Research on Application of Power Electronics Technology in Wireless Charging System for Household Appliances

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Abstract. With the popularity of smart home devices and the upgrading of energy management needs, wireless charging technology for household appliances has become a research hotspot in academia and industry due to its advantages of getting rid of the shackles of cables and improving security and spatial freedom. However, the traditional scheme is limited by the bottleneck of low efficiency, short transmission distance, poor electromagnetic compatibility, and so on, which makes it difficult to meet the needs of high-power electrical appliances wireless and whole house power supply scenarios. With the power electronics technology as the core, this paper systematically studies the key technologies, core issues, and future trends of home wireless charging systems. By combining previous research and the latest progress, it aims to provide theoretical support and a technical path for constructing an efficient, safe, and intelligent wireless energy network.

Keywords: Power Electronics, Wireless Charging System, Household Appliances

1 Introduction

With the rapid development of the Internet of Things (IoT) and smart homes, the traditional wired power supply mode is difficult to meet the needs of modern home equipment for flexibility, security, and aesthetics due to the disadvantages of complex wiring, vulnerable interface, space constraints and so on. Wireless charging technology provides a revolutionary solution for the power supply of household appliances through contactless energy transmission. According to the prediction of allied market research, the global home wireless charging market will exceed US $24 billion by 2030, with a compound annual growth rate of 22.3%. This growth is not only due to the popularity of consumer electronics (such as mobile phones and headphones) but also due to the wireless transformation demand of high-power equipment such as kitchen appliances and cleaning robots. In recent years, international academic and industrial circles have carried out intensive research around the improvement of wireless charging efficiency, long-distance transmission, and intelligent control, and made a series of breakthroughs:

A. J. Moshayedi (ed.), *Proceedings of the 2025 2nd International Conference on Electrical Engineering and Intelligent Control (EEIC 2025)*, Advances in Engineering Research 279,
https://doi.org/10.2991/978-94-6463-864-6_28

in terms of high-frequency and efficient energy conversion, the introduction of wide band gap semiconductor (GaN/ SiC) pushed the switching frequency to MHz level, and combined with LLC/ CLLC resonant soft switching technology, the system efficiency has achieved further breakthrough. In terms of long-distance transmission technology, magnetic resonance coupling and dynamic impedance matching technology extend the transmission distance to more than 50cm. In terms of the standardization process, the Qi standard of WPC alliance iterates to v2.0 to support up to 15W transmission, while the air fuel alliance focuses on 6.78mhz magnetic resonance technology to promote the standardization of medium power equipment (100W level).

However, despite the continuous progress of technology, the home wireless charging system still faces multiple bottlenecks: the transmission efficiency of high-power (>2000w) and long-distance (>50cm) is generally less than 50%, and the cost of GaN/ SiC devices remains high. The high-frequency magnetic field interferes with Wi-Fi/ Bluetooth communication, the heat dissipation pressure and device aging problems caused by high-frequency have not been completely solved, and many problems such as poor device compatibility caused by numerous private protocols still need to be solved.

This paper systematically analyzes the technical architecture, key technologies, core challenges, and innovation path of the home wireless charging system, focusing on the system composition and working principle, and analyzes the energy transmission mechanism of electromagnetic induction, magnetic resonance coupling, and mixed mode. Power electronics technology breakthrough: explore the contribution of key technologies such as high-frequency inverters, synchronous rectifiers, and soft switches to efficiency improvement. Intelligent control and safety design: study AI-enabled dynamic tuning, foreign object detection, and EMC optimization strategies.

This paper aims to provide a theoretical framework for technology evolution for academia, clarify the path of technology research and commercialization for industry, help wireless charging from "proof of concept" to "scale application", and promote the upgrading of smart homes to tailless and low-carbon.

