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Wireless Charging System in Smart Distribution Grids

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Abstract. With the growth of global energy demand and the aggravation of environmental issues, the integration of smart distribution grids and wireless charging technology has become a hot topic of research. This paper focuses on wireless charging systems in smart distribution grids, and through comparative research, explores their architecture, application modes, and key technologies. Based on the principles of electromagnetic induction, magnetic resonance, and other technologies, an efficiency model for wireless charging systems is constructed. The performance differences between wireless charging and traditional wired charging systems are compared and analyzed from the perspectives of construction costs, transmission distance, and transmission efficiency. Research has found that wireless charging systems offer significant advantages in terms of convenience and flexibility, but they also have disadvantages such as high initial costs and low transmission efficiency. In response to challenges such as multi-load management and high-voltage scenario adaptation, we propose solutions such as intelligent algorithm optimization and the application of new materials. Research indicates that wireless charging systems are an important innovative addition to smart grids. Their widespread adoption depends on technological progress, cost control, and collaboration among multiple parties, providing a reference for the future integration of smart grids and the new energy industry.

INTRODUCTION

With the continuous growth of global energy consumption and increasingly serious environmental issues, smart distribution grids, as a new type of power system architecture, are developing rapidly around the world. Smart distribution grids use advanced information and communication technologies to enable intelligent management and control of power systems, improve energy efficiency, and promote large-scale integration of renewable energy sources [1]. In this context, wireless charging technology, as an innovative solution that can significantly improve the convenience and flexibility of electricity use, is gradually being integrated into the smart distribution grid system. With the explosive growth of the electric vehicle market and the widespread adoption of mobile smart devices, traditional wired charging modes are no longer sufficient to meet diverse power needs [2]. Wireless charging systems use technologies such as electromagnetic induction and magnetic resonance coupling to achieve non-contact energy transfer, which not only simplifies the charging process and improves the user experience, but also provides more flexible load management and energy dispatch solutions for smart grids [3].

This paper aims to explore the application prospects and key technologies of wireless charging systems in smart grids. Through a comparative analysis with traditional wired charging systems, it reveals the characteristics of wireless charging systems in terms of construction costs, transmission distances, and efficiency. Additionally, it proposes optimization strategies to address the main challenges currently faced, providing a reference basis for the research and application of wireless charging systems in smart grids.

THEORETICAL BASIS OF WIRELESS CHARGING SYSTEMS IN SMART GRIDS

Architecture of Wireless Charging Systems

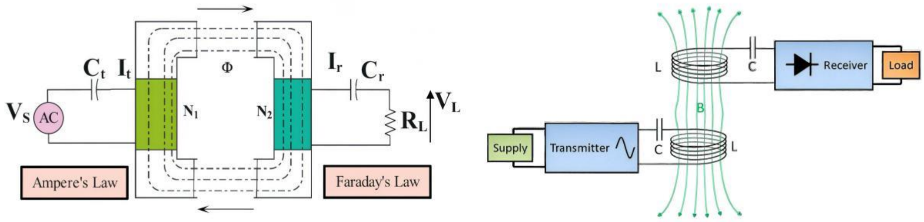

Figure 1. Wireless charging system architecture

As shown in Figure 1, a wireless charging system typically consists of two main parts: the power supply side and the load side. The power supply side includes an AC-DC converter, a high-frequency oscillator, and a transmitter coil. The load side consists of a receiver coil, a rectifier filter circuit, and a load. Energy is transferred between the two sides through an electromagnetic field without the need for a physical connection.

Application of Wireless Charging Systems in Smart Distribution Grids

The application modes of wireless charging systems in smart distribution grids mainly include fixed charging, dynamic charging, and hybrid charging. Fixed charging is suitable for electric vehicle parking lots, home appliances, mobile devices, and other scenarios. Users only need to place their devices in the designated area to charge them [3][4]. Dynamic charging allows devices to charge continuously while in motion, such as road-embedded charging systems for electric vehicles. The core technology lies in high-frequency electromagnetic coupling and resonant network design [5]. The hybrid charging mode combines the flexibility of mobile chargers with the stability of fixed charging points, making it particularly suitable for multi-device collaborative charging needs in industrial wireless sensor networks and smart factories [6].

