Development Status and Application Research of Wireless Charging Technology

Rongzheng Liu[1], Donghui Shao[2], Shisheng Xu[3, *]

[1]International Department, Suzhou No. 1 High School, Suzhou, Jiangsu, China

[2]Senior High School Division, Jining Confucius Senior High School, Jining, Shandong, China

[3]College of Electrical Engineering and Control Science, Nanjing Tech University, Nanjing, Jiangsu, China

* Corresponding Author Email: 200238@yzpc.edu.cn

Abstract. As the demand for convenience and flexibility in modern electronic devices and industrial systems continues to grow, wireless charging technology has become one of the key solutions to the limitations of traditional wired charging. This technology has demonstrated broad application prospects in various fields such as consumer electronics, industrial automation, and medical devices. This paper systematically reviews the latest developments in wireless charging technology, providing a detailed analysis of the fundamental principles, advantages and disadvantages, and application scenarios of different wireless charging methods, including electromagnetic induction, electric field coupling, magnetic resonance, and radio wave methods. To address the technical challenges encountered in long-distance wireless charging, the article explores optimized solutions such as metasurface designs and relay coils. The article also discusses the crucial roles of frequency modulation technology and clean energy harvesting in enhancing wireless power transmission efficiency. Furthermore, the article delves into the practical applications and development trends of wireless charging technology in areas like consumer electronics and industrial applications.

Keywords: Electromagnetic Induction, electric field coupling, magnetic resonance, radio waves, frequency and amplitude modulation technology.

1. Introduction

In the context of rapid technological advancement today, wireless charging technology has become one of the global research hotspots due to its convenience and safety. Since its initial proposal in the early 20th century, wireless charging has undergone significant development. By transmitting and converting energy through electromagnetic fields, this technology greatly enhances the flexibility and applicability of power transmission, freeing devices from the constraints of physical connections. For example, in the field of electric vehicles, electromagnetic induction wireless charging transmits power from underground transmitting coils to receiving coils on the vehicle, providing a convenient and highly flexible charging method [1]. Additionally, a bifurcated transmitting coil design for multi-power-level wireless charging of electric vehicles can significantly reduce infrastructure costs through series compensation of switches [2].

This paper aims to comprehensively review the current development status, basic principles, key technologies, and applications of wireless charging technology across various fields. It deeply analyzes the technical challenges and prospects, providing guidance and reference for the future development of wireless charging technology. First, the study will overview the basic principles of various types of wireless charging currently available and analyze their characteristics. Second, it will explore the relationship between power transmission and transmission distance, analyzing the technical challenges faced by long-distance wireless charging and possible solutions. Finally, the paper will evaluate in detail the practical applications of wireless charging technology in various fields, discussing its development trends and future prospects. Through this comprehensive review, the paper aims to provide a clear technical blueprint for researchers in related fields, promoting further research and application of wireless charging technology.

2. Overview of Wireless Charging Technology

2.1. Basic Principles

2.1.1. Electromagnetic Induction Type

Electromagnetic induction technology is based on Faraday's law of electromagnetic induction, which states that in a closed circuit, a changing magnetic field induces an electromotive force, thereby generating an electric current in the circuit. The coil in the charger (primary coil) generates a changing magnetic field through alternating current (AC). When another coil (secondary coil, i.e., the receiver's coil) is placed within this changing magnetic field, an electric current is induced in the coil. This current is then converted into direct current (DC) to supply the electrical device. Because this requires the two coils to be physically very close, the effective distance of electromagnetic induction is usually short, limited to the millimeter scale [3].

2.1.2. Electric Field Coupling Type

The principle of electric field coupling charging utilizes the induced electric field generated by coupling two sets of asymmetric dipoles in the vertical direction to transmit power. Typically, the charging module consists of two asymmetric dipoles arranged vertically; each dipole comprises active electrodes and ground electrodes in both the power supply and receiving sections. This technology is suitable for medium to long-distance charging and is low-cost and has low losses, making it relatively easier to embed into products. Therefore, it is applicable for underwater applications, dynamic wireless charging.

