Technological Advances in Wireless Charging Technology

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Abstract. In recent years, with the continuous development of new energy vehicles, traditional wired charging has become unable to meet people's practical needs. Research on wireless charging technology has garnered significant attention. This paper focuses on the research of wireless charging technology for electric vehicles. First, it points out that wired charging has drawbacks such as electric shock risks and high maintenance costs, then introduces the three mainstream wireless charging technologies: magnetic coupling resonance, electromagnetic induction coupling, and electromagnetic radiation. Magnetic coupling resonant systems transmit energy through resonant coils and are suitable for medium distances. Electromagnetic induction coupling relies on the magnetic field generated by the coil, making it suitable for close proximity. Electromagnetic radiation systems utilize electromagnetic wave radiation and are suitable for ultra-long distances. Literature analysis indicates that magnetic coupling resonance-based methods can achieve over 90% efficiency after optimization, electromagnetic induction methods can exceed 90%, while electromagnetic radiation methods range between 27.7% and 60%. Finally, the current status and development trends of wireless charging technology are discussed. Static wireless charging boasts broad applications and high efficiency, while dynamic wireless charging enables charging on the go. Bidirectional wireless charging holds promise for participating in grid energy storage and dispatch, offering valuable insights for the advancement of wireless charging technology for electric vehicles.

Keywords: Wireless Charging for Electric Vehicles; Magnetically Coupled Resonant; Electromagnetic Induction Coupling; Transmission efficiency.

1. Introduction

Currently, wired charging and wireless charging are the two most common charging methods for electric vehicles. Although wired charging is currently the mainstream method, it still has unavoidable drawbacks. For example, when connecting the charging cable to the charging port, electrical sparks may occur, posing a risk of electric shock. Wired charging equipment and cables require regular maintenance and upkeep, thereby increasing operating costs.

Professor Huang Xueliang's research team designed a real-time road charging system featuring multiple receiving coils. By optimizing control strategies and continuously adjusting power distribution based on load conditions, the system achieved high transmission efficiency [1]. At the 2018 Belt and Road Energy Ministers' Meeting and International Energy Transition Forum, the world's first “three-in-one” electronic highway was demonstrated. Professor Huang's team achieved dynamic wireless charging for electric vehicles using magnetic-coupled resonant wireless power transfer technology. This project has achieved multiple internationally leading innovations in wireless charging efficiency and electromagnetic environmental protection, offering novel solutions to enhance the convenience and safety of electric vehicle charging while addressing issues such as limited driving range [2]. In recent years, Lu Jianhua has conducted research on SS compensation structures, analyzing wireless power transmission systems with constant voltage sources and loads, and establishing a closed-form directional model. Their team primarily investigated two scenarios: both transmitter and receiver operating in resonance, and only the receiver operating in resonance. They discovered that the former scenario is a special case of the latter. Consequently, they performed computational analysis on the latter scenario, conducting detailed studies on voltage gain and output power. This provides guidance for subsequent system design [3].

The development of wireless charging technology for electric vehicles has been further accelerated.

The principles of charging technology primarily encompass the following three types: Magnetic coupling resonance type, electromagnetic induction coupling type, and electromagnetic radiation type.

Magnetic coupling resonance and electromagnetic induction coupling are both suitable for energy transmission over short distances. For longer-distance energy transmission, electromagnetic radiation is employed. However, the three aforementioned wireless charging technologies for electric vehicles still suffer from low efficiency.

Therefore, the development of wireless charging technology still needs to overcome a series of challenges. This paper primarily introduces the principles of three wireless charging technologies and their application scenarios, while analyzing and comparing the efficiency of these three wireless charging methods based on previous literature. The article concludes by discussing the current state and future trends of wireless charging technology.

2. Theoretical Foundation Analysis

2.1. Magnetic Coupling Resonant Wireless Charging Technology

Magnetic resonance coupling wireless charging technology is currently the most extensively researched and most promising wireless charging technology for widespread application. Magnetic coupling wireless charging technology is a wireless charging method that utilizes magnetic fields as the energy transmission medium. Its structure, as shown in Figure 1, primarily consists of two components: the transmitter and the receiver. The charging process of a magnetic resonance coupling wireless charging system can be briefly summarized as follows: the utility grid's power frequency AC current undergoes AC-DC rectification and DC-DC filtering for regulation. This yields a stable DC input voltage. This voltage then undergoes DC-to-AC high-frequency inversion to generate a high-frequency square wave signal. After passing through a resonant compensation network, this signal is transformed into a high-frequency sinusoidal wave and fed into the energy-transmitting coil. Through magnetic coupling, energy is transferred to the receiving coil. At the receiving end, the alternating current is reconverted to direct current via an AC-to-DC rectifier circuit. Finally, the current is regulated through the DC-DC converter to charge the load, thereby completing the vehicle's charging process.

