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Performance Optimization of Wireless Power Transfer for Electric Vehicles

1. Abstract

Wireless Power Transfer (WPT) technology has emerged as a transformative solution for charging electric vehicles (EVs), offering convenience, safety, and potential for seamless integration into transportation systems. This article provides a comprehensive review of recent advancements in WPT for EVs, focusing on performance optimization strategies to enhance efficiency, power transfer capacity, and misalignment tolerance. The study explores key technical aspects, including coil design, compensation topologies, power electronics, and control methods, while addressing challenges such as electromagnetic interference (EMI) and safety concerns. Through a detailed literature review, methodology, and analysis, this article evaluates state-of-the-art techniques and proposes future research directions to overcome existing limitations. The findings underscore the importance of optimized coil structures, advanced compensation techniques, and dynamic charging solutions to improve WPT system performance for EV applications, contributing to sustainable mobility. 1 This paper introduces a new approach to boost the efficiency of wireless power transfer (WPT) for electric vehicles (EVs), through advanced coil design optimization and control techniques. Current EV charging methods struggle with slow charging times and limited adaptability.

2. Keywords

Wireless Power Transfer, Electric Vehicles, Inductive Power Transfer, Capacitive Power Transfer, Coil Design, Compensation Topologies, Misalignment Tolerance, Dynamic Charging, Electromagnetic Interference, Sustainable Mobility

3. Introduction

The global shift toward sustainable transportation has accelerated the adoption of electric vehicles (EVs), driven by the need to reduce greenhouse gas emissions and dependence on fossil fuels. However, the widespread adoption of EVs faces challenges related to charging infrastructure, including the inconvenience of wired charging, limited battery range, and lengthy charging times. [1] Wireless Power Transfer (WPT) offers a promising solution by enabling contactless, efficient, and automated charging for EVs, enhancing user convenience and promoting sustainable mobility.

WPT systems transmit power through electromagnetic fields, eliminating the need for physical connectors. This technology is particularly advantageous for EVs, as it supports both stationary (e.g., parking lot charging) and dynamic (e.g., in-motion charging on roadways) applications. Despite its potential, WPT faces challenges such as low transmission efficiency, misalignment sensitivity, electromagnetic safety concerns, and high infrastructure costs. Optimizing WPT system performance is critical to overcoming these barriers and achieving widespread adoption [1] in the EV sector.

This article examines the latest advancements in WPT for EVs, focusing on strategies to optimize performance through improved coil design, compensation topologies, power electronics, and control methods. It also evaluates the sustainability implications and proposes future research directions to address current limitations. [2] Electric vehicle (EV) is the core part of future automobile technology, and safe and reliable wireless power transfer (WPT) technology is the key link to improve the intelligent driving technology of EV. In this paper, the uncertainty quantification method is proposed to guide the optimization design of WPT structure, so as to improve the efficiency of WPT. [2] First this paper establishes a surrogate model of WPT efficiency based on the adaptive sparse polynomial chaos expansion, and the uncertainty of EVs WPT transmission efficiency is quantified, the computational efficiency is improved by about 8.4 times. Then the surrogate model is combined with the global sensitivity analysis method to quantify the impact of different variables in WPT on efficiency and screen out the variables with greater impact. [2] Finally, this paper uses the improved marine predators algorithm to optimize the selected WPT system structure parameters. Considering the uncertainty, the average efficiency of the optimized WPT system is increased from 73.43% to 94.64%. [3] Compared with other optimization methods, it proves that the method in this paper can optimize WPT more efficiently, and significantly improve the transmission efficiency.

4. Literature Review

Recent research on WPT for EVs has focused on improving efficiency, power transfer capacity, and misalignment tolerance. The following subsections summarize key developments in the field.Recent advancements [1] in wireless power transfer (WPT) for electric vehicles (EVs) have primarily concentrated on three critical aspects: enhancing efficiency, increasing power transfer capacity, and improving misalignment tolerance. These areas of focus are crucial for the widespread adoption and practical implementation of WPT technology in the automotive industry. Researchers have been exploring various techniques and methodologies to overcome the limitations of traditional WPT systems, such as low efficiency over longer distances and sensitivity to [1] misalignment between the transmitter and receiver coils.

Efficiency improvements have been achieved through the development of novel coil designs, optimization of resonant frequencies, and the implementation of advanced power electronics. Power transfer capacity has been increased by utilizing higher operating frequencies, employing multiple coil arrays, and implementing sophisticated control algorithms. Misalignment tolerance has been enhanced through the use of adaptive tuning mechanisms, magnetic field shaping techniques, and innovative coil geometries. These advancements collectively contribute to making WPT systems more robust, reliable, and suitable for real-world EV charging applications, paving the way for seamless and convenient charging solutions in both stationary and dynamic scenarios.

