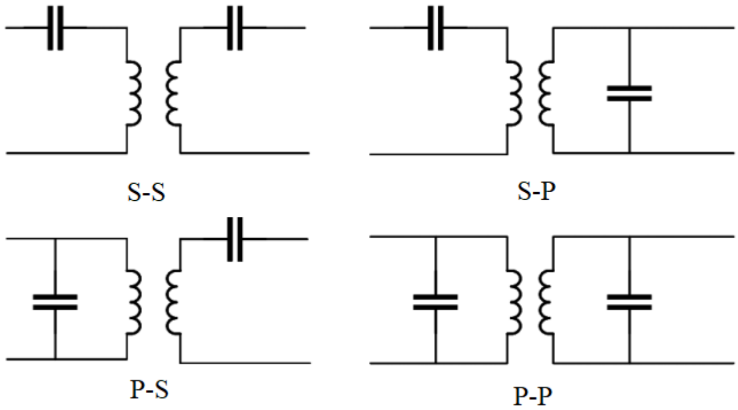

Figure 3. Four typical resonant compensation structures

3. Optimization Analysis of Coupling Coil

3.1. Analysis of Coil Structure Design

On electric vehicles, due to the limited location space, the most suitable coil is the planar spiral coil as shown in Figure 4. The planar spiral coil can be divided into round, square, hexagonal, octagonal, etc. When the wire length and other parameters are the same, the transmission performance of these four coils is analyzed and compared with the control variable method. The transmission performance of the planar circular coil is the highest, so using the planar circular coil can improve the transmission efficiency [6]. Since the electric vehicle wireless system operates on high-frequency alternating current, Leeds wire is employed to wind the coil to mitigate the skin effect, as illustrated in Figure 5.

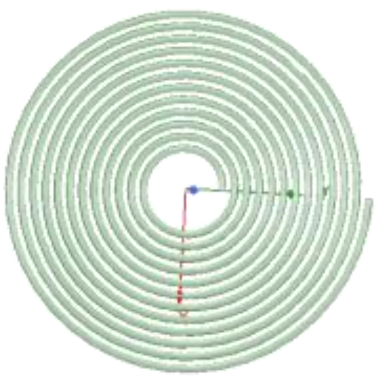

Figure 4. The planar spiral coil

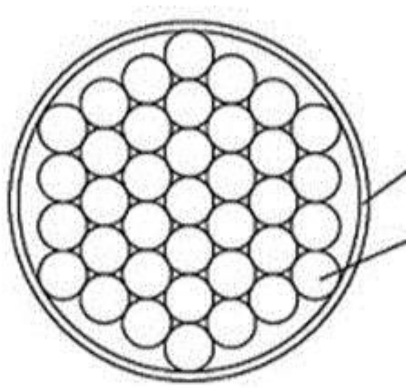

Figure 5. Leeds wire

3.2. Analysis of Coil Parameter

According to the mutual inductance formula: $M=\frac{\pi}{2}\times\frac{\mu\sqrt{N_1N_2}(r_1r_2)^2}{d^3}$ it can be concluded that the coil parameters are the main factors affecting mutual inductance. Where μ is the spatial permeability and the value is $\mu= 4\pi\times10^{-7}$; N_1、N_2 represent the numbers of turns in the transmitting and receiving coils; the radius of the coils are denoted as r_1 and r_2 ; d represents the distance between the transmitting coil and the receiving coil.

According to the formula, the selection of larger multi-turn coil will be more conducive to the transmission performance of the system. However, in practical applications, the structure and size of the coil will be limited by different environments, and when the radius and number of turns increase, the AC resistance of the coil will increase, which will have a certain negative impact on the system. Therefore, more references are needed for the rational design of coil structure [7].

In order to select appropriate parameter values, coupling coils can be built in Maxwell, Ansys and other simulation software and then set parameters and control variables, so as to obtain the impact of single parameter change on coupling coefficient and mutual inductance under the same conditions. Using the simulation results of mutual inductance and the coupling coefficient in relation to various parameters, the value range of optimization variables can be selected and the optimization model can be established. The coupling coil parameters (turns and radius of the coil, transmission distance) are taken as optimization variables, and the coupling coefficient is taken as optimization target. The optimization algorithms in Ansys optiSLang can be used to optimize coil parameters, and then the optimization results can be obtained [1]. Genetic algorithm, as shown in Figure 6, is one of the optimization algorithms in Ansys optiSLang, which is the population-based algorithm and is widely used [8]. Because it has the advantages of simple principle, few parameters, fast convergence, memorability, etc., and has more advantages in the optimization design of coil parameters. The coupling coefficient decreases as the migration distance increases, as well as with a larger working air gap [3]. However, the relative change in the coupling coefficient due to variations in the working air gap is more pronounced than that caused by changes in migration distance. Thus, it can be concluded that the working air gap has a more significant impact on the coupling coefficient.