Magnetic coupling resonant wireless charging technology requires specific coil dimensions and necessitates setting a designated frequency for protection. Its primary applications currently include consumer electronics, electric vehicles, medical implant devices, and industrial automation equipment. The transmission efficiency of magnetic coupling resonant wireless charging varies by application scenario. For instance, industrial robot charging can achieve over 92%, while implantable pacemaker charging reaches 75%-80%.

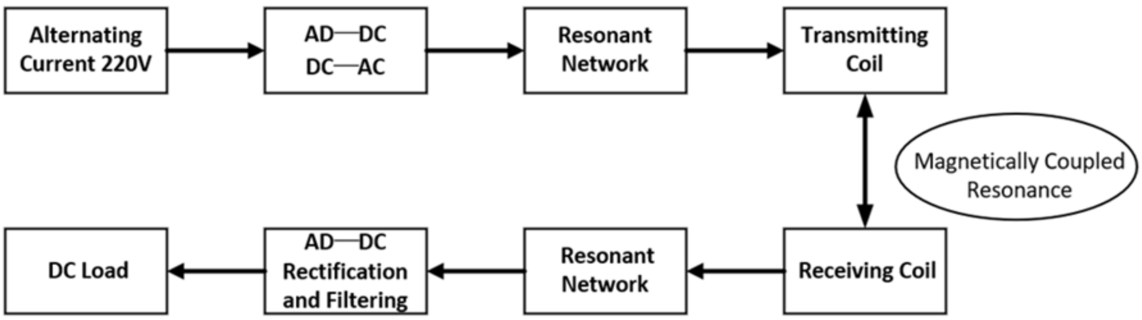

Fig. 1 Block Diagram of Magnetic Coupling Resonant Wireless Charging Principle

2.2. Magnetic Coupling Resonant Wireless Charging Technology

Electromagnetic induction coupling charging technology is currently a relatively mature and widely adopted technology. Electromagnetic induction coupling charging technology consists of two components: the transmitter and the receiver.

The electromagnetic induction coupling wireless charging process, as shown in Figure 2, features the transmitter system in the upper half. First, 220V AC power passes through a step-down rectifier module to obtain the required DC voltage. This DC voltage is then converted into high-frequency AC power via a high-frequency inverter circuit and delivered to the transmitter coil. The lower half of the diagram depicts the receiving-end system. The receiving coil generates an induced electromotive force through the magnetic field coupled by induction with the transmitting coil. This is converted into direct current via a rectifier and filter circuit, ultimately supplying power to the load.

Currently, electromagnetic induction-coupled wireless charging technology suffers from limitations such as short transmission distances (typically on the order of centimeters), stringent requirements for coil alignment, and significant energy loss. Its applications span consumer electronics, including smartphones, wireless earbuds, static charging for electric vehicles, and electric toothbrushes. Transmission efficiency generally ranges between 70% and 90%, though it fluctuates considerably due to multiple influencing factors.

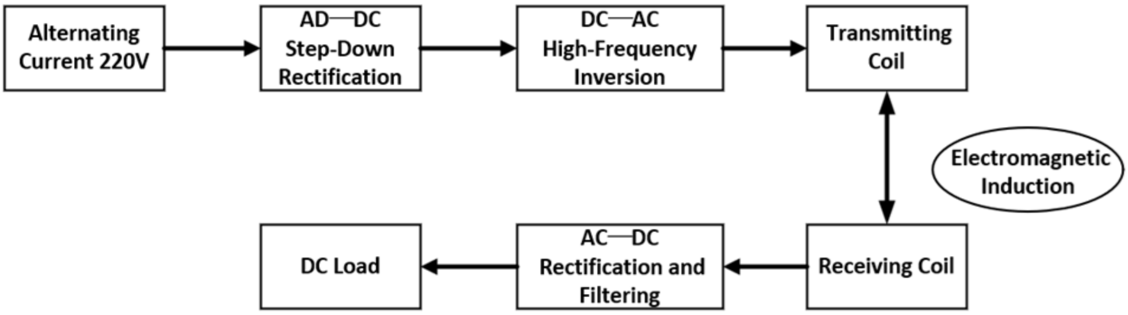

Fig. 2 Block Diagram of Electromagnetic Induction Coupling Wireless Charging Principle

