Comparison of Structure Efficiency of Wireless Charging Technology

Menghan Wang

School of Electrical Engineering, Tianjin University of Technology and Education, Tianjin, 300000, China

13507623996@163.com

Abstract. This study proposes a solution to the energy supply problem of high-end innovative products based on wireless charging technology. This technology has significant research value due to its significant convenience and driving role in the development of national science and technology. This article focuses on the breakthrough progress of wireless charging technology in key performance parameters such as transmission efficiency, applicable distance, and power capacity. Through a systematic review of literature, the implementation structure, work efficiency, and technical advantages and disadvantages of four mainstream wireless charging technologies are compared and analyzed. The research results indicate that the current mainstream wireless charging technology has achieved significant performance improvements compared to traditional solutions. This study provides important technical references and development ideas for China's scientific and technological innovation, and has positive significance for promoting technological progress in related fields.

Keywords: Contactless Power Transmission Technology, Electromagnetic Induction Type, Magnetic Resonance Type, Magnetic Coupling Type, Radiation Type

1 Introduction

With the development of the Internet, smart phones and electric vehicles, wireless charging, as one of the convenient, safe and suitable application scenarios, is gradually replacing wired charging as one of the main technologies of energy transmission in the future. However, different wireless charging methods (including electromagnetic induction, magnetic resonance, magnetic coupling, and radiation) have their own advantages and disadvantages in terms of transmission efficiency, applicable distance, and applicable power capacity due to differences in technical principles. The principle of electromagnetic induction is to generate a voltage during the process of magnetic field changes (Faraday's law); The principle of magnetic resonance is that the coils at the transmitting and receiving ends are designed to have the same resonant frequency; The principle of magnetic coupling generally includes

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resonant and radiative transmission of electromagnetic induction, but in a narrow sense, magnetic coupling only covers strong coupling systems that are non resonant; Radiation type is the transmission of energy through microwave or radio frequency in the far field. The electromagnetic induction method has high energy transmission efficiency due to symmetry, but transmission requires precise distance and precise alignment; Although radiation can transmit energy over long distances, its energy efficiency and safety are difficult to balance; Magnetic resonance imaging is suitable for medium distance range and has flexible positional tolerance, but its cost and technology are relatively complex. On the other hand, magnetic coupling imaging is suitable for low to medium power scenarios and requires medium to short distance transmission. Due to its sensitivity to coil requirements, it has a large offset tolerance. How to choose the optimal technology in complex application scenarios requires a comprehensive consideration of the advantages and disadvantages of each technology. This article compares the performance boundaries of four mainstream wireless charging technologies based on factors such as efficiency, transmission distance, cost, and safety, in order to provide theoretical basis for the selection of electric vehicle technology and provide prospects for the integration of multiple technologies to improve wireless charging technology.

2 Comparison of Wireless Charging Structures

Electromagnetic induction is based on the change of magnetic field between coils to generate current (Faradaylaw), with primary and secondary coils (usually planar spiral coils) that must be tightly coupled. Ferrite materials are used to achieve magnetic conductivity and reduce losses. The circuit is simple and the driving frequency is low (kHz level). Magnetic resonance structure is an LC resonant circuit formed by adding a capacitor to a coil, tuned to high frequency (MHz level). It can use larger coils or structures different from magnetic induction, and can have relatively large distances. The complex structure requires consideration of matching.

As shown in Figure 1, the magnetic coupling form here refers to a form of magnetic coupling that is different from the resonant form, such as a transfer coil or the coupling form of multiple coils. Structurally, it can have multi-layer coils or coil array structures, increasing the freedom of distance and position, but does not use resonance. Since it adopts a coil structure rather than an antenna, it does not necessarily meet the above requirements. The structure can have multiple layers of coils or coil array structures to increase the freedom of distance and position, but resonance is not used. Since a coil structure is used instead of an antenna, it may not necessarily meet the above requirements. The transmitting end of the radiation structure is an antenna array or directional antenna, and the receiving end is a rectifying antenna. The operating frequency can be in the GHz range (such as 2.4GHz or 5GHz), requiring RF circuits that can include power amplifiers and rectifiers. The complex structure requires processing high-frequency signals.

