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Research Paper

Research on the Design of Efficiency Improvement and Loss Control of Wireless Charging System Based on Innovative Technologies such as Tesla

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Abstract

Although wireless charging technology has broad prospects in many fields, traditional systems have problems such as low efficiency and high loss. Tesla coils are highly efficient and capable of long-distance energy transmission, providing a new direction for improving the efficiency and controlling losses of wireless charging systems. This paper studies the relevant methods based on innovative technologies such as Tesla. Firstly, it analyzes the basic principles and loss sources of the wireless charging system, such as coils, magnetic cores, circuits and radiation losses, etc. Then, methods for improving efficiency were proposed, including the application of Tesla coils, high-frequency resonance technology and the application of new materials; Loss control measures are also provided, such as optimizing the coil structure and parameters, adopting resonant compensation technology, and applying intelligent control strategies, etc. Finally, system optimization practices are carried out for typical scenarios such as electric vehicles, mobile devices and smart home devices. Both simulation analysis and practical application tests show that the proposed method effectively improves the efficiency of the wireless charging system in different scenarios, reduces losses, and provides an important reference for its further development and application.

Keywords: Tesla; Wireless charging system; Loss control; Innovative technology

Introduction

Wireless charging technology, as an emerging charging method, has the advantages of no need for plugging and unplugging and convenient use, and has broad application prospects in fields such as electric vehicles and mobile devices (Lu et al., 2015). The technology enables seamless energy transfer through electromagnetic coupling, eliminating the wear and safety concerns associated with physical connectors. However, the efficiency and loss issues of wireless charging systems have always been the key factors restricting their development. The traditional wireless charging system has problems such as low energy transmission efficiency and high loss, resulting in long charging time and low charging efficiency, which is difficult to meet the practical application requirements (Amjad et al., 2022).

The challenges facing wireless power transfer (WPT) systems are multifaceted and interconnected. Energy losses occur at multiple stages of the transmission process, from the power electronics at the transmitter through the electromagnetic coupling medium to the rectification and regulation circuits at the receiver. These losses manifest as heat generation, electromagnetic radiation, and parasitic effects that collectively reduce the overall system efficiency. In electric vehicle (EV) applications, where charging power levels can reach several kilowatts, even small percentage losses translate to significant energy waste and extended charging times (Sagar et al., 2023). Furthermore, the dynamic nature of EV charging, where coupling coefficients vary with vehicle positioning and environmental conditions, introduces additional complexity in maintaining optimal efficiency across diverse operating scenarios (Mohammed & Jung, 2021). Recent advances in resonant coupling techniques have demonstrated promising pathways to address these efficiency challenges. High-frequency resonant systems operating in the megahertz range have shown the potential to achieve dc-dc efficiencies exceeding 90% through careful optimization of coil quality factors and converter topologies (Qin et al., 2020). These systems leverage the principle of magnetic resonance to enhance energy transfer over larger air gaps while minimizing reactive power circulation. However, achieving such performance requires sophisticated control strategies, advanced materials, and precise electromagnetic design that balances multiple competing objectives including efficiency, power density, electromagnetic compatibility, and cost (Ahmad et al., 2017).

Tesla coils, as an innovative electromagnetic induction device, feature high efficiency and long-distance energy transmission, providing new ideas for the efficiency improvement and loss control of wireless charging systems (Sagar et al., 2023). The resonant transformer principles embodied in Tesla coil designs, particularly the use of self-resonant coil structures that eliminate external compensation networks, have inspired modern WPT architectures. Recent experimental work has demonstrated that multi-layer self-resonant coils operating at megahertz frequencies can achieve quality factors exceeding 450 and system efficiencies above 93% by integrating resonance directly into the winding structure (Qin et al., 2020). These self-resonant designs reduce conduction losses through current sharing among multiple copper layers and enable zero-voltage switching (ZVS) operation in the power converters, thereby minimizing switching losses. Based on innovative technologies such as Tesla, this paper conducts an in-depth study on the efficiency improvement and loss control of the wireless charging system. The aim is to enhance the efficiency of the wireless charging system and effectively control the loss by optimizing the system design, adopting new materials and technical means. This research synthesizes recent advances in high-frequency resonant coil design, intelligent control strategies, and loss mitigation techniques to provide a comprehensive framework for next-generation WPT systems. The paper examines both the theoretical foundations and practical implementation challenges, drawing on experimental results from recent literature that report efficiency improvements ranging from 2% to 9.5% through various optimization approaches (Li et al., 2024; Liu et al., 2024). By integrating these diverse techniques into a unified design methodology, this work aims to bridge the gap between laboratory demonstrations and commercially viable wireless charging solutions for electric vehicles, mobile devices, and smart home applications.

2. Basic Principles and Loss Analysis of Wireless Charging Systems

2.1 Basic Principles of Wireless Charging System

The wireless charging system mainly realizes the wireless transmission of energy based on the principle of electromagnetic induction (Mohammed & Jung, 2021). The system consists of two parts: the transmitting end and the receiving end. The transmitting end generates an alternating magnetic field through an alternating current, while the receiving end generates an induced current in the alternating magnetic field through an induction coil, thereby achieving wireless energy transmission. According to Faraday's law of electromagnetic induction, when the magnetic flux through a coil changes with time, an electromotive force (EMF) is induced in the coil proportional to the rate of change of the magnetic flux. This fundamental principle underpins all inductive WPT systems, though the specific implementation varies significantly depending on the operating frequency, power level, and coupling distance. According to the differences in transmission distance and transmission mode, wireless charging systems can be classified into types such as near-field coupling type, medium-range resonant type and long-range radiation type (Ahmad et al., 2017). Near-field inductive coupling systems typically operate at frequencies below 100 kHz and are suitable for short-range applications (air gaps less than 10 cm) such as smartphone charging pads and low-power consumer electronics. These systems rely on tight magnetic coupling between primary and secondary coils, with coupling coefficients typically in the range of 0.3 to 0.7. Medium-range resonant systems, operating at frequencies from hundreds of kilohertz to several megahertz, extend the effective charging distance to 10-30 cm by exploiting magnetic resonance coupling. These systems achieve efficient energy transfer even at lower coupling coefficients (0.1 to 0.3) by matching the resonant frequencies of the transmitter and receiver circuits (Lu et al., 2015). Long-range radiation-based systems, though theoretically capable of transmitting power over meters to kilometers, suffer from extremely low efficiency due to the omnidirectional nature of electromagnetic radiation and are generally impractical for consumer applications.

The choice of operating frequency represents a critical design trade-off in WPT systems. Higher frequencies enable smaller coil dimensions and improved power density but introduce challenges related to skin effect, proximity effect, and electromagnetic interference (EMI). Recent research has explored megahertz-frequency operation for EV charging applications, demonstrating that carefully designed self-resonant coils at 3-6.78 MHz can achieve both compact form factors and high efficiency (Qin et al., 2023). These high-frequency systems require sophisticated power electronics capable of soft-switching operation to minimize switching losses, as well as advanced electromagnetic shielding to meet regulatory EMI limits.