2.1.3. Magnetic Resonance Type

In contrast, magnetic resonance is based on a unique physical principle known as coupled resonance. When two resonators (such as two coils with the same natural frequency) are within a certain distance, one resonator (the transmitter) can excite the resonance of the other resonator (the receiver) through its vibrational energy, thereby effectively transmitting energy. This method allows energy transmission over relatively longer distances (usually up to several tens of centimeters) and is less sensitive to the efficiency-distance relationship compared to electromagnetic induction, thus providing greater flexibility and convenience in charging scenarios [4].

2.1.4. Radio Wave Type

Radio wave wireless power transmission technology is another method for capturing and converting energy from radio waves (RF waves). This approach leverages the propagation characteristics of radio waves to collect ambient energy over longer distances from various sources (e.g., radio transmitters, and Wi-Fi routers). RF energy harvesting devices typically include one or more antennas for receiving RF signals and conversion circuits for transforming the captured RF energy into usable electrical power. Although each conversion is relatively inefficient and suitable only for low-power devices, this method provides a continuous energy supply, making it particularly suitable for Internet of Things (IoT) sensors and devices [5].

2.2. Analysis of Transmission Methods' Characteristics

Electromagnetic induction charging is one of the most mature and widely used wireless power transmission technologies. This technology has also found extensive applications in small electronic devices like wireless earbuds, mainly due to its relatively simple principle. However, its main drawbacks include the need for specific placement positions and the possibility of metal induction contacts overheating [6]. Electric field coupling charging technology is considered a promising wireless charging solution because its position does not need to be fixed, it has high conversion efficiency, and generates less heat. Unlike magnetic resonance and radio wave charging, electric field coupling technology is more suitable for specific applications like underwater equipment, although it is relatively bulky and has lower power output. Magnetic resonance charging has become one of the popular technologies for wireless charging of electric vehicles due to its suitability for long-distance,

high-power charging and moderate conversion efficiency [7]. Nevertheless, the issues of lower efficiency and potential safety hazards cannot be overlooked. Radio wave charging technology stands out for its long-distance transmission capability and flexible charging environment, making it suitable for applications such as small electronic devices and medical equipment. Although this technology has low charging efficiency and is susceptible to electromagnetic interference, its ability to transmit over long distances offers a flexible solution that does not require precise charging positions [8]. The following is Table 1, which presents their transmission distances, advantages and disadvantages, as well as application scenarios.

Table 1. Comparison of different wireless charging technologies

Transmission Technology	Transmission Distance	Advantages	Disadvantages	Application Scenarios
Electromagnetic Induction Type	Several mm to several cm	Suitable for short-distance charging; simple principle.	Requires specific placement; metal contacts may overheat.	Small electronic devices
Electric Field Coupling Type	Several mm to several cm	Position doesn't need to be fixed; high conversion efficiency; low heat generation.	Large size; low power output.	Underwater equipment
Magnetic Resonance Type	Several cm to several m	Suitable for long-distance, high-power charging; moderate conversion efficiency.	Low efficiency; potential safety hazards.	Electric vehicles
Radio Wave Type	Greater than 10 meters	Long-distance transmission capability; flexible charging environment.	Low charging efficiency; susceptible to electromagnetic interference.	Small electronic devices; medical equipment

3. Optimization of Wireless Power Transmission Schemes

3.1. Physical Fundamentals

The core principle of wireless charging technology is that when a current is applied to the transmitting coil on the transmitter side, the electromagnetic field it generates is collected by the receiving coil on the other end. The receiving coil then converts this magnetic field back into current within itself, which is subsequently integrated and fed into the target battery. A critically important process here is the mutual conversion of energy. Due to the influence of the distance between the transmitting and receiving coils, the energy value of the magnetic field decreases significantly as the distance increases, which in turn greatly impacts the electrical energy converted by the receiving coil.

3.2. Challenges and Solutions for Long-Distance Wireless Charging

Given the current distance limitations of wireless charging technology, it is necessary to explore how to achieve high-power wireless power transmission over long distances.

Firstly, as the distance between the transmitter and receiver increases, the efficiency of wireless charging decreases significantly. This phenomenon is an inevitable result of inherent losses in electromagnetic wave propagation and resonant inductive coupling over distance.