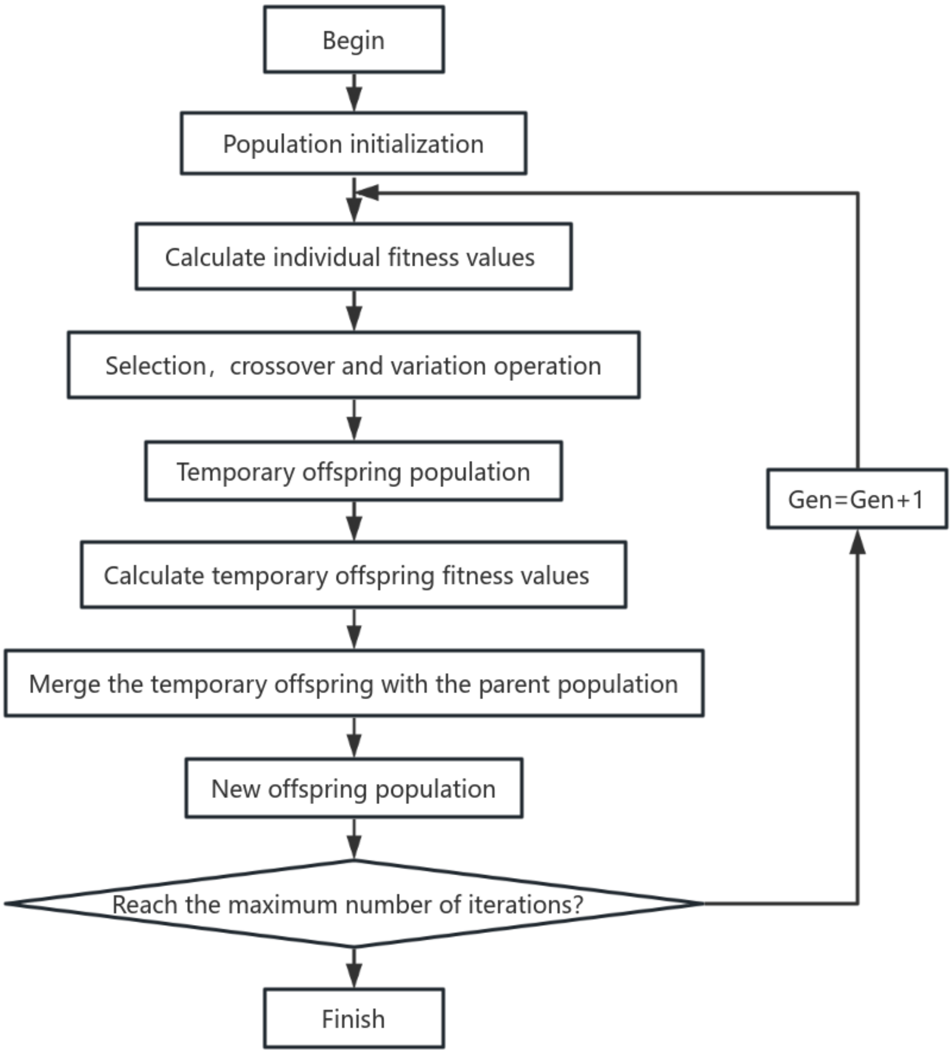

Figure 6. Flow chart of genetic algorithm optimization

4. Conclusion

This essay begins by introducing the fundamental theory of wireless power transmission, discusses the selection of wireless charging that may be applicable to electric vehicles, then introduces the composition of magnetic coupling resonant wireless charging system, explains its working principle, and introduces the most common resonance compensation structure in the circuit, and summarizes the method of how to choose the resonance compensation structure. Then, the optimization design of the coupling coil is analyzed. First, the coil structure is determined to be planar and circular and the coil is wound with Leeds wire. Secondly, the main parameters affecting the transmission performance of the coil are analyzed, and how to optimize the parameters and how to choose the algorithm are described.

This essay conducts a theoretical analysis and optimal design of the wireless charging system for electric vehicles, offering insights into the research and development of magnetic coupling resonant systems. However, it has certain limitations: first, a physical model of the wireless charging system has not been constructed due to constraints. Second, while the power conversion circuit is critical for the wireless charging system, this essay lacks an optimization design for that circuit.

Reference

[1] DOU Shengyue. Design of magnetic Coupling resonant electric vehicle wireless charging System. Chang 'an university, 2022.

[2] Zhou Tao. Electric vehicle charging system coupling analysis and coil design. Shandong University, 2020.

[3] Shi Jialan. Electric vehicle charging system technology research. Chongqing Three Gorges College, 2023.

[4] LIU Jie. Design and Implementation of Wireless Charging System for Electric Vehicles. Nanjing: Southeast University, 2019.

[5] Yue Qiao, Lv Hui, Wang Yafei, et al. Research on Wireless Charging Technology for Electric Vehicles. China Automobile, 2024, (04):50-58.

[6] JIA Yuanyuan. Analysis and optimization design of magnetic coupling mechanism of resonant radio energy transmission system. Beijing Jiaotong University, 2018.

[7] Zhi-da Yang. The optimal design of the electric vehicle charging system. Shenyang university of technology, 2023.

[8] Hu Peng, Song Chao. Parameter Analysis of standard Genetic Algorithm. Computer Knowledge and Technology,2009,5 (02):421-422.