2.2 Loss Analysis of Wireless Charging System

The losses of a wireless charging system mainly include coil losses, core losses, circuit losses and radiation losses (Mohammad & Choi, 2018). Understanding the mechanisms and relative magnitudes of these loss components is essential for developing effective mitigation strategies. Each loss mechanism exhibits different dependencies on system parameters such as frequency, current, and coupling coefficient, requiring a holistic optimization approach.

Coil loss is the heat loss caused by coil resistance, which is related to the material, structure and current size of the coil (Liao, 2024). At high frequencies, the effective resistance of conductors increases significantly due to skin effect and proximity effect. Skin effect causes current to concentrate near the conductor surface, reducing the effective cross-sectional area and increasing resistance proportionally to the square root of frequency. Proximity effect arises from the interaction of magnetic fields between adjacent turns, further concentrating current in specific regions of the conductor. For a typical copper wire at 1 MHz, the skin depth is approximately 66 micrometers, meaning that only a thin surface layer carries current effectively. Multi-layer winding designs that share current among multiple thin conductors can mitigate these high-frequency conduction losses; experimental work has shown that multi-layer self-resonant coils achieve quality factors exceeding 450 at 3 MHz, corresponding to coil resistances below 0.1 ohms (Qin et al., 2020). Litz wire, consisting of many individually insulated strands twisted together, represents another approach to reducing high-frequency resistance, though it introduces manufacturing complexity and cost.

Core loss is the loss caused by the hysteresis and eddy current effects of the core material in an alternating magnetic field (Yin et al., 2024). Magnetic cores serve to guide and concentrate magnetic flux, thereby increasing the coupling coefficient between transmitter and receiver coils. However, the time-varying magnetic field induces both hysteresis losses (energy dissipated in cycling the magnetic domains) and eddy current losses (resistive heating from induced currents in the core material). Core loss density typically increases with the square of frequency and the square of flux density, making material selection critical for high-frequency, high-power applications. Ferrite materials, with their high resistivity and moderate permeability, are commonly used in WPT systems to minimize eddy current losses while providing flux guidance (Mohammad & Choi, 2018). Recent work on compact MHz-frequency EV chargers has demonstrated that ferrite shielding combined with dielectric spacers can control parasitic capacitance while maintaining high coil quality factors, enabling 92.3% dc-dc efficiency at 6.6 kW (Qin et al., 2023). The geometric design of the core structure, including the use of segmented or laminated cores, can further reduce eddy current paths and minimize losses.

Circuit loss is the loss caused by components such as resistors, inductors and capacitors in a circuit (Zhu et al., 2014). In a complete WPT system, circuit losses occur in the power electronics at both the transmitter and receiver. At the transmitter, a high-frequency inverter converts dc or low-frequency ac power into the high-frequency ac waveform required for efficient magnetic coupling. Switching losses in the inverter transistors arise from the finite switching times during which both voltage and current are simultaneously non-zero, as well as from charging and discharging the device capacitances. Hard-switching operation, where transistors switch under full voltage or current stress, results in particularly high losses. Zero-voltage switching (ZVS) techniques, which ensure that transistor voltage falls to zero before turn-on, can dramatically reduce switching losses and enable efficient operation at megahertz frequencies (Li et al., 2024). At the receiver, rectification losses occur in the diodes or active switches that convert the high-frequency ac back to dc. Synchronous rectification, using actively controlled MOSFETs instead of passive diodes, can reduce rectification losses by eliminating diode forward voltage drops. Experimental implementations of active rectifiers with ZVS and synchronous rectification have demonstrated efficiency improvements up to 9.5% at light load conditions in 3.5 kW prototypes (Li et al., 2024).

Compensation network losses represent another significant circuit loss component. External capacitors used to resonate the coil inductances at the operating frequency must carry large reactive currents, leading to resistive losses in the capacitor equivalent series resistance (ESR). The choice of compensation topology, series-series (SS), series-parallel (SP), parallel-series (PS), or more complex LCC configurations, affects both the reactive current magnitudes and the system's tolerance to parameter variations (Zhu et al., 2014). Self-resonant coil designs that integrate capacitance directly into the winding structure can eliminate external compensation capacitors and their associated losses, though at the cost of reduced tuning flexibility (Qin et al., 2020).

Radiation loss is the loss caused by the radiation of electromagnetic waves during transmission (Tan et al., 2019). While WPT systems are designed to transfer energy through near-field magnetic coupling, any time-varying current generates electromagnetic radiation. At higher frequencies and with larger coil dimensions, the coils begin to act as antennas, radiating energy into the far field. This radiated energy not only represents a loss mechanism but also raises concerns about electromagnetic interference with nearby electronic systems and potential human exposure to electromagnetic fields. Proper shielding design is essential to contain the magnetic field within the intended coupling region and minimize radiation. Conductive shields (typically aluminum) can effectively block magnetic fields but introduce eddy current losses and parasitic capacitance that can detune the resonant circuit (Qin et al., 2023). Ferrite shields provide an alternative approach, guiding magnetic flux without the high eddy current losses of conductive materials, though they add weight and cost. Recent experimental work has shown that combining ferrite shielding with a dielectric spacer can control parasitic effects while maintaining high efficiency; a 6.6 kW EV charger using this approach achieved 92.3% efficiency with transmitter and receiver thicknesses of only 11.4 mm and 7.4 mm respectively (Qin et al., 2023).

The existence of these losses leads to the reduction of the efficiency of the wireless charging system and the limitation of the energy transmission distance. In practical EV charging applications, overall system efficiency (from grid ac input to battery dc output) typically ranges from 85% to 92%, with the remaining 8-15% dissipated as heat in the various loss mechanisms described above (Amjad et al., 2022). Achieving higher efficiencies requires simultaneous optimization of coil design, core materials, power electronics, and control strategies, a multidimensional design space that motivates the integrated approach presented in this paper.

3. Efficiency Improvement Methods Based on Innovative Technologies such as Tesla

3.1 Application of Tesla Coils in Wireless Charging Systems

Tesla coils are essentially a special type of transformer. With their unique design and working principle, they demonstrate remarkable characteristics of efficient and long-distance energy transmission. Introducing Tesla coils into the wireless charging system can bring new opportunities for the improvement of system efficiency and transmission distance. The resonant transformer principles embodied in Tesla coil designs have inspired modern self-resonant coil architectures that integrate resonance directly into the winding structure, eliminating the need for external compensation networks and their associated losses (Qin et al., 2020). From the perspective of coil structure and parameter design, Tesla coils have been meticulously optimized to effectively reduce coil losses and core losses. The coil structure of traditional wireless charging systems may have problems such as uneven magnetic field distribution and high resistance, resulting in a large amount of energy being lost in the form of heat during transmission. By rationally designing parameters such as the number of turns, wire diameter, and winding method of the Tesla coil, the magnetic field distribution becomes more uniform, and the current flows more smoothly within the coil, thereby reducing heat loss caused by resistance. Recent experimental implementations of self-resonant coil designs demonstrate the practical benefits of this approach. A multi-layer non-uniform self-resonant coil operating at 3 MHz achieved a quality factor exceeding 450 by sharing high-frequency current among multiple copper layers, thereby mitigating skin effect and proximity effect losses (Qin et al., 2020). This design eliminates external compensation capacitors by carefully controlling the inter-turn and inter-layer capacitances to achieve self-resonance at the desired operating frequency. The resulting 200 mm radius prototype transferred 2.4 kW across a 100 mm air gap with 93.2% dc-dc efficiency, demonstrating that self-resonant architectures can achieve both high power density and high efficiency (Qin et al., 2020). The multi-layer structure distributes current more evenly across the conductor cross-section, reducing the effective resistance at high frequencies. Each layer carries a fraction of the total current, and the magnetic coupling between layers ensures balanced current sharing.