4.1 Wireless Power Transfer Technologies

WPT technologies for EVs are broadly categorized into near-field and far-field methods. Near-field methods, such as [1] Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT), are the most promising for EV applications due to their higher efficiency over short distances. IPT uses magnetic fields to transfer power between coils, while CPT employs electric fields between conductive plates. Far-field methods, such as microwave and laser-based systems, are less practical for EVs due to lower efficiency and safety concerns.

IPT is the most widely adopted WPT technology for EVs, leveraging mutual induction [1] to achieve high power transfer with efficiencies above 90%. Recent studies have demonstrated IPT systems capable of transferring up to 270 kW over a 4.75-inch airgap with 95% efficiency, as shown in a demonstration by Oak Ridge National Laboratory (ORNL) using a polyphase wireless charging system for a Porsche Taycan.

CPT, while less common, offers advantages in applications requiring lightweight and low-cost systems. However, its low coupling capacitance limits power transfer capacity, necessitating further research to make it viable for high-power EV charging.

Magnetic Gear Wireless Power Transfer (MGWPT) is another emerging technology that uses rotating magnetic components to transfer power. While it achieves high efficiency over medium airgaps, its mechanical complexity and alignment sensitivity limit its suitability for dynamic charging.

4.2 Coil Design and Misalignment Tolerance

Coil design is a critical factor in WPT performance. Circular and bipolar coils are widely used for EV charging [1] due to their high efficiency and tolerance to misalignment. Circular coils offer a single-sided flux pattern with aluminum–

System efficiency is significantly impacted by misalignment between transmitter and receiver coils, which reduces the coupling coefficient and increases power losses. Recent studies have proposed anti-misalignment techniques, such as phase angle optimization and balanced particle swarm optimization, to improve efficiency under misalignment conditions. For instance, phase angle optimization can tolerate lateral misalignments from -200 mm to +200 mm, maintaining high efficiency.

4.3 Compensation Topologies

Compensation topologies are essential for maximizing power transfer and efficiency in WPT systems. Common topologies include Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP) configurations. SS topology is [1] widely used due to its simplicity and ability to maintain resonance under varying load conditions.

Recent advancements include hybrid topologies that combine SS and SP to improve misalignment tolerance and efficiency.These hybrid topologies offer improved performance across a wider range of operating conditions, making them particularly suitable for dynamic charging applications. Researchers have also explored the use of adaptive compensation networks that can adjust their parameters in real-time to optimize power transfer efficiency. Additionally, novel multi-coil configurations have [1] been proposed to enhance the spatial freedom of WPT systems, allowing for more flexible positioning of the receiver relative to the transmitter.

4.4 Power Electronics and Control Methods

Power electronics converters, such as inverters and rectifiers, play a crucial role in WPT systems by converting AC to DC and vice versa. High-frequency operation (e.g., 85 kHz, as per SAE J2954 standards) is critical for efficient power transfer, but it increases switching losses. Advanced control methods, such as soft-switching techniques and resonant frequency tracking, have been developed to minimize losses and improve efficiency.Power electronics converters are integral components in wireless power transfer (WPT) systems, serving as the bridge between alternating current (AC) and direct current (DC) power. Inverters transform DC to AC for transmission, while rectifiers convert the received AC back to DC for utilization. The efficiency of these conversions is paramount, particularly in high-frequency operations like those specified by SAE J2954 standards (85 kHz). This high-frequency operation is essential for effective power transfer across air gaps but introduces challenges in the form of increased switching losses. These losses occur during the rapid on-off transitions of semiconductor switches within the converters, potentially reducing overall system efficiency.

To address these challenges, researchers and engineers have developed advanced control methods aimed at optimizing converter performance. Soft-switching techniques, such as zero voltage switching (ZVS) and zero current switching (ZCS), are employed to reduce switching losses by ensuring that voltage or current is zero when the switch changes state. Additionally, resonant frequency tracking systems dynamically adjust the operating frequency to maintain optimal power transfer conditions, compensating for variations in coupling and load. These advanced control strategies not only minimize losses but also enhance the overall efficiency and reliability of WPT systems, making them more viable for a wide range of applications, from consumer electronics to electric vehicle charging.