2.3. Electromagnetic Radiation Wireless Charging Technology

Electromagnetic radiation-based systems encompass laser and microwave radiation types, where radio energy transmission is achieved through directional radiation of electromagnetic waves through space. The transmitter comprises a power source, an electromagnetic wave conversion module, and a transmitting antenna, while the receiver includes a receiving antenna, conversion circuitry, and a DC output. Energy is transmitted from the primary-side transmitting antenna to the secondary-side receiving antenna via electromagnetic waves. Upon receiving the energy, the receiving antenna converts it into the required direct current through a conversion circuit, ultimately supplying power to the load, as shown in Figure 3.

Electromagnetic radiation operates across frequency bands ranging from MHz to GHz. Its radio energy transmission does not require fixed power transfer points, making it suitable for long-distance power transmission with high power capacity. However, transmission efficiency declines sharply with increasing distance, and it is susceptible to environmental interference. At the same time, this transmission method must take into account radiation environmental issues, as radio frequency signals can cause harm to the human body. Electromagnetic radiation-based wireless charging is suitable for specialized fields such as aerospace, satellites, and military applications, but is not suitable for wireless charging of household electronic devices like mobile phones.

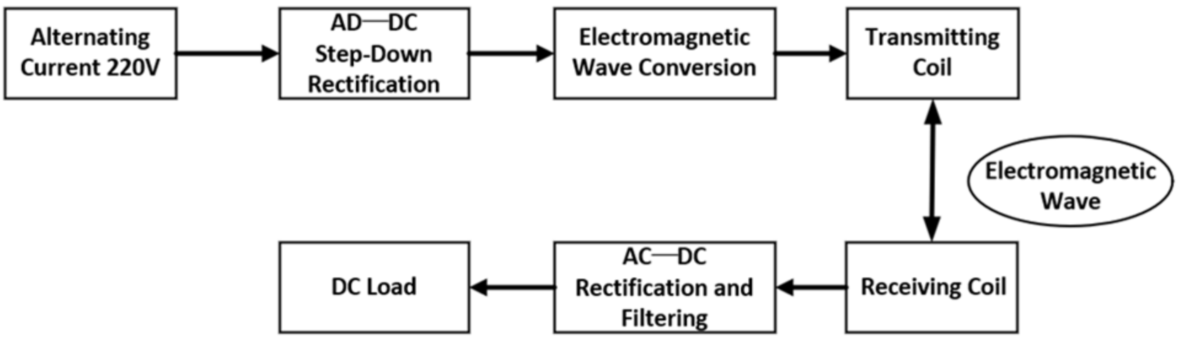

Fig. 3 Block Diagram of Electromagnetic Radiation Wireless Charging Principle

2.4. Efficiency Comparison Analysis

Based on the first three wireless charging technologies, electromagnetic radiation-based wireless charging can achieve transmission distances reaching the kilometer level, enabling ultra-long-range transmission. However, its transmission efficiency is relatively low, hovering around 50%. At the same time, consideration must be given to whether radiation may impact human health and the environment during transmission. Currently, electromagnetic radiation-based wireless charging is widely used in fields such as rail transit and satellites. Magnetic coupling resonance transmission ranks second in distance, reaching up to meters. It enables medium-range transmission with an efficiency of approximately 70%. This technology is currently widely adopted in medical devices. Electromagnetic induction charging has the shortest transmission distance, limited to just a few centimeters. Therefore, electromagnetic induction wireless charging is only suitable for close-range charging. Its transmission efficiency is around 70%, making it ideal for wireless charging of small electronic devices such as electric toothbrushes and mobile phones. The characteristics of the three technologies are summarized and compared as shown in Table 1.