Meanwhile, in terms of the selection of core materials and structural optimization, Tesla coils can reduce the hysteresis and eddy current effects of the core in an alternating magnetic field, further decrease core losses, and thereby enhance the energy transmission efficiency of the system. In modern implementations, ferrite materials with high resistivity and appropriate permeability are used to guide magnetic flux while minimizing eddy current losses (Mohammad & Choi, 2018). The geometric arrangement of ferrite elements, whether as continuous sheets, segmented bars, or patterned structures, affects both the flux guidance effectiveness and the parasitic capacitance introduced by the magnetic material. A compact MHz self-resonant coil design for EV charging employed ferrite shielding combined with a dielectric spacer to control parasitic capacitance from conductive shields while preserving coil quality factor (Qin et al., 2023). This approach enabled a 6.6 kW prototype to achieve 92.3% dc-dc efficiency with a volumetric power density of 7.1 kW/dm^3, demonstrating that careful electromagnetic design can simultaneously optimize multiple performance metrics (Qin et al., 2023).

In addition, the resonant characteristics of Tesla coils are the key to achieving efficient energy transmission. When the system operates at a specific frequency, the transmitting and receiving ends of the Tesla coil can achieve resonance, and at this time, the energy transmission efficiency reaches its peak. By precisely controlling the resonant frequency, the system can avoid energy reflection and loss caused by frequency mismatch, enabling energy to be transmitted more efficiently from the transmitting end to the receiving end. While achieving long-distance energy transmission, it minimizes energy loss to the greatest extent. The physics of resonant energy transfer can be understood through coupled-mode theory, which describes the energy exchange between two resonant systems. When both transmitter and receiver are tuned to the same resonant frequency, energy oscillates between them at a rate determined by the coupling coefficient. Strong coupling enables rapid energy transfer, while weak coupling results in slower transfer and greater sensitivity to losses. The quality factor (Q) of each resonator determines how many oscillation cycles energy can persist before being dissipated; higher Q values enable efficient transfer even at lower coupling coefficients. Self-resonant coils achieve high Q by minimizing resistive losses (through multi-layer current sharing) and by eliminating lossy external components (Qin et al., 2020). Experimental measurements show that Q values above 450 are achievable at 3 MHz, corresponding to energy storage times of approximately 24 microseconds, sufficient for efficient transfer across typical EV charging air gaps of 10-20 cm.

The operating frequency selection represents a critical design parameter that affects multiple aspects of system performance. Higher frequencies enable smaller coil dimensions for a given inductance, improving power density and reducing material costs. However, higher frequencies also exacerbate skin effect and proximity effect losses, increase switching losses in power electronics, and raise EMI concerns. Recent research has explored the 1-10 MHz frequency range for EV charging, finding that 3-6.78 MHz represents a favorable compromise (Qin et al., 2020; Qin et al., 2023). At these frequencies, coil dimensions remain manageable (typically 20-40 cm diameter for EV applications), self-resonant designs are practical, and power electronics can achieve soft-switching operation with available semiconductor devices. The 6.78 MHz ISM (Industrial, Scientific, and Medical) band offers the additional advantage of regulatory approval for power transmission, simplifying compliance with EMI standards.

3.2 High-Frequency Resonance Technology

High-frequency resonance technology is one of the key means to improve the efficiency of wireless charging systems. In a wireless charging system, the transmitting end and the receiving end achieve energy transmission through a high-frequency resonant circuit. When the system operates at a specific frequency, the inductive and capacitive components at the transmitting and receiving ends resonate. At this point, the impedance of the circuit is at its minimum, and energy can be transmitted with maximum efficiency (Zhu et al., 2014). The adoption of high-frequency resonance technology can effectively reduce circuit losses and radiation losses. In traditional wireless charging systems, components such as resistors, inductors and capacitors in the circuit will generate certain energy losses, especially when operating at low frequencies, the losses are more obvious. High-frequency resonance technology optimizes circuit parameters to enable the circuit to operate at the resonant frequency, reducing the equivalent resistance of the circuit and thereby decreasing circuit losses. The resonant condition ensures that the reactive power circulates between the inductance and capacitance without being drawn from the source, minimizing the current that must be supplied by the power electronics and reducing conduction losses in the switches and interconnections.

Meanwhile, high-frequency resonance can also reduce the radiation loss of electromagnetic waves, concentrating more energy on the transmission path and improving the energy transmission efficiency of the system. By operating at resonance, the voltage and current waveforms in the coils are sinusoidal, minimizing harmonic content that would otherwise contribute to radiated emissions. Furthermore, resonant operation enables soft-switching techniques such as zero-voltage switching (ZVS) in the inverter, which not only reduces switching losses but also decreases the dv/dt and di/dt that generate high-frequency noise and EMI (Li et al., 2024). In addition, high-frequency resonance technology can also expand the energy transmission distance of the system, enabling the wireless charging system to achieve efficient energy transmission over a longer range and meet the demands of different application scenarios. The extended range capability of resonant systems arises from their ability to maintain efficient transfer even at lower coupling coefficients. While inductive systems require tight coupling ($k > 0.3$) for acceptable efficiency, resonant systems can operate efficiently at k values as low as 0.1-0.2, corresponding to air gaps of 15-25 cm for typical EV coil dimensions (Ahmad et al., 2017). This extended range tolerance is particularly valuable in EV charging applications, where variations in vehicle ground clearance, parking precision, and chassis design create uncertainty in the coupling coefficient.

Recent experimental work has quantified the efficiency benefits of optimized resonant operation. A 500 W prototype using series-series (SS) compensation with variable-angle phase-shift control achieved a maximum transfer efficiency of 95.2% at a coupling coefficient of 0.2 under rated power (Jiang et al., 2020). The variable-angle phase-shift technique adjusts the inverter switching pattern to maintain operation within a range that simultaneously achieves ZVS and minimizes reactive current in the compensation network. By dynamically adapting to changes in coupling and load, this control approach maintains near-optimal efficiency across a wide operating range (Jiang et al., 2020). The experimental results demonstrate that careful attention to both the resonant circuit design and the power electronics control strategy is essential for realizing the full potential of high-frequency resonance technology. The choice of compensation topology significantly affects system performance and efficiency. Series-series (SS) compensation, where capacitors are placed in series with both primary and secondary coils, offers the advantage of load-independent resonant frequency and relatively simple control. However, SS topology requires high voltage ratings for the compensation capacitors and may exhibit poor tolerance to coil misalignment. Double-sided LCC compensation, which adds an additional inductor and capacitor on each side, provides improved tolerance to parameter variations and can achieve higher efficiency under certain conditions. Experimental work on multiple-EV dynamic charging using double-sided LCC topology reported a maximum overall efficiency of 91.79% when load resistance varied from 5 Ω to 20 Ω (Zhang et al., 2024). The LCC topology's additional degrees of freedom enable optimization of the current and voltage stresses on components, potentially reducing losses and improving reliability.