3.2.1. Metasurface design

To address this issue, one strategy is to incorporate a metasurface. Experiments have shown that with a designed metasurface, when the distance is maintained within 100 cm, the maximum transmission power can stabilize at about 83% output [9]. It has the advantages of being unaffected by geometric shapes, offering high transmission efficiency, and allowing for longer distances. Additionally, this strategy demonstrates the possibility of placing the receiver at any distance on the metasurface relative to the transmitter and effectively coupling to it. However, metasurfaces operate at a single frequency and lack universality, and they are actually implemented using wires. This reduces convenience and increases operational costs and safety risks.

3.2.2. Use of relay coils

Another method is to insert relay coils between the transmitting and receiving coils, based on different frequency changes during transmission, to adjust the transmission power via the relay coils, thereby achieving optimal power delivery [10]. Under normal circumstances, when the transmission distance changes, the coupling coefficient and the input impedance of the resonators also change accordingly. Therefore, when there is a mismatch between the source output impedance and the load impedance, the system cannot deliver maximum power to the load. The relay coil can solve this problem through its variable number of coil turns. Secondly, compared to other methods, the relay coil can function in under-coupled regions, highlighting its transmission advantages. In addition, the relay coil occupies a small area and causes less loss to the system. However, inevitably, even when impedance matching is achieved, as the receiver moves away from the transmitter, power loss will increase due to changes in the quality factor of the relay coil under different operating states.

In summary, the power and distance issues of wireless charging technology have been addressed to varying degrees through different approaches, but some new problems inevitably arise in the process. Long-distance wireless charging technology still faces challenges, such as the lack of more effective methods to significantly increase wireless transmission distance without adding extra losses, while ensuring easy installation and strong practicality [11]. When enhancing electromagnetic field energy to improve coil performance, the cost will inevitably increase significantly [12]. Increasing the number of transmitting coils introduces varying gap sizes between different coil combinations, leading to vastly different effects. Therefore, considering economic efficiency, practicality, and the reduction of additional consumption, long-distance wireless charging still faces many challenges and uncertainties that need to be resolved.

4. Other Optimization Methods for Wireless Power Transmission Performance

4.1. Frequency Modulation and Amplitude Modulation Techniques

Frequency modulation (FM) and amplitude modulation (AM) are important strategies for optimizing power transmission. For example, periodic frequency modulation can significantly reduce the harmonic amplitude of motor currents [13]. Similarly, in wireless power transmission, these techniques have the potential to markedly enhance performance under various scenarios. Research indicates that wireless power transmission systems combining frequency modulation (FM) and phase-shift modulation (PSM) strategies can achieve a power transmission efficiency of up to 88.45% at 300 W [14]. Furthermore, in more complex situations such as electric vehicle applications, frequency modulation technology can substantially reduce startup transients, minimizing overstress between components caused by current overshoot [15]. On the other hand, it can also optimize data transmission performance and anti-interference capabilities in kilowatt-level wireless charging environments for electric vehicles, thereby facilitating high-speed simultaneous communication [16].

4.2. Clean Energy Harvesting and Reuse

Given the current trend toward using clean energy, harvesting energy from the surrounding environment is evidently an excellent renewable strategy. Although such energy harvesting provides

very limited power for devices, energy harvesting technology is crucial for powering small sensors and power modules in today's industrial environments [17]. Taking radio frequency (RF) harvesting circuits as an example, antennas receive radio signals from the atmosphere, and rectifiers convert the alternating current (AC) into direct current (DC) for use. Figure 1 illustrates the basic logic of such a circuit [18].