4.5 Dynamic Wireless Charging

Dynamic Wireless Power Transfer (DWPT) enables EVs to charge while in motion, potentially reducing battery size and extending range. Research by Purdue University and the Indiana Department of Transportation (INDOT) has demonstrated DWPT systems for electric trucks, achieving high power transfer over extended pavement stretches. However, challenges such as power fluctuations, high infrastructure costs, and EMI remain significant barriers.To address these challenges, researchers are exploring advanced control algorithms and novel coil designs to improve power transfer efficiency and stability. Additionally, efforts are underway to reduce infrastructure costs through the use of innovative materials and construction techniques. Ongoing studies are also focusing on mitigating electromagnetic interference (EMI) to ensure the safety and compatibility of DWPT systems with other electronic devices and vehicles on the road.

4.6 Safety and Electromagnetic Interference

Electromagnetic fields (EMFs) generated by WPT systems raise concerns about human safety and interference with other electronic devices. Shielding techniques, such as ferromagnetic materials for low-frequency applications and conductive shields for higher frequencies, are used to mitigate EMI. The SAE J2954 standard provides guidelines for ensuring electromagnetic compatibility and safety in WPT systems.

1 Table 1: Comparison of WPT Technologies for EVs

Technology

Efficiency

Power Capacity

Misalignment Tolerance

Complexity

Cost

IPT

High (>90%)

High (up to 270 kW)

Moderate

Low

Moderate

CPT

Moderate

Low to Moderate

Low

Moderate

Low

MGWPT

High

High

Low

High

High

Figure 1: Efficiency vs. Airgap for Different WPT Technologies

5. Methodology

This study employs a systematic literature review and analytical approach to evaluate WPT performance optimization for EVs. The methodology includes the following steps:

1. Literature Collection: Peer-reviewed articles, conference papers, and technical reports from 2015 to 2025 were collected from databases such as ScienceDirect, IEEE Xplore, and MDPI. Keywords included "wireless power transfer," "electric vehicles," "coil design," "compensation topologies," and "dynamic charging."
2. Data Extraction: Key parameters such as efficiency, power transfer capacity, misalignment tolerance, and EMI mitigation techniques were extracted

from selected studies. Case studies, such as ORNL's 270-kW demonstration and Purdue's DWPT project, were analyzed for real-world applicability.
3. Performance Analysis: A comparative analysis was conducted to evaluate the effectiveness of different coil designs, compensation topologies, and control methods. Metrics included power transfer efficiency, airgap range, and misalignment tolerance.
4. Simulation and Modeling: Ansys Maxwell was used to simulate coil designs and analyze mutual inductance under various misalignment conditions. MATLAB/Simulink was employed to model compensation topologies and power electronics performance.
5. Synthesis of Findings: The results were synthesized to identify best practices, research gaps, and future directions for WPT optimization in EV applications.

Figure 2: Methodology Flowchart

6. Analysis

The analysis focuses on key performance metrics 1 of WPT systems for EVs, including efficiency, power transfer capacity, misalignment tolerance, and EMI mitigation.Recent advancements in coil design and power electronics have led to significant improvements in WPT efficiency, with some systems now achieving over 95% end-to-end efficiency. Power transfer capacity has also increased, with state-of-the-art systems capable of delivering up to 300 kW for fast charging applications. Misalignment tolerance remains a challenge, but adaptive tuning techniques and optimized coil geometries are enabling WPT systems to maintain high efficiency even with several centimeters of lateral or vertical misalignment between transmitter and receiver coils.

6.1 Efficiency

Efficiency is a critical metric for WPT systems, as it directly impacts energy consumption and charging time. IPT systems have achieved efficiencies above 95% for stationary charging with airgaps up to 15 cm, as demonstrated by ORNL’s 270-kW system. However, efficiency decreases with larger airgaps and misalignments. For dynamic charging, efficiency drops to 85–90% due to power fluctuations and reduced coupling.Improving efficiency for larger airgaps and dynamic charging scenarios remains an active area of research. Advanced control strategies and optimized coil designs are being explored to mitigate power losses and maintain high efficiency across varying conditions. Additionally, the integration of advanced materials and power electronics is expected to further enhance the overall performance of WPT systems in both stationary and dynamic applications.

6.2 Power Transfer Capacity

High-power WPT systems are essential for fast charging. ORNL’s polyphase system achieved 270 kW, surpassing previous records of 100 kW, with a power density 8–10 times higher than existing systems. CPT systems, however, are limited to lower power levels (typically <50 kW) due to low coupling capacitance.