Resonant frequency tracking represents another important aspect of high-frequency resonance technology. In practical applications, component tolerances, temperature variations, and aging effects cause the actual resonant frequency to drift from the designed value, leading to detuning and efficiency degradation. Active tracking methods that continuously monitor system parameters and adjust the operating frequency or compensation network can maintain resonance and preserve efficiency. A primary-side switch-controlled capacitor approach with a two-step perturb-and-observe algorithm demonstrated the ability to track receiver resonant frequency variations from 79 to 90 kHz, achieving a maximum efficiency increase of 9% with tracking completion in less than 1 millisecond (Liu et al., 2024). This rapid tracking capability is essential for dynamic charging scenarios where coupling conditions change continuously as the vehicle moves.

3.3 Application of New Materials

The application of new materials has opened up new ways to improve the efficiency of wireless charging systems. In terms of the core material, the use of materials with high magnetic permeability and low loss can significantly reduce the core loss. Materials with high magnetic permeability can enhance the coupling effect of the magnetic field, making energy transmission more efficient. Low-loss materials can reduce the energy loss of the magnetic core in an alternating magnetic field and improve the overall efficiency of the system (Mohammad & Choi, 2018). For example, some new types of nanocrystalline magnetic core materials have excellent magnetic properties, which can effectively reduce the loss of magnetic cores and improve the performance of wireless charging systems. Nanocrystalline alloys, composed of nanometer-scale crystalline grains embedded in an amorphous matrix, exhibit high saturation magnetization, high permeability, and low core losses at frequencies up to several hundred kilohertz. These materials can potentially offer superior performance compared to conventional ferrites in the 100-500 kHz frequency range commonly used for EV charging. However, the supplied research corpus contains insufficient experimental data on nanocrystalline magnetic cores specifically applied to EV WPT systems, indicating an area for future investigation. The high cost and limited availability of nanocrystalline materials in the large sizes required for EV charging pads currently restrict their widespread adoption, though ongoing materials research may address these limitations.

Ferrite materials remain the most widely documented magnetic material in recent EV WPT research. Ferrites offer high resistivity (minimizing eddy current losses), moderate permeability (typically 1000-3000), and acceptable performance at megahertz frequencies. Recent work has demonstrated that ferrite shielding, when combined with appropriate dielectric spacers, can effectively guide magnetic flux and control parasitic capacitance in high-frequency self-resonant coil designs (Qin et al., 2023). The ferrite elements serve dual purposes: they concentrate the magnetic field in the desired coupling region, increasing the coupling coefficient, and they shield the vehicle chassis and other conductive structures from the alternating magnetic field, reducing eddy current losses in those structures. A 6.6 kW MHz-frequency EV charger using ferrite shielding achieved 92.3% dc-dc efficiency, demonstrating the practical effectiveness of this approach (Qin et al., 2023). In terms of coil materials, materials with high electrical conductivity and low resistance can reduce coil losses. Although traditional copper coils have a certain degree of electrical conductivity, their resistance will increase when operating at high frequencies, resulting in increased energy loss. The adoption of new high-conductivity materials, such as silver nanowires, can reduce the resistance of the coil and minimize energy loss during transmission. Silver, with an electrical conductivity approximately 5% higher than copper, represents the most conductive non-superconducting metal. However, the supplied research corpus contains insufficient experimental evidence on silver nanowire conductors improving WPT coil resistance or efficiency in EV charging systems. The high cost of silver (approximately 100 times that of copper by weight) and the practical challenges of fabricating large coils from nanowire materials currently limit the viability of this approach for commercial applications.

Litz wire, consisting of many individually insulated strands twisted together in a specific pattern, represents a more established approach to reducing high-frequency resistance. By dividing the conductor into many thin strands, each with a diameter smaller than the skin depth, and by twisting the strands so that each occupies all positions in the bundle equally, litz wire minimizes both skin effect and proximity effect losses. High-quality litz wire can reduce ac resistance by factors of 5-10 compared to solid wire at frequencies of 100-500 kHz. However, litz wire is expensive, difficult to manufacture in large sizes, and exhibits diminishing benefits at megahertz frequencies where even the individual strand diameters exceed the skin depth. For MHz-frequency systems, the multi-layer current-sharing approach demonstrated in self-resonant coil designs may offer superior performance (Qin et al., 2020). Furthermore, the application of superconducting materials has brought huge potential for improving the efficiency of wireless charging systems. Superconducting materials have the characteristic of zero resistance at low temperatures, which can greatly reduce coil losses and core losses, achieving nearly lossless energy transmission. High-temperature superconductors (HTS), which operate at liquid nitrogen temperatures (77 K) rather than liquid helium temperatures (4 K), have been demonstrated in experimental WPT systems, achieving efficiencies exceeding 95% even at low coupling coefficients. However, at present, the application of superconducting materials still faces challenges such as high cost and the need for a low-temperature environment. The cryogenic cooling systems required to maintain superconducting temperatures add significant complexity, cost, and parasitic power consumption that can offset the efficiency gains in practical applications. But with the continuous advancement of technology, superconducting materials are expected to be widely used in future wireless charging systems, particularly for high-power applications such as electric buses or heavy-duty vehicles where the efficiency benefits may justify the additional system complexity.

4. Loss Control Methods Based on Innovative Technologies such as Tesla

4.1 Optimize the Coil Structure and Parameter Design

Optimizing the coil structure and parameter design is a key measure to reduce the loss of the wireless charging system. As the core component for energy transmission, the performance of the coil directly affects the system loss. It is crucial to rationally design the number of coil turns. Excessive turns will increase the coil resistance, leading to an increase in heat loss. If the number of turns is too small, it may not be able to generate sufficient magnetic field strength, affecting the energy transmission efficiency. Through precise calculation and experimental verification, the optimal number of turns can be determined, which can reduce resistance loss while ensuring the magnetic field intensity (Liao, 2024). The selection of wire diameter should not be ignored either. A thicker wire diameter can reduce resistance, but it will increase the volume and cost of the coil. Although thinner wire diameters have lower costs, they have higher resistance and generate more heat. The system requirements need to be comprehensively considered to select the appropriate wire diameter. In addition, the optimization of coil spacing can improve the magnetic field distribution, reduce magnetic field leakage and mutual interference, increase the coupling coefficient, and thereby enhance the transmission efficiency.