In a smart grid environment, the application of wireless charging systems is also closely integrated with functions such as energy management, load balancing, and demand response. For example, through intelligent scheduling algorithms, wireless sensor networks can analyze power grid data in real time, optimize transmission, distribution, and user interaction, and achieve efficient decision-making and resource management, such as dynamic capacity expansion, rapid fault isolation, and intelligent control of user-side loads, thereby improving power grid reliability and energy efficiency [7]. In addition, wireless charging systems can also be integrated with distributed energy systems, such as photovoltaic power generation and energy storage systems, to achieve efficient utilization of local energy [8].

With the continuous advancement of technology, the application of wireless charging systems in smart grids is evolving toward high power, long-distance, and simultaneous charging of multiple devices. Researchers are exploring the use of wireless charging technology to provide fast charging solutions for electric buses and heavy-duty trucks. At the same time, wireless charging technology is also being integrated with emerging technologies such as the Internet of Things and artificial intelligence, providing new impetus and possibilities for the development of smart grids [9].

PERFORMANCE COMPARISON BETWEEN WIRELESS CHARGING SYSTEMS AND TRADITIONAL WIRED CHARGING SYSTEMS

Comparison of Construction Costs

From the perspective of early construction costs, the equipment costs of wireless charging systems are significantly higher than those of traditional wired charging systems. In terms of equipment costs, wireless charging technology is relatively new, and the industrial chain is not yet complete, resulting in higher costs for related equipment and materials. Traditional wired charging technology is relatively mature, with a simple hardware structure and a high degree of standardization, resulting in low costs after mass production. Taking electric vehicle charging as an example, the core components of magnetic coupling resonance wireless charging systems (such as transmitter coils, high-frequency inverters, detection sensors, etc.) account for 40% to 50% of the total cost, with a single set costing approximately 2 to 3 times more than a wired charging station of the same power [10]. In terms of infrastructure construction, wireless charging requires the installation of underground coils or road-embedded systems. The construction cost of a dynamic wireless charging road per mile is approximately 28 million RMB, while the construction cost of a traditional wired charging station is approximately 60 million RMB. Calculated based on a single station covering 1 mile, the cost of wireless charging is more than 46 times that of wired charging [11]. In terms of installation and maintenance costs, wireless charging systems are more complex to install. Take static wireless charging as an example. It requires precise calibration of the positions of the transmitter and receiver to ensure electromagnetic coupling efficiency, which increases construction difficulty and time costs. Dynamic wireless charging requires the dense installation of coils beneath the road surface, with construction periods lasting several months, whereas traditional wired charging stations typically only require a few weeks to install. In addition, wireless charging systems have high maintenance costs. Their high-frequency inverters, detection sensors, and other precision components have relatively high failure rates. Furthermore, once the underground coils are damaged, repairs require excavating the road surface, significantly increasing costs. In contrast, maintenance of wired charging systems mainly focuses on charging station interfaces and cables. The technology is mature and maintenance is convenient, with annual maintenance costs amounting to approximately 3%–5% of equipment costs, while wireless charging systems may reach 5%–8%.

However, from the perspective of long-term operation and maintenance costs, wireless charging systems have certain advantages. Wireless charging systems do not require frequent replacement of charging cables, thereby reducing maintenance costs. A. Ambika et al. pointed out that wired charging stations incur high maintenance costs on an ongoing basis. These costs, combined with high upfront installation costs, cause operators to question their economic viability, especially in areas with low electric vehicle penetration rates, where the return on investment is even more uncertain [12]. Liu et al. analyzed the operating mechanism of the dynamic wireless charging lane (DWCL) system and verified that this technology enables buses to recharge while driving through wireless charging lanes, thereby reducing the time spent at terminal charging stations and lowering life cycle costs through optimized battery capacity and shared charging infrastructure [13].

Overall, although the initial construction costs of wireless charging systems are high, their long-term operating costs and potential indirect benefits may offset this disadvantage. With the maturation of technology and large-scale application, the cost of wireless charging systems is expected to decrease further, improving their economic feasibility.

Transmission Distance Analysis

Transmission distance is a core indicator of the flexibility and coverage of energy transmission in smart distribution grids, directly affecting the system's ability to adapt to ubiquitous devices. Traditional wired charging systems rely on physical cables, which can achieve long-distance transmission of thousands of meters on high-voltage power lines, but their terminal charging distance is limited by cable length, typically between 1 and 5 meters. In the power supply scenario of distributed equipment in distribution grids, it is difficult to meet the flexible power supply requirements of dynamic equipment deployment, which is fundamentally contradictory to the development goals of smart distribution grids, namely “plug-and-play and ubiquitous interconnection.”