2 Overview and Key Technologies of Wireless Charging Systems for Household Appliances

The wireless charging system for household appliances is a technology system based on non-contact energy transmission, and its core function is to achieve wireless transmission of electrical energy through electromagnetic fields. There are three main types of wireless energy transmission methods: electromagnetic induction, electromagnetic resonance, and electromagnetic radiation. Electromagnetic induction is currently the most commonly used wireless power transmission method, and its technology has been mass-produced, with lower production costs than other technologies. Based on these methods, many novel applications have been achieved, and various wireless power transfer (WPT) techniques, from chip-scale WPT to room-scale WPT, have been presented [1]. The system consists of two major parts: the transmitter and the receiver. The collaborative work of each module ensures efficient and safe energy transmission.

2.1 Composition and Working Principle of Wireless Charging System for Household Appliances

Transmitter. As the energy supply unit of the system, the design of the transmitter needs to meet the requirements of high-frequency energy generation, magnetic field regulation, and intelligent management. The power input and rectification module converts the main power into DC power. It uses the boost circuit and average current control algorithm to improve the power factor and reduce the harmonic pollution to the power grid. Then, the high-frequency inverter module converts DC into high-frequency AC (100 kHz-10 kHz) and generates a high-frequency alternating magnetic field through the transmitting coil and resonant network, which is resonant coupled with the receiving end [2]. This is achieved through Faraday's law of electromagnetic induction. When the transmitting coil is connected with high-frequency alternating current, an alternating magnetic field will be generated around it. After the receiving coil cuts the magnetic induction line, the electromotive force will be induced to realize electric energy transmission.

Receiver. The receiver is integrated inside the appliance, and its design needs to take into account both efficient energy reception and regulated output. The receiving coil and resonance compensation device form a strong coupling resonance system by tuning the coils at the transmitting end and the receiving end to the same resonance frequency and transferring the energy to the subsequent circuit through near-field magnetic resonance. Subsequently, the rectifier and voltage regulator module convert high-frequency AC to stable DC for household appliances. At the same time, the feedback and protection module feeds back the load status in real-time and implements protection. For example, when the coil temperature exceeds a certain degree, the output power is reduced step by step to avoid device damage.

2.2 Analysis of Key Technologies of Wireless Charging System for Household Appliances

High Frequency Power Generation and Inverter Technology. The full bridge/half bridge inverter topology is adopted to convert DC to AC through high-frequency switch. The traditional silicon-based MOSFET is limited by switching loss, which is difficult to support MHz frequency, while wide band gap semiconductor devices (such as GaN and SiC) can increase the switching frequency to 1 – 10 MHz due to their high electron mobility and high-temperature resistance.

To reduce switching losses, zero voltage switching (ZVS) or zero current switching (ZCS) technology is adopted. Taking LLC resonant converter as an example, the resonant cavity (inductance capacitance inductance network) is used to make the switch turn on when the voltage/current crosses zero, to reduce the switching noise and loss.

The experiment compares the pulse width modulation (PWM) converter using hard switching technology and LLC resonant converter using soft switching technology. Under the following experimental conditions: Vin=300 to 400V, Vout=48V, and Pout=1kW, the switching frequency for PWM is 100kHz, and the switching frequency for LLC is from 80kHz to 120kHz (when the switching frequency is increased, the results will be more favorable to LLC resonant converter since the switching loss in LLC resonant converter is much less than PWM converter). Experiments show that LLC resonant, which uses ZVS technology, can reduce the secondary conduction loss from 34W to 14.4W, improving the inverter efficiency by about 3% [3].

High Efficiency Rectification and Voltage Stabilization Technology. Traditional diode rectifier has large loss due to forward voltage drop (0.3–0.7 V). With the increase of output current demand, low-voltage MOSFET replaces diode as synchronous rectifier (SR) switch. The on voltage drop of MOSFET (determined by the on resistance) is much lower than that of diode, which significantly reduces the on loss and improves efficiency. In addition, the high frequency switching characteristics of MOSFET support higher switching frequency, which can reduce the volume of transformer and filter elements [4].

The adaptive DC-DC conversion selects the buck, boost, or buck-boost topology according to the load demand. For example, the wireless charging receiver of mobile phone uses a buck converter to output 5v/2a, while high-power equipment such as a vacuum cleaner needs a boost converter to output 24v/5a. A peak current mode control algorithm is introduced to suppress input voltage fluctuation.