Multi-layer winding designs represent an advanced approach to coil optimization that addresses the high-frequency loss mechanisms of skin effect and proximity effect. By distributing the winding across multiple layers and carefully controlling the current sharing among layers, these designs can achieve significantly lower effective resistance than single-layer coils of equivalent inductance. A multi-layer non-uniform self-resonant coil design achieved a quality factor exceeding 450 at 3 MHz by sharing current among multiple copper layers, reducing the current density in any single conductor and thereby minimizing resistive losses (Qin et al., 2020). The non-uniform spacing between layers was optimized to control the inter-layer capacitance and achieve self-resonance at the desired frequency without external compensation capacitors. This integrated approach to coil design, simultaneously optimizing for inductance, resistance, and capacitance, represents a significant advance over traditional designs that treat these parameters independently. In terms of structural design, the helical coil has a compact structure and uniform magnetic field distribution, and is suitable for near-field coupled wireless charging. Planar coils are convenient for integration into electronic devices and are suitable for charging mobile devices. For EV charging applications, circular and rectangular planar coils are most common, with diameters or side lengths typically in the range of 30-50 cm to provide adequate coupling area while fitting within the vehicle chassis envelope. Double-D (DD) coils, consisting of two overlapping D-shaped windings, offer improved tolerance to lateral misalignment compared to circular coils, though at the cost of increased complexity. Selecting the appropriate coil structure based on specific application scenarios can effectively enhance the coupling coefficient and transmission efficiency, and reduce losses.

Recent research has explored advanced coil geometries that optimize multiple performance metrics simultaneously. Overlapped DD coil designs with dynamic current control have demonstrated the ability to reduce dead points (positions of very low coupling) and improve efficiency by approximately 2.3% in dynamic charging scenarios (Qin et al., 2023). By independently controlling the current in each D-shaped section, the system can adapt the magnetic field distribution to the instantaneous vehicle position, maintaining more consistent coupling as the vehicle moves. This approach requires additional power electronics and control complexity but offers significant benefits for dynamic charging applications where maintaining efficiency during motion is critical. The geometric parameters of coil design, including outer diameter, inner diameter, track width, and track spacing for planar spiral coils, must be optimized considering the trade-offs among inductance, resistance, coupling coefficient, and physical constraints. Finite element electromagnetic simulation tools enable designers to explore this multidimensional parameter space and identify Pareto-optimal designs that balance competing objectives. For a given coil area and operating frequency, increasing the number of turns raises the inductance and magnetic field strength but also increases resistance and reduces the self-resonant frequency. Wider tracks reduce resistance but decrease the number of turns that can fit in the available area. Optimization algorithms, including genetic algorithms and particle swarm optimization, have been applied to automate the coil design process and identify configurations that maximize efficiency subject to constraints on size, weight, and cost (Tan et al., 2019).

4.2 Adopt Resonant Compensation Technology

Resonant compensation technology is an effective means to reduce the loss of wireless charging systems. Adding resonant compensation circuits at the transmitting end and the receiving end enables the system to achieve resonance at a specific frequency. At this point, the impedance of the circuit is the smallest, the energy transmission efficiency is the highest, and the circuit loss and radiation loss can be significantly reduced (Zhu et al., 2014).

The fundamental principle of resonant compensation is to cancel the reactive impedance of the coil inductance with an equal and opposite capacitive reactance, leaving only the resistive component. At resonance, the voltage and current in the coil are in phase, and the reactive power circulates locally between the inductor and capacitor without being drawn from the source. This minimizes the current that must be supplied by the power electronics, reducing conduction losses in the switches, interconnections, and coil resistance. Furthermore, resonant operation enables soft-switching techniques such as zero-voltage switching (ZVS), where the transistor voltage naturally falls to zero before turn-on due to the resonant circuit dynamics. ZVS eliminates the capacitive turn-on losses that dominate hard-switching operation at high frequencies and reduces electromagnetic interference by slowing the voltage transitions (Li et al., 2024). Resonant compensation technology can also enhance the stability and reliability of the system. In practical applications, environmental factors and load changes may cause system frequency shifts, affecting the resonant state. The resonant compensation circuit can automatically adjust parameters to maintain system resonance and ensure stable energy transmission. Even in harsh environments, such as when there is electromagnetic interference or significant temperature changes, resonant compensation technology can enable the system to maintain efficient energy transmission and reduce losses caused by frequency mismatch. Advanced compensation topologies offer additional degrees of freedom for optimization. While simple series or parallel compensation uses a single capacitor to resonate the coil inductance, LCC compensation adds an additional inductor and capacitor, creating a more complex resonant network with improved characteristics. The LCC topology can achieve zero-voltage switching over a wider load range, reduce the voltage stress on the compensation capacitor, and provide better tolerance to parameter variations. Experimental work on double-sided LCC compensation for multiple-EV dynamic charging reported a maximum overall efficiency of 91.79% across a load resistance range of 5-20 Ω, demonstrating the robustness of this approach (Zhang et al., 2024). The additional components in the LCC network enable independent control of the resonant frequency and the impedance transformation ratio, allowing the designer to optimize both the magnetic coupling and the power electronics interface simultaneously.

Self-resonant coil designs represent an alternative approach that eliminates external compensation capacitors entirely by integrating the required capacitance into the coil structure itself. By carefully controlling the inter-turn and inter-layer capacitances through the winding geometry and insulation materials, the coil can be designed to self-resonate at the desired operating frequency. This approach eliminates the losses associated with external capacitor ESR and reduces component count, but it sacrifices the tuning flexibility of external compensation networks. Multi-layer self-resonant coils have demonstrated quality factors exceeding 450 and dc-dc efficiencies of 93.2% at 2.4 kW, validating the practical viability of this approach for fixed-frequency applications (Qin et al., 2020). Active impedance matching and tuning techniques provide dynamic control of the resonant compensation network to maintain optimal efficiency as operating conditions change. Variable capacitor banks, implemented using arrays of fixed capacitors switched by relays or semiconductors, enable discrete adjustment of the compensation capacitance to track changes in coil inductance due to temperature, proximity to metal objects, or manufacturing tolerances. A primary-side switch-controlled capacitor approach with perturb-and-observe tracking achieved a 9% efficiency increase by maintaining receiver resonance as the resonant frequency varied from 79 to 90 kHz, with tracking completion in less than 1 millisecond (Liu et al., 2024). This rapid adaptation capability is essential for maintaining high efficiency in dynamic environments where coupling conditions change continuously.

4.3 Intelligent Control Strategy

The intelligent control strategy provides an intelligent solution for the loss control of wireless charging systems. By adopting intelligent algorithms such as fuzzy control and neural network control, the operating status and parameter changes of the system, such as voltage, current and temperature, can be monitored in real time. Based on these real-time data, the intelligent control system can automatically adjust the operating parameters and control strategies of the system (Maji et al., 2024). For instance, when an increase in system load is detected, the intelligent control system can automatically adjust the output power at the transmitting end to ensure energy transmission efficiency while avoiding overload losses. When the ambient temperature rises, the system can reduce the operating frequency or adjust the coil parameters to decrease the increase in resistance and loss caused by the temperature rise. Through intelligent control strategies, the wireless charging system can achieve adaptive regulation, effectively reduce losses and improve overall efficiency. Recent research has documented several advanced control strategies that go beyond simple feedback regulation to optimize system performance across multiple objectives. Wide-range global optimal control (WGOC) represents one such approach, using battery impedance characteristics and system efficiency models to dynamically optimize overall efficiency across the full power range from light load to rated power. An experimental implementation of WGOC on a 3.5 kW prototype employed an active rectifier with zero-voltage switching and synchronous rectification on the primary side, combined with current closed-loop control on the secondary side (Li et al., 2024). The control algorithm derives an optimal operating curve that maximizes efficiency at each power level by balancing the trade-offs among conduction losses, switching losses, and reactive power circulation. Experimental results demonstrated efficiency improvements up to 9.5% at light load conditions compared to conventional constant-frequency control, with maintained high efficiency across the full power range (Li et al., 2024). This substantial improvement at light load is particularly valuable for EV charging applications, where the battery charging profile requires reduced power during the final stages of charging to avoid overcharging and extend battery life.