In contrast, the transmission distance of wireless charging systems depends on the type of technology used.

Electromagnetic induction technology transmits energy through magnetic field coupling between coils. The effective transmission distance is typically between a few millimeters and a few centimeters, and can be extended to 20 cm with optimized design. Although the distance is extremely short, it demonstrates unique advantages in the power supply of fixed equipment in distribution networks. Dr. P. Kabilamani and his team achieved energy transmission using a small induction coil module with a 20V low-voltage input. The system integrates high-precision sensors to monitor voltage, current, and temperature data in real time. Experimental verification showed that the modified electromagnetic induction wireless charging technology achieved a charging efficiency of 85.1%, but the transmission distance was limited to 5-20cm, requiring strict alignment of the coils. This solution provides an efficient and secure wireless power supply solution for fixed devices such as sensors [14].

Magnetic resonance technology utilizes the principle of resonant coupling to achieve medium-range energy transmission with an effective distance of tens of centimeters to 1 meter. Similarly, in the field of wireless charging, Xu Jie and others used magnetic resonance technology to achieve a stable power supply at a vertical distance of 0-15 cm between the transmitter and receiver, with a transmission efficiency of over 80%, breaking through the distance limitations of traditional inductive charging [15].

Radio frequency technology converts electrical energy into radio frequency signals via antennas, which are then radiated. At the receiving end, rectifier antennas convert the radio frequency energy back into direct current. In theory, this enables energy transmission over longer distances, but its efficiency decreases sharply with increasing distance. Nachiket Ayir et al. built a test platform based on software-defined radio and conducted experiments to evaluate the efficiency of different waveforms in RF wireless power transmission. They proved that channel attenuation is significantly negatively correlated with overall DC-DC efficiency: when channel attenuation exceeds 20dB, the efficiency of all waveforms drops sharply to an extremely low level [16].

The transmission distance characteristics of wireless charging technology in distribution grids complement those of traditional wired charging, forming a complementary pattern of "short-distance flexible adaptation-long-distance stable transmission": electromagnetic induction dominates near-field sealed equipment, magnetic resonance supports medium-distance dynamic loads, and radio frequency explores long-distance ubiquitous power supply; while wired charging maintains its irreplaceable advantage in distribution grid trunks and high-power fixed scenarios.

Transmission Efficiency Comparison

Transmission efficiency is a core indicator of charging system performance, directly affecting energy utilization and charging speed. Traditional wired charging systems use direct physical connections, resulting in low energy loss during transmission and typically achieving transmission efficiencies of over 90%. In contrast, wireless charging systems typically have lower transmission efficiency than wired charging systems, but significant progress has been made in recent years. C. C. Lee et al. proposed a novel wireless charging system for electric vehicles, which improved energy transfer efficiency from 75.05% to 82.5% by optimizing the magnetic rod configuration, representing an absolute efficiency improvement of 7.45 percentage points. The key improvement lies in guiding the magnetic flux through magnetic rods and reducing eddy current losses. At the same time, a three-dimensionally rotatable charging coil network has been designed that can dynamically adapt to the vehicle's parking position to maintain efficient transmission [17].

The transmission efficiency of RF charging technology is relatively low, typically ranging from 30% to 50%, and decreases rapidly with increasing distance. However, RF charging technology still has advantages in specific application scenarios, such as powering distributed low-power IoT devices [18].

Although the transmission efficiency of wireless charging systems is currently lower than that of wired charging systems, their convenience and flexibility advantages may offset efficiency losses in certain application scenarios. With continuous technological advances, the transmission efficiency of wireless charging systems is expected to further improve, narrowing the gap with wired charging systems.

Performance Comparison Summary

Table 1 summarizes the comparison results of the two charging systems in terms of various indicators.