Fig. 1. Magnetic resonance imaging (MRI) image

3 Methodology

3.1 Case study of wireless charging

In recent years, with the popularization of smart devices, the limitations of traditional wired charging methods in terms of convenience and safety have gradually become prominent, making wireless power transmission technology a research hotspot. Firstly, Yang Juan introduced the research and development of wireless power transmission devices. The article systematically expounded the research background and significance of wireless power transmission devices, compared and analyzed the development status at home and abroad, and looked forward to the future development trend, laying a macroscopic perspective for subsequent research. Based on Faraday's law of electromagnetic induction and Maxwell's electromagnetic field theory, the article deeply analyzed the wireless charging system model and its equivalent circuit, systematically explained the theoretical basis, and on this basis, constructed the basic circuit structure of the electromagnetic induction wireless charging device including the transmitting end and the receiving end, laying a theoretical foundation for subsequent research. Subsequently, the article conducted rigorous calculations and analyses on the power generation circuit, square wave signal generation circuit, power amplification circuit, LC resonant circuit at the transmitting end, and the LC resonant circuit, rectifier circuit, filter circuit, and load circuit at the receiving end of the system, clarifying the specific circuit implementation plan and component selection. Through Protues circuit simulation and physical construction testing, it was confirmed that the basic circuit could achieve the expected function and had good performance. To further improve the system performance, the article optimized the basic system from two dimensions. First, by using the timer/interrupt technology of the single-chip microcomputer, variable control signals were generated to dynamically adjust the circuit state of the system, achieving multi-level function switching, and users could flexibly control it through buttons. Second, by integrating A/D conversion, LED display module and single-chip microcomputer (MCU) control technology, the system was endowed with the function of real-time monitoring of the output voltage at the load end and digital display. Finally, the article successfully developed a wireless power transmission system with adjustable charging power and real-time monitoring and digital display of the charging voltage. Through Protues simulation software testing and physical debugging optimization, the electromagnetic induction wireless charging device was found to be rich in functions and superior in performance, demonstrating good application potential [1].

The research by Yan Kai and others shows that among the key components of magnetic resonance wireless chargers, the XKT-510 chip stands out due to its unique advantages. This chip can complete the development work with only a few external components. In the wireless charging system, it is based on the core principle of electromagnetic energy conversion and plays a crucial role in wireless energy transmission. Its receiving circuit is managed by the IC, which is responsible for real-time signal conversion and status monitoring. It can intelligently control fast charging for different types of batteries. The figure 2 shows the hardware block diagram of the system. Looking at the magnetic resonance wireless charger chip XKT - 510.Power supply provides the initial electrical energy input for the entire wireless charging system, serving as the energy source. Transmitting circuit is combined with the XKT - 510 chip, it converts the power supply's electrical energy into alternating electromagnetic field signals suitable for magnetic resonance wireless transmission. During this process, the chip is responsible for key processing such as signal modulation and driving, precisely controlling parameters such as transmission power and frequency to ensure efficient energy transmission. Receiving coil is based on the principle of magnetic resonance, it resonates with the transmitting end, efficiently coupling and receiving the energy transmitted from the transmitting end, converting the magnetic field energy into electrical energy. Receiving circuit: Processes the received electrical energy, such as rectification, filtering, and voltage stabilization, to make it a stable direct current that meets the requirements of subsequent loads. LED light receives the processed electrical energy to achieve illumination, visually demonstrating the application effect of the wireless charging system after energy transmission. The entire block diagram presents the magnetic resonance wireless charging system equipped with the XKT - 510 chip, showing the energy transfer process from power supply to receiving and then to the load application. The XKT-510 series IC provides a reliable guarantee for the stable operation of wireless induction intelligent charging and power management systems. The TP4057 chip also has outstanding features. Its internal integrated PMOSFET structure and anti-reverse charging circuit design eliminate the need for additional external detection resistors and isolation diodes, effectively simplifying the circuit structure. In addition, the TP4057 is equipped with a thermal feedback control mechanism that automatically adjusts the upper limit of the charging current according to the chip's temperature changes, avoiding performance degradation or safety hazards due to overheating. Its standard charging voltage is set at 38V, demonstrating good adaptability and stability in various application scenarios [2].