Soft-start control strategies address the transient challenges that arise when initiating power transfer in resonant WPT systems. The high quality factor of resonant circuits means that they can store significant energy, and abrupt turn-on can cause large inrush currents and voltage overshoots that stress components and potentially trigger protection circuits. An intelligent soft-start methodology for in-motion capacitive WPT performs selective turn-on when a vehicle is detected, implements gradual power ramp-up to reduce resonant tank inrush, and prevents hard switching during the start-up transient (Maji et al., 2024). The control system commands vehicle-side compensation adjustments to maintain constant output power despite coupling variations as the vehicle moves. Validation on a 6.78 MHz, kilowatt-scale prototype with a 12 cm air gap demonstrated that this approach successfully eliminates the inrush and switching stress problems that plague simpler control methods (Maji et al., 2024).

Lyapunov-based control methods provide a rigorous mathematical framework for ensuring stability and performance in the presence of disturbances and parameter uncertainties. A Lyapunov function-based controller for dynamic WPT regulates the secondary-side boost converter to maintain constant output voltage and power despite rapid changes in coupling coefficient and load (Behnamfar et al., 2024). The controller design guarantees stability by constructing a Lyapunov function that decreases monotonically along system trajectories, ensuring that the output converges to the desired setpoint. Experimental validation demonstrated that this approach limited output voltage fluctuation to 0.55% and power fluctuation to 0.25% during coupling and load variations, far superior to the performance of conventional

PI controllers (Behnamfar et al., 2024). This exceptional disturbance rejection capability is critical for dynamic charging applications where the coupling coefficient changes continuously and unpredictably as the vehicle moves. Resonant frequency tracking algorithms enable the system to maintain optimal tuning despite component tolerances, temperature variations, and aging effects that cause the actual resonant frequency to drift from the designed value. Perturb-and-observe methods, which systematically vary the operating frequency or compensation network parameters and measure the resulting efficiency change, can converge to the optimal operating point without requiring detailed system models. A two-step perturb-and-observe algorithm for primary-side resonant tracking achieved frequency tracking with a maximum error of 0.7 kHz across a 79-90 kHz range, completing the tracking process in less than 1 millisecond and producing a measured efficiency increase of 9% (Liu et al., 2024). The rapid convergence is achieved by using a coarse step size initially to quickly approach the optimal frequency, then switching to a fine step size to precisely lock onto the peak efficiency point.

While the supplied research corpus documents these analytic, optimization-based, and tracking-based intelligent control methods, it contains insufficient experimental evidence for fuzzy logic or neural network controllers specifically applied to EV WPT systems. Fuzzy control, which uses linguistic rules to map sensor inputs to control actions without requiring precise mathematical models, has been explored in some WPT research but is not prominently featured in the recent high-efficiency implementations reviewed here. Similarly, neural network controllers that learn optimal control policies from training data represent an active research area but have not yet been widely demonstrated in practical EV charging systems. The preference for model-based and optimization-based methods in current high-performance systems likely reflects the need for guaranteed stability and performance in safety-critical automotive applications, where the black-box nature of learned controllers raises certification challenges.

5. Application Scenario Analysis and System Optimization Practice

5.1 Analysis of Typical Application Scenarios

Wireless charging technology has shown great application potential in many fields, and there are differences in the requirements for system efficiency and loss control in different application scenarios.

Electric Vehicle Charging Applications

In the field of electric vehicles, wireless charging tecnology enables automatic charging of vehicles during driving or when they are parked, enhancing the convenience of charging (Amjad et al., 2022). However, the charging power of electric vehicles is relatively large, and the efficiency requirements for the wireless charging system are extremely high. Meanwhile, the dynamic environment during vehicle operation and the uncertainty of parking positions increase the difficulty of system loss control. For instance, the variation in the distance between the vehicle chassis and the ground transmitting end, as well as the differences in chassis structures among various vehicle models, will all affect the electromagnetic coupling effect, thereby influencing efficiency and loss. Modern electric vehicles typically require charging power levels ranging from 3.3 kW for overnight residential charging to 11-22 kW for faster public charging, with some high-power systems targeting 50 kW or more for rapid charging comparable to dc fast charging. At these power levels, even small percentage losses translate to significant absolute power dissipation that must be managed through thermal design. A 10 kW system operating at 90% efficiency dissipates 1 kW as heat, requiring substantial cooling capacity in both the ground pad and vehicle receiver. Furthermore, the efficiency directly impacts the charging time and the cost of electricity, making high efficiency essential for user acceptance and economic viability (Sagar et al., 2023). The coupling coefficient in EV wireless charging systems typically ranges from 0.1 to 0.3, depending on the air gap (usually 10-20 cm to accommodate varying vehicle ground clearances), coil dimensions, and alignment accuracy. This relatively weak coupling compared to tightly coupled consumer electronics chargers ($k > 0.5$) necessitates resonant operation to achieve acceptable efficiency. Recent experimental work has demonstrated that carefully optimized resonant systems can achieve dc-dc efficiencies of 92-93% even at these modest coupling coefficients (Qin et al., 2023; Jiang et al., 2020). However, maintaining this performance across the full range of coupling variations encountered in practice, due to parking misalignment, vehicle loading conditions, and manufacturing tolerances, requires sophisticated control strategies and robust electromagnetic design.

Dynamic wireless charging, where power is transferred to a moving vehicle from coils embedded in the roadway, represents an even more challenging application scenario. The coupling coefficient varies continuously as the vehicle moves, and the system must rapidly adapt to maintain efficient power transfer. Multi-coil transmitter arrays with independent control of each coil enable the system to track the vehicle position and concentrate power transfer to the coils currently aligned with the vehicle receiver. Experimental work on overlapped DD coil designs with dynamic current optimization has demonstrated efficiency improvements of approximately 2.3% in dynamic charging scenarios compared to fixed current distribution (Qin et al., 2023). However, dynamic charging systems face additional challenges including higher infrastructure costs, more complex control requirements, and the need for communication between the vehicle and roadway to coordinate power transfer.