TABLE 1. Comparison of the performance of wireless charging systems and traditional wired charging systems

Performance Indicator	Wireless Charging System	Traditional Wired Charging System
initial construction costs	Higher (1.5-2 times that of wired systems)	lower
Long-term maintenance costs	lower	High (requires regular replacement of cables)
transmission distance	Electromagnetic induction: several millimeters to several centimeters Magnetic resonance: several tens of centimeters to 1 meter Radio frequency: theoretically up to several meters	1-5 meters (limited by cable length)
transmission efficiency	Electromagnetic induction: 85%-90% Magnetic resonance: 75%-85% Radio frequency: 30%-50%	90%-97%
Ease of use	High (no physical connection required)	Middle (requires manual connection)
flexibility	High (dynamic charging possible)	Low (fixed charging position)
safety	Medium (electromagnetic radiation must be considered)	High (direct physical connection)
Applicable scenarios	Mobile devices, electric vehicles, public transportation, IoT devices	Various electronic devices, high-power charging

As can be seen from Table 1, wireless charging systems and traditional wired charging systems each have their own advantages. Wireless charging systems excel in terms of convenience and flexibility, making them particularly suitable for mobile devices and scenarios that require frequent charging. However, there is still room for improvement in terms of transmission efficiency and initial construction costs. Traditional wired charging systems have advantages in terms of transmission efficiency and high-power charging, but they offer less flexibility in use.

Wireless charging systems have broad application prospects in smart grids, particularly in areas such as electric vehicles, public transportation, and the Internet of Things. With continuous technological advances and cost reductions, wireless charging systems are expected to complement traditional wired charging systems in more scenarios, providing users with more diverse and convenient charging solutions.

APPLICATION CHALLENGES AND OPTIMIZATION

In smart power grids, wireless charging systems and wireless power transmission technologies face numerous challenges in the field of energy transmission. In terms of multi-load energy management, the new power system faces complex coupling scenarios involving multiple power sources and multiple loads. For example, when multiple electric vehicles are wirelessly charged simultaneously, power distribution becomes uneven, system efficiency decreases, and electromagnetic interference and coordinated control between multiple devices become challenging, thereby affecting grid stability [19]. In high-voltage, high-power scenarios, traditional wireless power transmission technologies face challenges related to insulation design and electromagnetic compatibility. High-voltage environments can easily cause equipment insulation breakdown, and high-frequency electromagnetic radiation may interfere with power grid signals. Additionally, input voltage imbalance issues in series inverters can lead to equipment overload risks, limiting their application in high-voltage transmission grids [20].

In response to the above challenges, optimization efforts can be pursued from multiple angles.

In terms of multi-load cooperative control, a single inverter single transmission coil topology can be used in combination with a dual-frequency LCC-S compensation network design. Different frequencies are used as independent transmission channels to achieve decoupling between loads, effectively reducing electromagnetic interference and coupling effects between multiple devices. By optimizing the compensation network parameters using the differential evolution algorithm and the Lagrange multiplier method, the number of design variables was reduced from seven to one. Taking into account the parasitic resistance of the inductor, high efficiency and high power transmission were achieved. This method ensures load independence and constant voltage output without complex control, solving the problems of uneven power distribution and reduced system efficiency when multiple loads are connected simultaneously, thereby improving grid stability [21].

For high-voltage applications, a five-coil multi-relay wireless power supply system has been designed, utilizing compensated capacitor parameter adjustment to achieve constant voltage output and zero-phase angle input, thereby resolving voltage imbalance issues in series inverters. Additionally, the system innovatively integrates multiple relay coils with epoxy resin composite insulators into a single encapsulated unit, meeting 35kV voltage withstand requirements. This design ensures high-voltage insulation performance, while also effectively isolating power frequency high-voltage electric field interference through a 201kHz high-frequency operating mode. Experimental results show that the system achieves a transmission efficiency of 84.5% at a power of 44.38W, combining high-voltage insulation safety with electromagnetic compatibility [22].

CONCLUSION

This study delves into the key technologies, application scenarios, and development trends of wireless charging systems in smart grids. Through a comparative analysis of wireless charging systems and traditional wired charging systems, we find that wireless charging technology offers significant advantages in terms of convenience and flexibility, making it particularly suitable for small-scale residential or campus applications. However, wireless charging systems still face challenges in terms of charging efficiency, transmission distance, and cost.

Wireless charging systems, as an innovative charging method, are becoming an indispensable component of smart grids. As technology continues to advance and application scenarios expand, wireless charging systems will make significant contributions to the development of smart grids and the widespread adoption of new energy technologies. However, to achieve the widespread adoption of wireless charging technology, collaborative efforts from governments, businesses, and research institutions are needed to strengthen policy support, increase R&D investment, advance standardization processes, and continuously enhance public awareness and acceptance of this technology. Only through such efforts can the full potential of wireless charging systems be realized, driving the sustainable development of smart grids and the new energy industry.

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