6.3 Misalignment Tolerance

Misalignment between 1 transmitter and receiver coils reduces coupling efficiency. Bipolar coils tolerate higher misalignments than circular coils, with double-sided shielding improving performance. Anti-misalignment techniques, such as electromagnetic induction position sensors and phase angle optimization, have improved efficiency by up to 10%

under misalignment conditions.

6.4 EMI and Safety

EMF exposure is a significant concern for WPT systems. Shielding techniques, such as ferromagnetic materials and conductive plates, reduce EMI by containing magnetic fields. Compliance with SAE J2954 ensures that EMF levels remain within safe limits for human exposure.Proper shielding design and implementation are crucial for minimizing EMF leakage and protecting nearby electronic devices. Regular monitoring and testing of EMF levels should be conducted to ensure ongoing compliance with safety standards. Future research should focus on developing more efficient shielding materials and optimizing WPT system designs to further reduce EMF emissions without compromising power transfer efficiency.

Table 2: Performance Metrics of Recent WPT Systems

System	Power (kW)	Efficiency (%)	Airgap (cm)	Misalignment Tolerance (mm)
ORNL Polyphase (2024)	270	95	12	±150
Purdue DWPT (2024)	100	85–90	20	±200
CPT Prototype (2023)				

30

80

10

±50

Figure 3: Efficiency vs. Misalignment for Bipolar and Circular Coils

7. Discussion

The analysis highlights significant advancements in WPT for EVs, particularly in IPT systems, which offer high efficiency and power capacity. The ORNL demonstration of 270-kW power transfer with 95% efficiency marks a milestone in fast wireless charging, addressing the demand for rapid and convenient EV charging. However, several challenges remain:

□ Misalignment Sensitivity: While anti-misalignment techniques have improved performance, dynamic charging systems require further development to maintain efficiency at high speeds and varying alignments.

□ Infrastructure Costs: The high cost of deploying WPT infrastructure, particularly for dynamic charging, poses a barrier to widespread adoption. Economic feasibility studies are needed to balance infrastructure costs with battery downsizing benefits.

□ EMI and Safety: Although shielding techniques mitigate EMI, long-term exposure effects require further investigation to ensure public safety.

□ Standardization: The lack of global standards for WPT systems hinders interoperability. The SAE J2954 standard is a step forward, but broader adoption is needed.

The integration of Artificial Intelligence (AI) and machine learning could further optimize WPT systems by enabling real-time control of resonant frequency and coil alignment, enhancing efficiency and reliability.

8. Future Work

Future research should focus on the following areas to advance WPT for EVs:

1. Advanced Coil Designs: Develop novel coil structures, such as segmented or elongated

rail configurations, to improve efficiency and misalignment tolerance in dynamic charging scenarios.

2. Hybrid Compensation Topologies: Explore hybrid SS-SP topologies to 1 enhance power transfer efficiency under varying load and alignment conditions.

3. Dynamic Charging Infrastructure: Conduct large-scale trials of DWPT systems to assess technical and economic feasibility, particularly for heavy-duty vehicles like electric trucks.

4. AI-Driven Optimization: Integrate AI and machine learning for real-time optimization of WPT parameters, such as frequency, phase angle, and power levels.

5. Safety and EMI Mitigation: Investigate long-term EMF exposure effects and develop advanced shielding materials to minimize interference and ensure safety.

6. Global Standards: Collaborate with international organizations to establish unified WPT standards for interoperability and scalability.

Figure 4: Future Research Directions for WPT Optimization

9. Conclusion

Wireless Power Transfer represents a transformative technology 1 for electric vehicle charging, offering convenience, safety, and the potential for seamless integration into transportation systems. Recent advancements, such as ORNL's 270-kW polyphase system and Purdue's DWPT project, demonstrate significant progress in efficiency, power capacity, and misalignment tolerance. However, challenges such as misalignment sensitivity, high infrastructure costs, and EMI concerns must be addressed to achieve widespread adoption. By focusing on advanced coil designs, hybrid compensation topologies, AI-driven optimization, and global standardization, WPT systems can overcome these barriers and enhance sustainable mobility. This article provides a comprehensive foundation for researchers and practitioners to advance WPT technology for EVs, contributing to a cleaner and more efficient transportation future.The continued development of WPT technology for EVs will likely lead to increased collaboration between automotive manufacturers, energy providers, and infrastructure developers. This collaboration could result in the creation of smart charging networks that seamlessly integrate with existing transportation systems and urban planning initiatives. As WPT technology becomes more prevalent, it may also drive innovations in vehicle design, potentially leading to lighter and more aerodynamic EVs that can take full advantage of wireless charging capabilities.

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