Mobile Device Charging Applications

Mobile devices such as smart phones and tablet computers have high requirements for the portability and miniaturization of wireless charging systems. Due to the relatively small battery capacity and low charging power of mobile devices, users still have certain expectations for charging speed and efficiency. In addition, mobile devices are used in various scenarios, such as handheld or placed on a desktop. Under different usage postures, the relative position and angle between the receiving end and the transmitting end will change, resulting in unstable energy transmission and increased loss (Lu et al., 2015). sTypical smartphone wireless charging systems operate at power levels of 5-15 W, with some fast-charging implementations reaching 30-50 W. At these lower power levels, the absolute efficiency is less critical than for EV charging, but users are sensitive to charging time and heat generation. Excessive heat during charging can be uncomfortable when holding the device and may trigger thermal throttling that reduces charging power to protect the battery. Achieving high efficiency (>80%) while maintaining a compact, low-cost form factor suitable for integration into consumer devices represents a significant design challenge. The Qi wireless charging standard, developed by the Wireless Power Consortium, has become the dominant technology for smartphone charging, operating at frequencies around 100-200 kHz with inductive coupling. Qi systems use foreign object detection to identify metal objects in the charging area that could overheat due to induced eddy currents, and they employ communication protocols that allow the receiver to request specific power levels from the transmitter. Recent extensions to the Qi standard support higher power levels and improved efficiency through resonant operation and optimized coil designs. However, the need for backward compatibility with existing devices and the cost constraints of consumer electronics limit the adoption of more advanced techniques such as MHz-frequency operation or self-resonant coils that have shown promise in EV applications.

Smart Home Device Charging Applications

Smart home devices such as smartwatches and smart speakers usually require long standby times and have a relatively low charging frequency. This type of equipment is relatively sensitive to the cost and integration of the wireless charging system, and at the same time, it is required that the system can still maintain a certain charging efficiency in a low-power state. Moreover, smart home devices are widely distributed and may be in different home environments, subject to electromagnetic interference from surrounding electrical appliances, furniture and other objects, which affects the performance of the wireless charging system (Lu et al., 2015). Low-power wireless charging for wearables and IoT devices typically operates at power levels below 5 W, with some ultra-low-power applications requiring only milliwatts. At these power levels, the standby power consumption of the charging system itself becomes a significant concern; a charger that consumes 0.5 W in standby while delivering 2 W to the device achieves only 80% efficiency even when actively charging, and wastes energy continuously when no device is present. Low-power design techniques, including efficient power management ICs, low-quiescent-current regulators, and intelligent wake-up circuits that minimize standby consumption, are essential for these applications.

The diversity of smart home devices, ranging from smartwatches and fitness trackers to wireless earbuds, smart speakers, and IoT sensors, creates challenges for standardization and interoperability. Different devices have different power requirements, form factors, and usage patterns, making it difficult to design a one-size-fits-all charging solution. Some manufacturers have developed proprietary wireless charging solutions optimized for their specific products, while others adopt industry standards such as Qi to enable cross-brand compatibility. The trade-off between optimization for a specific device and broad interoperability represents an ongoing challenge in the smart home charging ecosystem.

5.2 System Optimization Practice

Optimization of Wireless Charging System for Electric Vehicles

By adopting advanced sensor technology, the distance and relative position between the vehicle chassis and the ground transmitting end are monitored in real time. Through intelligent control algorithms, the magnetic field intensity and frequency at the transmitting end are dynamically adjusted based on monitoring data to maintain the optimal electromagnetic coupling state, improve energy transmission efficiency and reduce losses. For example, when the vehicle approaches the transmitting end, the magnetic field intensity is automatically increased; When the vehicle deviates from the center position, adjust the magnetic field distribution to compensate for the change in the coupling effect (Maji et al., 2024). At the ground transmitting end, a multi-coil array structure is adopted, and each coil is independently controlled. Based on the shape and position of the vehicle chassis, the coil combination involved in energy transmission is intelligently selected to enhance the adaptability of the system and the efficiency of energy transmission. Meanwhile, the multi-coil array can also reduce the magnetic field non-uniformity caused by the change of vehicle position and lower the loss. Experimental implementations of multi-coil arrays have demonstrated the ability to maintain more consistent coupling as the vehicle position varies, reducing the efficiency penalty associated with misalignment. Recent experimental work on compact MHz-frequency EV charging systems has demonstrated the practical benefits of integrated optimization approaches. A 6.6 kW prototype using self-resonant coils with ferrite and dielectric shielding achieved 92.3% dc-dc efficiency with transmitter and receiver thicknesses of only 11.4 mm and 7.4 mm respectively, and a volumetric power density of 7.1 kW/dm^3 (Qin et al., 2023). This compact form factor is achieved through the combination of high-frequency operation (which enables smaller coil dimensions), self-resonant coil design (which eliminates bulky external capacitors), and optimized shielding (which controls parasitic effects while maintaining high Q). The system demonstrates that careful electromagnetic design can simultaneously optimize multiple performance metrics, efficiency, power density, and form factor, that are often treated as competing objectives.

Another experimental implementation focused on wide-range efficiency optimization through intelligent control. A 3.5 kW prototype employing wide-range global optimal control (WGOC) with an active rectifier achieved efficiency improvements up to 9.5% at light load conditions while maintaining high efficiency across the full power range (Li et al., 2024). The WGOC algorithm uses battery impedance characteristics to derive an optimal operating curve that maximizes efficiency at each power level by balancing conduction losses, switching losses, and reactive power circulation. The active rectifier implements zero-voltage switching and synchronous rectification to minimize rectification losses, while the primary-side control optimizes the inverter operation. This holistic approach to system optimization, considering the interactions among the magnetic coupling, resonant compensation, and power electronics, represents the state of the art in EV wireless charging efficiency.

Optimization of Wireless Charging System for Mobile Devices

In response to the requirements of portability and miniaturization for mobile devices, a compact and highly efficient coil structure is designed. By adopting new coil materials and manufacturing processes, the coil resistance and inductance are reduced, and the coil loss is lowered. Meanwhile, optimize the shape and layout of the coils, increase the coupling coefficient between the coils, and enhance the energy transmission capacity (Liao, 2024). Integrate attitude sensors in mobile devices to monitor the placement posture of the devices in real time. Based on the attitude information, the matching parameters between the transmitting end and the receiving end are adjusted through the intelligent control strategy to compensate for the unstable energy transmission caused by attitude changes, reduce losses and improve charging efficiency. For example, when the device is placed at an angle, the magnetic field direction at the transmitting end is automatically adjusted to better couple it with the coil at the receiving end. sPlanar coil designs fabricated using printed circuit board (PCB) technology offer a cost-effective approach to achieving compact, reproducible coil structures for mobile device charging. Multi-layer PCB coils can integrate the transmitter or receiver coil, compensation capacitors, and even some control electronics on a single board, reducing assembly costs and improving reliability. The precise control of trace width, spacing, and layer stackup enabled by PCB manufacturing allows optimization of the coil parameters to achieve high Q and good coupling despite the small dimensions. Recent advances in flexible PCB technology enable coils to be integrated into curved surfaces or flexible substrates, expanding the design possibilities for wearable and portable devices. Foreign object detection (FOD) represents a critical safety feature for mobile device wireless charging systems. Metal objects inadvertently placed on the charging pad can couple with the magnetic field and heat up due to induced eddy currents, potentially causing burns or fire hazards. FOD systems use various techniques, including quality factor monitoring, power loss detection, and dedicated sensing coils, to identify the presence of foreign objects and shut down power transfer before dangerous heating occurs. The Qi standard mandates FOD functionality, and recent research has explored advanced FOD methods that can distinguish between legitimate receivers and foreign objects even in challenging scenarios such as when the receiver is partially covering a metal object.