Intelligent Power Management and Security Protection Technology. Power electronics technology realizes accurate power regulation and system safety through closed-loop control. The closed-loop power control adopts the strategy of combining PWM and pulse frequency modulation (PFM): use PFM to reduce switching loss under light load, and switch to PWM to ensure power density under heavy load [5].

Foreign object detection (FOD) is the core guarantee technology for the safe operation of wireless charging systems. Its core task is to identify and prevent metal objects (such as coins, keys, etc.) from entering the charging area to avoid fire or equipment damage caused by eddy current heating. FOD can be divided into system parameter detection methods, wave-based detection methods, and field-based detection methods [6]. The system parameter detection method is based on power difference and impedance change to identify abnormalities and relies on a high-precision Hall sensor and MCU algorithm to quickly turn off (response<10ms). The wave-based detection method generates high-frequency signals through a swept frequency inverter and combines a phase-locked loop (PLL) to track resonant frequency offset and phase distortion to suppress harmonic interference. The field-based detection method uses magnetic sensor array or auxiliary coil to monitor the magnetic field distribution and uses differential amplification and edge calculation to locate metal foreign bodies.

3 Application of Power Electronics Technology in Wireless Charging System

3.1 High Efficiency Power Converter

The power converter of the home wireless charging system should meet the following requirements: high conversion efficiency (>95%) to reduce losses. Increasing the switching frequency to 100 khz~10 MHz to reduce the volume of magnetic components (such as transformers and inductors). Wide load adaptability to cover the power range from 5W (mobile phones) to 2000W (kitchen appliances) and still maintain high efficiency under light load. Low electromagnetic interference (EMI), fast dynamic response, high reliability, etc.

To achieve high-efficiency energy conversion, soft switching technology has become the key scheme. In the mainstream topology, the LLC resonant converter, with its full load range soft switching characteristics, can achieve 97% efficiency in low and medium power scenarios (50W–500W) and low EMI, but the design of magnetic components is complex. The phase-shifted full bridge (PSFB) is suitable for high-power (>1kW) applications and can achieve ＞ 95% efficiency combined with silicon carbide (SiC) devices, but its light load performance is poor [7]. Class E amplifier has the advantages of MHz high frequency and small size, which is suitable for small power equipment such as electric toothbrushes, but it is sensitive to parameters and limited power (<100W) [8]. In contrast, LLC is more balanced between comprehensive performance and cost, while the phase-shifted full bridge combined with Sic scheme has more advantages in high-power kitchen appliances.

3.2 Precise Power Control Strategy

The power control of the home wireless charging system needs to meet the following key requirements: High-efficiency transmission to maintain high overall efficiency under different loads and reduce energy waste. Dynamic response capability: when the load changes suddenly (such as equipment access or disconnection), it can be adjusted quickly to reduce the response time and output voltage fluctuation. Safety protection: real-time monitoring of overvoltage, overcurrent, and overheating, and timely triggering of protection. Anti-interference: restrain coil offset, temperature drift, and other interference to ensure output stability. Low standby power consumption to save energy.

The precise power control strategy based on power electronics technology mainly includes closed-loop control strategy and maximum efficiency tracking (MET) strategy. Closed-loop control regulates the system output through real-time feedback, which is the core means of wireless charging power control. The MET strategy ensures that the system always operates in the optimal efficiency range by dynamically adjusting the working point. Among them, the main methods of closed-loop control strategy include proportional integral differential (PID) control and model predictive control (MPC). MET strategy realizes frequency tracking control by resonant frequency detection and phase-locked loop (PLL) synchronization technology, and impedance matching control by dynamic compensation network and algorithm control. The advantage of PID control is that it has high efficiency under fixed load, but the efficiency decreases significantly when the load fluctuates [9]. The advantage of MPC control is that the efficiency is stable under high-power dynamic load, but the efficiency is slightly low under light load due to algorithm reasons [10]. The advantage of MET strategy is that the efficiency of medium-distance transmission is significantly improved, but the switching loss increases at high frequency. At the same time, the cost of PID control is low, suitable for low-power, low-cost electrical appliances. The cost of MPC control is higher, which is suitable for high-end appliances with medium power.