Table 1. Efficiency Comparison Analysis of Wireless Charging Method

Transmission method	Magnetically coupled resonant	Electromagnetic induction	Electromagnetic radiation type
Transmission distance	cm-m	mm-m	km
Transmission efficiency	Around 70%	Around 70%	Around 50%
Vantage	Medium distance charging	Proximity Charging	Remote charging
Drawbacks	Electromagnetic shielding	Position fixed	Inefficiency
Areas of application	Medical devices, etc. Electric toothbrushes, cell phones, etc. Orbiting satellites, etc.	Medical devices, etc. Electric toothbrushes, cell phones, etc. Orbiting satellites, etc.	Medical devices, etc. Electric toothbrushes, cell phones, etc. Orbiting satellites, etc.

3. Efficiency Comparison Analysis

3.1. Research on Magnetic Coupling Resonant Wireless Charging Technology and Optimization Directions

Magnetic coupling resonant wireless charging exhibits varying performance across different studies, and its efficiency can be significantly improved through optimization. Wengyuan's research indicates that fractional-order systems achieve a 0.58% increase in transmission efficiency compared to integer-order systems. The optimized system further enhances efficiency by 4.5%. Although the initial efficiency remains unspecified, the optimization clearly demonstrates a significant improvement in efficiency [4]. The asymmetric D4Q double-layer coil structure proposed by Xu Xianfeng's team achieves a transmission efficiency of 90.39% at a 230mm transmission distance, maintaining 85.2% efficiency even under misalignment conditions. Compared to the D4 structure, its efficiency improves by 11%, demonstrating significant advantages in both efficiency and stability [5]. Zhang Lei's research demonstrates that employing a dual LCC-type compensation network combined with an optimized coil and fuzzy control system can effectively enhance efficiency. Although specific efficiency figures were not provided, this approach has been validated as effective in improving efficiency, thereby boosting the performance of wireless charging systems [6].

Through the above research, it is evident that the efficiency of magnetic coupling resonant wireless charging can be optimized to achieve high levels through rational design. Under specific conditions, some optimized structures can reach 90% efficiency while demonstrating strong resistance to misalignment.

3.2. Electromagnetic Induction Coupled Wireless Charging Technology and Optimisation Direction Research

The efficiency of electromagnetic induction wireless charging varies depending on technical solutions and application scenarios. Jiang Xinqiang's research points out that by optimising the planar circular coil structure (equal reduction coil with 25mm inner diameter and 50mm outer diameter and adding ferrite), adopting the LCC-S compensation structure and the full-bridge inverter circuit, the system's maximum transmission efficiency exceeds 90%, and it is equipped with Qi-compliant foreign object detection, which is both safe and efficient [7]. Liu Gang team used PCB to produce a coreless circular spiral inductor coil, the study found that the transmission distance in 5mm within the best efficiency, but did not specify the specific efficiency value, only pointed out that there is a low efficiency problems need to be optimized, and its program is suitable for short distance less than 5mm, power less than 5W equipment [8]. The system, based on an H-bridge inverter (140kHz switching frequency) and an LC resonant circuit designed by Y. Geng et al. achieves a maximum efficiency of 86% under 30V input and 24V/2.2A output conditions and is stable for 8 hours of continuous operation, which is suitable for portable devices [9].

From the above material analysis, it can be seen that the electromagnetic induction wireless charging after optimization of the highest efficiency can be more than 90%, most of the practical solutions have an efficiency of 86% and above, short distance and small power scenarios under the efficiency of the performance of the better, but there is still room for optimization.

3.3. Electromagnetic Radiation, Wireless Charging Technology and Optimization Direction Research

Radiant wireless charging technology efficiency varies significantly by technology type and design scheme. The microwave wireless charging circuit developed by Boqiang Xu's team realizes more than 60% rectification efficiency in the 1.5GHz-2.5GHz frequency band through the broadband rectifier circuit architecture of the multiplexing mechanism, and has the ability to work in dual frequency bands, which is suitable for the demands of the Internet of Things (IoT) and other scenarios [10]. The RF wireless charging system designed by Song Fugang does not specify a specific efficiency value, but it improves the energy conversion efficiency by optimizing the antenna structure and the RF DC conversion circuit, and it can transmit stably in the 915MHz and 2.4GHz bands, with the longest distance up to 2 meters. However, there is the problem that the conversion efficiency has to be optimized, and the overall efficiency performance still needs to be improved [11]. In the laser wireless charging scheme proposed by Siyuan Fang et al, the photovoltaic conversion efficiency of the monocrystalline silicon photovoltaic cell at the receiving end is 27.7%, and the system can realize a 5W output power, which demonstrates the practicality in remote charging scenarios [12].