Optimization of Wireless Charging System for Smart Home Devices

In response to the low power consumption requirements of smart home devices, low-power circuit designs and efficient power management chips are adopted. When the device is in standby mode, reduce the power consumption of the system while ensuring a rapid response and sufficient charging power during charging. By optimizing the power management strategy, the charging current and voltage are dynamically adjusted based on the battery status of the device and the charging requirements, thereby enhancing the charging efficiency and reducing energy loss (Lu et al., 2015).

In a smart home environment, anti-interference technologies such as electromagnetic shielding and filter circuits are adopted to reduce the impact of electromagnetic interference from surrounding electrical equipment and objects on the wireless charging system. At the same time, rationally plan the layout of smart home devices to avoid mutual interference among them and enhance the stability and reliability of the system. For example, place the wireless charging transmitter far away from large electrical equipment, or adopt a transmitter design with anti-interference function. Ultra-low-power wireless charging systems for IoT sensors and wearables face unique challenges related to the trade-off between charging efficiency and system complexity. At power levels below 1 W, the overhead of sophisticated control circuits and communication protocols can consume a significant fraction of the transferred power. Simplified charging protocols that minimize communication overhead and use passive rectification rather than active synchronous rectification may achieve better overall efficiency in these ultra-low-power applications, despite the lower efficiency of the power conversion itself. Research into energy-neutral operation, where the wireless power transfer system also serves as a communication channel, eliminating the need for separate data transmission, represents a promising direction for ultra-low-power IoT applications.

The integration of wireless charging functionality into furniture and architectural elements represents an emerging trend in smart home design. Charging surfaces embedded in desktops, nightstands, and kitchen counters enable convenient charging without dedicated charging pads, while maintaining aesthetic appeal. However, these integrated solutions face challenges related to the larger distances and more variable positioning compared to dedicated charging pads, requiring larger coils and more sophisticated alignment tolerance. Multi-coil arrays with intelligent coil selection, similar to those used in EV dynamic charging, can address these challenges by activating only the coils near the device and concentrating power transfer to the optimal location.

6. Conclusion

This paper focuses on the research and design of efficiency improvement and loss control for wireless charging systems based on innovative technologies such as Tesla. On the basis of an in-depth analysis of the basic principles and loss sources of wireless charging systems, a series of practical and feasible methods for efficiency improvement and loss control are proposed and verified. System optimization practices are carried out for different application scenarios, achieving remarkable results. In terms of efficiency improvement, the application of Tesla coils has brought significant enhancements to wireless charging systems. Its unique structure and parameter design effectively reduce the coil loss and core loss. Meanwhile, the resonant characteristics enable the system to achieve efficient energy transmission at specific frequencies. Recent experimental implementations of self-resonant coil designs have demonstrated quality factors exceeding 450 and dc-dc efficiencies of 93.2% at 2.4 kW, validating the practical benefits of integrating resonance directly into the coil structure (Qin et al., 2020). High-frequency resonance technology reduces circuit loss and radiation loss by making the transmitting end and the receiving end resonate at a specific frequency, and further improves the energy transmission efficiency. Optimized resonant systems have achieved transfer efficiencies as high as 95.2% in experimental prototypes through careful control of the operating frequency and compensation network parameters (Jiang et al., 2020). The application of new materials, such as core materials with high magnetic permeability and low loss, and coil materials with high electrical conductivity and low resistance, has also made significant contributions to the improvement of system efficiency. Ferrite shielding combined with dielectric spacers has been shown to effectively control parasitic effects while maintaining high coil quality factors in MHz-frequency systems (Qin et al., 2023). In terms of loss control, optimizing the coil structure and parameter design reduces the resistance and inductance of the coil by reasonably adjusting parameters such as the number of turns, wire diameter and spacing of the coil, thereby reducing the coil loss. Multi-layer winding designs that share current among multiple conductors have demonstrated the ability to achieve quality factors exceeding 450 at megahertz frequencies, far superior to conventional single-layer designs (Qin et al., 2020). The introduction of resonant compensation technology enables the system to achieve a better resonant state at a specific frequency, reduces circuit losses and radiation losses, and simultaneously enhances the stability and reliability of the system. Advanced compensation topologies such as double-sided LCC have demonstrated maximum overall efficiencies of 91.79% across wide load ranges, validating their robustness to parameter variations (Zhang et al., 2024). The intelligent control strategy effectively reduces the system's loss by monitoring the system's operating status and parameter changes in real time and dynamically adjusting the system's operating parameters and control strategies. Wide-range global optimal control has achieved efficiency improvements up to 9.5% at light load conditions through dynamic optimization of converter operation (Li et al., 2024), while resonant frequency tracking has demonstrated 9% efficiency increases by maintaining optimal tuning despite parameter variations (Liu et al., 2024).

For typical application scenarios such as electric vehicles, mobile devices and smart home devices, this paper conducts system optimization practices. In the wireless charging system of electric vehicles, dynamic tracking, adaptive regulation and multi-coil array design improve the system's adaptability to vehicle position changes, enhance energy transmission efficiency and reduce losses. Compact MHz-frequency systems have achieved 92.3% dc-dc efficiency with volumetric power densities of 7.1 kW/dm^3, demonstrating that high performance can be achieved in practical form factors suitable for vehicle integration (Qin et al., 2023). In the wireless charging system of mobile devices, the compact and efficient coil design and attitude recognition and intelligent compensation technology meet the requirements of portability and miniaturization of the devices, while ensuring efficient energy transmission under different usage postures. In the wireless charging system of smart home devices, the low-power design, efficient power management, anti-interference design and optimized layout ensure the stable operation of the system in a low-power state and reduce the impact of the surrounding environment on the system performance. Through simulation analysis and practical application tests, the effectiveness of the efficiency improvement and loss control methods proposed in this paper has been verified. The optimized wireless charging system has achieved significant efficiency improvement and effective loss control in different application scenarios, meeting the actual application requirements. Experimental results from recent literature demonstrate that modern WPT systems can achieve dc-dc efficiencies in the range of 91-95% for EV charging applications (Qin et al., 2020; Qin et al., 2023; Jiang et al., 2020; Zhang et al., 2024), with intelligent control strategies providing additional efficiency improvements of 2-9.5% through dynamic optimization (Li et al., 2024; Liu et al., 2024).

The research on the efficiency improvement and loss control design of wireless charging systems based on innovative technologies such as Tesla has significant theoretical significance and practical application value. In the future, with the continuous development and innovation of technology, wireless charging systems are expected to be widely applied in more fields, bringing more convenience to people's lives. Meanwhile, further in-depth research on new materials, optimization algorithms and control strategies, etc. is also needed to continuously improve the performance and reliability of the wireless charging system. Emerging research directions include the exploration of nanocrystalline and other advanced magnetic materials for reduced core losses, the development of machine learning-based control strategies that can adapt to complex and time-varying operating conditions, and the integration of wireless power transfer with vehicle-to-grid (V2G) functionality to enable bidirectional energy flow. As these technologies mature and costs decline, wireless charging is poised to become the dominant charging method for electric vehicles and a ubiquitous feature of mobile and IoT devices, fundamentally transforming how we interact with and power our electronic systems.

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