3.3 EMC Design and Optimization

In wireless charging systems for household appliances, high-frequency switches, and their strong magnetic field characteristics can easily cause electromagnetic compatibility issues, including conducted interference, radiated interference, and internal coupling interference within the system. The source of conducted interference is the switching noise of high-frequency inverters, at the same time, Protection devices like varistors and filters in one equipment will also influence the impact on neighboring equipment, shunting intentional signals or causing resonances, resulting in high currents between equipment [11]. The source of radiation interference is the antenna effect formed by the transmission coil and PCB wiring, which radiates high-frequency magnetic fields and affects nearby wireless devices (such as Wi-Fi and Bluetooth). The source of internal coupling interference in the system is the leakage magnetic coupling of the transmitting and receiving coils to the control circuit, which can cause false triggering or signal distortion.

The EMC optimization methods based on power electronics technology mainly include filtering technology, magnetic shielding technology, soft switching technology, and spread spectrum modulation technology. Filtering technology reduces interference between the power grid and equipment by suppressing noise in the transmission path. Common mode sensors have lower costs and are suitable for general use, but they are larger. Differential mode sensors have higher costs and are suitable for use in high-power electrical appliances [12]. Magnetic shielding technology reduces radiation interference and internal coupling by blocking magnetic field leakage. The principle of ferrite magnetic shielding is to attach high permeability ferrite (such as Mn Zn material) to the bottom of the coil to constrain the magnetic field path. The principle of a metal shielding cover is that an aluminum or copper shielding cover cancels out external magnetic fields through eddy current effects. Similarly, ferrite magnets have lower costs and are lighter in weight, but their magnetic permeability decreases at high temperatures. Metal shielding covers have better efficiency but higher cost [13]. Soft switching technology reduces EMI from the source by reducing switch transient noise. The principle is as described earlier. Spread spectrum modulation technology disperses the energy spectrum and reduces peak interference. The principle is to randomly oscillate a fixed switching frequency (such as 100 kHz) within a certain range to disperse the noise energy. The advantage of this is that it does not require additional hardware and is suitable for low-cost solutions. However, it may introduce low-frequency ripple and require an increase in output filtering capacitors.

4 Problems Faced and Future Trends

4.1 Technical Problems

At present, wireless charging systems for household appliances still face many problems, including cost issues, insufficient standardization, efficiency issues, electromagnetic compatibility issues, safety issues, and so on [14]. The integrated design and large-scale application of power electronics technology can effectively address cost issues, while also promoting multi-protocol compatibility to improve standardization. The conversion efficiency and electromagnetic compatibility issues mentioned earlier can also be solved through power electronics technology.

4.2 Future Trends

The future home wireless charging system will rapidly develop towards higher power, long-distance transmission, and deep intelligence. Power electronics technology, as the core support, drives change through multiple paths such as greater power, long-distance breakthroughs, and intelligent collaborative upgrades. Among them, artificial intelligence algorithms are deeply integrated with power electronic control to achieve multi-device adaptive power allocation, real-time optimization of electromagnetic environment, and linkage with home energy management systems to improve electricity economy [15].

5 Conclusion

Wireless charging technology for household appliances, as the core driving force of the smart home energy revolution, is undergoing a leapfrog development from basic power supply to high efficiency, intelligence, and global coverage. This article introduces the components of a wireless charging system for household appliances and analyzes its basic principles through two parts: the transmitting end and the receiving end. Subsequently, this article focuses on the key role of power electronics technology in these technologies. The article analyzes the three key technologies and challenges of high-efficiency power converters, precise power control strategies, and electromagnetic compatibility design and optimization, and compares different strategies and applicable scenarios based on power electronics technology. Finally, the article analyzes the current technical problems faced by wireless charging technology for household appliances and envisions its future development trends.

Power electronics technology continues to break through the efficiency boundaries and scenario limitations of household wireless charging through device innovation, topology innovation, and intelligent upgrading. In the future, with the interdisciplinary integration of materials science, artificial intelligence, and energy management, wireless charging will surpass a single power supply function and evolve into the energy hub of smart homes, leading to a new era of "tailless" low-carbon living.

6 References

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