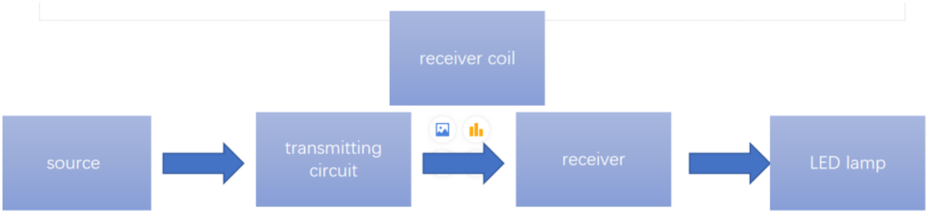

Fig. 2. System hardware block diagram

Zhang Zhimin's research focuses on wireless charging technology for electric vehicles. At the beginning of the study, the author elaborated on the operating principle of the overall system for wireless charging of electric vehicles, conducted a detailed comparative analysis of the performance differences between the basic compensation topology and the bilateral LCC compensation topology, and based on the characteristics of the bilateral LCC compensation topology, combined with magnetic coupling coils, innovatively proposed a set of system parameter optimization design schemes, laying a solid foundation for the subsequent design and development of wireless charging systems. In the research on magnetic coupling coils, the author first introduced the basic characteristics of common magnetic coupling coils, and then based on the characteristics of circular coils and DD-type coils, designed the DDO-type coil, and specifically proposed the system parameter optimization strategy for this coil. Through professional software simulation, the author conducted a comprehensive comparison of the performance of circular coils, DD-type coils, and the newly designed DDO-type coils, and the results showed that the DDO-type coil performed better in dealing with position offsets and had stronger adaptability. Regarding the challenges faced by metal detection technology in electric vehicle wireless charging, the author conducted in-depth research and proposed a new metal detection method based on the principle of electromagnetic induction and centered on self-inductance change detection. Through rigorous theoretical derivation and simulation tests, the feasibility of this method was verified, significantly improving the stability and accuracy of metal detection. To further verify the research results, the author built an electric vehicle wireless charging system prototype and a metal detection device. Through extensive experimental tests, it was fully proved that the system parameter optimization design method, the DDO-type coil, and the self-inductance change type metal detection device were feasible and technologically superior, providing important references for the practical application of electric vehicle wireless charging technology [3].

Yu Tao's research focuses on the design and optimization of underwater wireless charging systems. In the study, the underwater wireless charging system is scientifically decomposed into three core components: the primary circuit, the underwater coupling circuit, and the secondary circuit. Based on the functional requirements of each part of the circuit, the author carefully designed the corresponding primary and secondary circuits. At the same time, fully considering the special medium characteristics of the underwater environment, an excellent underwater coupling circuit was constructed, and through repeated debugging experiments, radio energy transmission in the underwater environment was successfully achieved. During the selection process of underwater magnetic core types, the author conducted simulation experiments using electromagnetic field calculation software to accurately obtain the coupling coefficient of the magnetic core in water under different spacing conditions. Based on the simulation experiment data, a magnetic core with a higher coupling coefficient under the same spacing was selected. This measure not only ensured the efficient performance of the magnetic core but also significantly improved the testing efficiency. To enhance the performance of the underwater radio energy transmission system, the author deeply studied the issue of system energy consumption and introduced an underwater power compensation circuit in the design, effectively reducing the reactive power of the system and significantly improving the energy transmission efficiency. Considering that underwater pressure batteries are prone to shorten their service life under over-discharge or over-charging conditions, the author specially designed a complete battery management system to ensure the safety of the batteries carried by underwater unmanned vehicles. Finally, through rigorous underwater pressure battery charging and discharging experiments, the reliability and stability of the developed underwater pressure battery and the accompanying battery management system were fully verified [4].

3.2 Comparison of advantages and disadvantages of wireless charging technology

For electromagnetic induction type, there is a clear comparison in Table 1, its transmission efficiency is high (70%~95%), suitable for close range transmission and has strong stability. The technology is mature and has a high level of commercialization. However, its disadvantages are short transmission distance (1.0mm~5.0mm), strict alignment requirements for coils, and sensitivity to metal foreign objects, which can easily cause heating phenomena. The advantages of magnetic resonance imaging are medium distance transmission (10cm~1m), extremely high deflection ability, strong penetration ability through non-metallic materials, and suitability for various scenarios. However, its disadvantages include a rapid decrease with distance (50%~85%) and system complexity, requiring matching of resonant frequencies; The advantage of magnetic coupling is high efficiency (75%~90%), which is suitable for low to medium power industrial applications. It not only has a simple structure but also has a low cost. The disadvantage is poor anti deflection ability and relatively fixed position positioning. The unique advantages of radiation type include ultra long-distance transmission, mobile devices, and wide coverage area, without the need for physical contact; The disadvantage is that the efficiency is too low (10%~50%), there is too much energy loss, and there is a hidden danger of high-frequency radiation. It needs to be used in accordance with national electromagnetic standards.