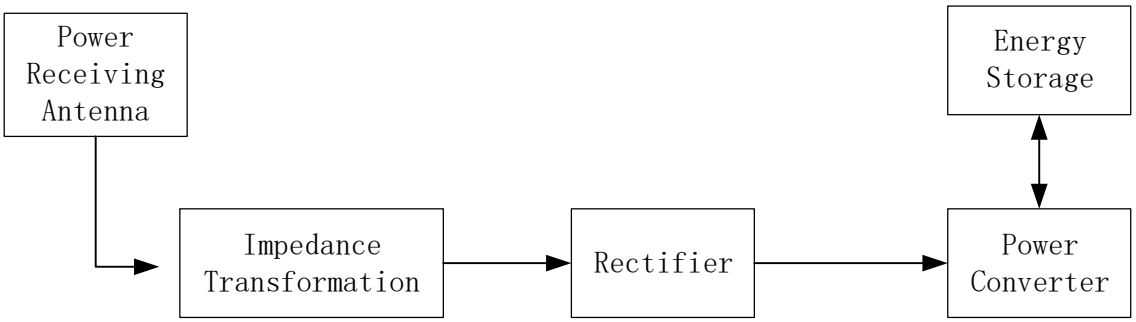


Figure 1. RF acquisition circuit flowchart

Neetu Ramsaroop and colleagues constructed an RF harvesting circuit that, after testing, was able to store the minimum 5 mV load required for charging mobile device batteries [19]. Additionally, by targeting solar energy for harvesting, it can also play a role in high-power scenarios. Wang Cong and others simulated a hybrid framework by combining solar energy harvesting with wireless charging technology, which could reduce battery consumption by 20% [20].

5. Analysis of Application Fields

5.1. Consumer Electronics

The application of wireless charging technology in consumer electronics is growing rapidly, especially in smartphones, wearable devices, and home automation systems. This technology not only enhances charging convenience but also extends the device lifespan by reducing the use of cables and connectors [21]. Additionally, wearable devices like smartwatches and health monitors have begun adopting wireless charging because lighter and seamless charging solutions align well with users' needs for portability and comfort [22]. The following is Table 2 which presents a comparison of different wireless charging standards, as well as their respective current status, standards, and major challenges.

Table 2. Analysis of the current status and challenges of wireless charging for different device types

Device Type	Current Status	Common Wireless Charging Standards	Main Challenges
Mobile phones	Qi standard; good compatibility and ease of use	Qi	Charging speed
Smartwatches	Proprietary standards; limited by miniaturization and power requirements	Qi/Proprietary standards	Miniaturization
Wireless Earbuds	Low power requirements; good compatibility	Qi/Proprietary standards	Battery life

5.2. Industrial Applications

Wireless power transmission technology also has widespread advantages and potential in industrial environments. Traditional wired connections in such settings may pose operational risks or limitations. For example, in hazardous areas containing explosive materials, conventional electrical connections can act as ignition sources, creating significant safety hazards. Wireless power transmission addresses this issue by enabling energy transfer without physical contact, thereby reducing ignition risks and improving operational safety [23]. Moreover, adopting wireless power transmission systems in automation and manufacturing processes can reduce downtime associated with cable wear, ultimately enhancing operational efficiency [24].

The introduction of wireless power transmission has also significantly impacted the mobility and flexibility of industrial machinery and robots. Automated Guided Vehicles (AGVs) are crucial for material transport in factories, and the mobile charging capabilities provided by wireless power transmission enhance their advantages. This continuous operation capability significantly reduces idle time usually associated with traditional charging methods, promoting smoother and more efficient logistics workflows [25].

In terms of energy management and sustainability, wireless power transmission technology facilitates the deployment of extensive sensor networks without relying on battery replacements, thereby reducing waste and maintenance costs. The ability to wirelessly charge sensors and devices offers opportunities to integrate wireless power transmission with renewable energy sources, ensuring continuous power supply for industrial sensors and equipment. This integration highlights the potential of wireless power transmission to contribute to sustainable energy solutions in industrial environments [26].

6. Conclusion

Wireless charging technology has established itself as a core area of global technological research, demonstrating enormous development potential and a wide range of applications. This paper provides an in-depth review of wireless charging technology, thoroughly showcasing its comprehensive development from basic principles to optimization strategies and application fields. From electromagnetic induction to electric field coupling, magnetic resonance, and radio wave methods, various charging technologies exhibit unique advantages tailored to different application scenarios. In exploring the relationship between power and transmission distance, the study analysis in detail the technical challenges in long-distance wireless charging and their solutions. Although transmission distance limitations still exist, technological advancements have significantly improved both the range and efficiency of transmission, as well as integration with clean energy. Furthermore, the rapid expansion of wireless charging technology in consumer electronics and industrial applications further validates the speed and breadth of its technological progress. Therefore, wireless charging technology possesses profound development potential.

Looking ahead, the development of wireless charging technology still needs to address multiple challenges such as improving efficiency, controlling costs, and ensuring safety. Continuous research and innovation will be key to driving technological progress. At the same time, the integration and compatibility of wireless charging technology with renewable energy also indicate important directions for future research. This paper aims to provide valuable references and insights for researchers and engineers in the field, with the hope of promoting wireless charging technology toward more efficient and widespread applications.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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