Overall, the current wireless radiation charging technology has an efficiency of 27.7%-60% or more. Different technology paths have a large efficiency gap, but the microwave technology in a specific frequency band has relatively outstanding performance, while the radio frequency and laser technologies still has a large optimization space.

4. Trends in Wireless Charging Technology

4.1. Dynamic Wireless Charging

Dynamic wireless charging devices, i.e., whole sections of road are used as charging devices, with segmented wireless charging devices being the most commercially available. The principle is to lay multiple sets of energy transmitting coils on the road so that each set of transmitting coils can work individually and have its own tuning network. It can be switched and controlled by intelligent control algorithms to realize charging while driving. Several such roads have been built in China, and in 2018 the world's first three-in-one electronic highway was unveiled in the new energy town of Tongli, Suzhou, which can not only wirelessly charge new energy vehicles but also serve as a solar-powered photovoltaic highway. In the industrial logistics field, AGV robots also use dynamic wireless charging, which can play a big role in the scene. the domestic enterprises have been through the AGV path section laying track, using supercapacitor charging speed characteristics, so that the AGV passes through the section with fast charging replenishment, so as to realize 24-hour continuous work.

4.2. Bi-directional Wireless Charging

Already, there is the ability for cell phones to reverse charge secondary or other phones, and two-way wireless charging for electric vehicles is a similar concept. If dynamic wireless charging technology can be popularized, electric vehicles can be replenished in real time during the driving process. It will be possible to use the surplus battery power and power supply power from its own battery to supply power to other equipment through the vehicle coil, and even be able to serve as an energy storage carrier for the power grid transmission. Two-way infinite charging eliminates the need for manual plugging and unplugging compared to wired charging, making charging more automated and intelligent. This is important in a driving environment that is constantly undergoing constant bumps. Two-way wireless charging also has advantages in safety. High-power charging generally chooses high voltage to improve the charging efficiency, which can not be avoided, and the power supply car is dragged between the thick high-voltage lines. However, in the rain and snow, extreme weather can cause all kinds of accidents.

Two-way charging of electric vehicles will also bring more convenient living scenarios. An example of this is drone charging, where a drone can drop back into an electric vehicle at any time to charge it. In the future, electric vehicles will be equipped with two-way will be a new pattern, the current global power supply mostly from the base-loaded power plants, in order to reduce costs and improve the efficiency of power generation, power plants will usually be a long period of time constant operation of power generation, but when off-peak hours when the demand for electricity is reduced, continuous operation of most of the electricity issued by the pumped storage.

If the two-way charging technology allows EVs to re-supply the power stored in their batteries to the grid, and then the EVs are integrated into the power management system to be regulated as part of the overall energy network scheduling, and when the power demand decreases in off-peak periods, the surplus power is stored in the remaining batteries, and then reversed to be supplied to the grid during peak periods, then the gap between peaks can be minimized, and more elasticity can be added to the use of energy. Of course, the current technical research on two-way wireless energy transmission is still focused on the theoretical and experimental research stage and needs to be further explored.

5. Conclusion

This paper focuses on the study of wireless charging technology for electric vehicles, comparing the risk of electric shock and the high maintenance cost of wired charging, and focuses on the analysis of the three mainstream technologies of magnetic coupling resonance type, electromagnetic induction coupling type and electromagnetic radiation type. Magnetic coupling resonance type is suitable for medium distance transmission, the optimized efficiency can be more than 90%, used in medical and industrial equipment; electromagnetic induction type is a mature technology for short distance, the efficiency can be more than 90%, widely used in consumer electronics and static charging; electromagnetic radiation type is suitable for ultra-long-distance transmission, the efficiency of 27.7%-60%, limited to special areas.

The study also examines the status and trends in the development of wireless charging technology. Static charging is widely used and has high efficiency, dynamic charging can realize charging while traveling, and there are practical cases in China. Two-way charging is expected to participate in grid energy storage and peaking, although it is still in the theoretical research stage but the development prospects are very promising. Wireless charging technology needs to be further developed to optimize its efficiency and improve its stability in multi-scenario applications

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