Table 1. Comprehensive Comparison of Four Technologies

Technology	Structured Core	Distance	Degree of Freedom in Position	Efficiency	Typical Applications
Electromagnetic Induction Type	Double Coil Tight Coupling	Short, Less Than 5 Centimeters	Low	High	Mobile Phones, Wearable Devices
Magnetic Resonance	Resonant Circuit+Loosely Coupled Coil	Middle (Cm)	Medium To High	Medium To High	Electric Vehicles, Household Appliances
Magnetic Coupling	Multi-Coil or Magnetic Core Enhanced Coupling	Middle (Cm)	High	High	Industrial Equipment, Medical Implants
Radiation Type	Antennas And High-Frequency Circuits	Long (Greater Than)1m)	Low	Low	Internet Of Things, Drones

4 Application of Wireless Charging

The current wireless charging application scenarios mainly focus on emerging industries such as smartphones and manufacturing in the aerospace industry.

Li Yuzhou designs a wireless charger for mobile phones based on electromagnetic induction technology, which consists of a transmitting module unit and a receiving module unit. The power supply passes through the transmitting module and emits energy through the transmitting coil, while the receiving coil of the receiving module generates induced current due to the changing magnetic flux. This current belongs to AC and needs to be further rectified and filtered by the receiving module to be converted into DC, in order to achieve the purpose of charging the mobile phone battery. In order to achieve the universality of overcharging for mobile phones, this technology has designed a voltage control circuit in the receiving module circuit, USB port charging, and a battery level LED indicator during the charging process [5].

Starting from the thermal optimization of the magnetic resonance wireless charging system and improving the transmission efficiency of the system, Zheng Zhichao designed a low heat loss magnetic resonance wireless charging system that achieved a power output of 192W while ensuring a high efficiency product of the system. Starting from the external cooling of the system, a liquid cooling plate with a serpentine flow channel was designed as the system's heat dissipation device, which reduces the temperature of the system during operation and effectively improves the transmission efficiency of the system [6].

The low-frequency magnetic resonance wireless charging system studied by Zhang Jian usually uses two coils, usually wound with Leeds wire, and usually contains an iron core to generate a magnetic field. The use of iron cores makes the coils very bulky. Going forward means increasing the frequency and reducing the coil. They have now achieved a wireless charging frequency of 160kHz at the kilowatt level. The increase in frequency can even make the coil very small without using an iron core [7].

With the development of drone technology, unmanned aircraft, due to their high flexibility, have been widely applied in various fields such as remote sensing monitoring, plant protection, and inspection. However, the limited endurance of drones has become a bottleneck for their execution of long-distance tasks. By reasonably laying out unmanned self-activated charging stations along the flight path and introducing wireless charging technology, the problem of power supply for drones during long-distance operations can be effectively solved, significantly increasing their endurance time. Based on this, Jiang Yunlong conducted in-depth research on the wireless charging system for drones, starting from four dimensions: magnetic coupling device, radio energy transmission circuit, closed-loop power control system, and experimental verification. He aimed to create a fully automated, lightweight, portable, and energy-efficient wireless charging solution for drones. Given the unique shape, compact internal space, and limited payload of drones, the research team focused on innovating the structure and parameters of the magnetic coupling device, proposing a orthogonal magnetic coupling device, and conducting comprehensive optimization. During the development of the magnetic coupling device, the structures of the transmitting and receiving components were improved and the magnetic field characteristics were studied. Using parameter scanning technology to explore the optimal coupling coefficient, with the dual goals of improving coupling efficiency and reducing the weight of the receiving end, the size parameters of the orthogonal magnetic coupling device were finely adjusted. Using the ANSYS-Maxwell finite element analysis software to build a simulation model, the magnetic field distribution law was deeply analyzed; at the same time, a physical model was made, and the impedance analysis method was used to evaluate its adaptability to position offset. In addition, with the core of achieving lightweighting of the receiving end and efficient charging, the design and research work of the circuit topology of the wireless charging system suitable for drones were carried out [8].

Li Tong conducted in-depth research on the magnetic coupling radio power transmission system. Through comprehensive simulation and actual testing, he achieved precise control over each module of the system. In the system design phase, for the core component of the coil, he combined the system performance indicators and modeling analysis results to scientifically determine the optimal coupling distance and accurately measured the inductance value of the coil, laying the foundation for the efficient operation of the system. In the foreign object detection (FOD) function testing, Li Tong conducted systematic tests on three different detection methods, deeply analyzing the technical advantages and limitations of each method, providing data support for optimizing the detection scheme. In the hardware circuit testing stage, through meticulous analysis and debugging, the stability and reliability of the circuit design were verified, ensuring that the system could be adapted to Qi-standard wireless charging mobile phones and meet practical application requirements. In the system performance evaluation phase, simulation and actual measurement were conducted on the transmission efficiency and power consumption under different power conditions. The results showed that the system could achieve the expected performance indicators regardless of whether it was a low-power load or a high-power load. Additionally, through comprehensive temperature testing, the safety and stability of the system during long-term operation were further verified, ensuring that it always remained in the optimal working condition [9].

In the field of microwave wireless charging systems, traditional narrowband rectifier circuits often adopt the classic structure of "filter - matching - rectification - filter", which has the problem of bandwidth limitation. In response to this situation, Xu Boqiang innovatively proposed a rectifier circuit architecture based on the multi-channel multiplexing mechanism. This design maintains high efficiency while significantly expanding the working bandwidth of the rectifier circuit. Based on this innovative idea, he successfully designed a dual-channel broadband rectifier circuit with a working frequency range of 1.5GHz - 2.5GHz. Through actual testing, its rectification efficiency was stable at around 60%, demonstrating excellent performance. To further optimize the circuit performance, Xu Boqiang improved the circuit filtering structure by adopting a shared filter design scheme, which significantly reduced the circuit size and achieved the miniaturization of the broadband rectifier circuit. In the current and future industries such as mobile internet, Internet of Things, and industrial control, as the concept of green and low-carbon becomes more profound, there is an increasingly urgent need for technologies in the microwave wireless charging system in terms of high efficiency, wide bandwidth, miniaturization, and isolation of energy and information transmission frequency bands. Xu Boqiang's research results provide new ideas and solutions for the technological development in related fields, and have significant theoretical value and practical significance [10].

5 Challenge and Development

Electromagnetic induction technology is widely used in the field of electronic products, such as mobile phones and electric toothbrushes; In the field of biomedicine, medical devices commonly used for implantation in the body, such as pacemakers and detection systems implanted in the human body; In the industrial field, such as AGV automatic guided transport vehicles, these belong to the low-power field. The wireless charging technology for electric vehicles belongs to the high-power field, making it more difficult to implement, but this technology has been proven to be feasible. Magnetic resonance imaging can compensate for the shortcomings of existing electromagnetic induction based wireless charging power transmission distances, and has broad application prospects. However, there are still many shortcomings in the field of wireless charging for electric vehicles, such as high resonance frequency or low transmission power, which cannot meet the charging needs of electric vehicles; Electric field coupling is generally used for short-range low-power power transmission and has many common application areas with electromagnetic induction power transmission, such as biomedical and electronic product fields. However, its performance is poor in long-distance and high-power power transmission scenarios, and further research is needed. Although the radiation-based power transmission technology has certain characteristics, its high working frequency, low system energy efficiency, and the fact that the transmission distance exceeds the actual requirements of wireless charging for electric vehicles make it difficult to be adapted to this application scenario. In the field of wireless charging for electric vehicles, this technology has gradually lost its competitiveness and its usage frequency has decreased. However, in specific scenarios with different requirements for transmission distance and frequency such as unmanned aircraft and solar space stations, the radiation-based power transmission technology can still demonstrate unique advantages and show good application potential and broad development space.

6 Conclusion

The intelligent advancement of wireless charging technology is replacing wired charging in the past, which is a trend of technological advancement and also a general trend. This article provides a qualitative improvement and leap forward in terms of the advantages and disadvantages of the efficiency structure compared to many literature technologies that have been improved before and now. The hardware design based on electromagnetic induction has improved the layout of the multi coil array, giving it good stability; Magnetic resonance imaging uses finite element method to establish a three-dimensional model that directly guarantees medical and health equipment; The magnetic coupling method significantly improves the anti-offset capability compared to traditional topology efficiency through LCL-LC; Radiation overcomes the bottleneck problem through microwave DC conversion. Talents and researchers in the high-tech field should pay more attention to my findings, because it provides a comparison of technological innovation in different literature before, which can intuitively identify the areas for improvement and also conduct graphical analysis. However, there will be more prominent research issues waiting for us to explore in the future.

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