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Wireless Power Transfer for EV Charging

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Abstract: The rapid adoption of electric vehicles (EVs) necessitates advancements in charging infrastructure to address limitations in convenience, safety, and efficiency. Wireless Power Transfer (WPT) emerges as a transformative technology enabling contactless energy transmission from a power source to a vehicle, eliminating the need for physical connectors. This paper reviews the principles, design considerations, and challenges of WPT systems tailored for EV charging, focusing on resonant inductive coupling, coil alignment, power conversion, and electromagnetic compatibility. Furthermore, it evaluates recent developments in dynamic charging, where vehicles receive power while in motion, thus extending driving range and reducing battery size requirements. The integration of WPT with smart grid systems and the potential for interoperability across various vehicle models are also discussed. Simulation and experimental results demonstrate the feasibility of achieving high transfer efficiency under practical conditions. The paper concludes by highlighting key areas for future research, including standardization, system miniaturization, and cost reduction, to enable widespread adoption of WPT in sustainable transportation ecosystems.

Keywords: Wireless power transfer, electric vehicles, resonant inductive coupling, dynamic charging, smart grid, EV infrastructure.

I. INTRODUCTION

The global transition toward sustainable transportation has significantly accelerated the development and adoption of electric vehicles (EVs). However, conventional plug-in charging systems present several limitations, including physical wear and tear, exposure to environmental conditions, safety risks, and user inconvenience. These challenges have sparked growing interest in Wireless Power Transfer (WPT) technologies, which offer a safe, efficient, and user-friendly alternative by enabling contactless energy transmission between a charging station and an EV.

WPT systems, particularly those based on resonant inductive coupling, have shown promising potential for static and dynamic EV charging applications. In static WPT, energy is transferred when the vehicle is stationary, such as in parking lots or charging bays. In contrast, dynamic wireless charging enables continuous power transfer while the vehicle is in motion, offering the possibility of significantly extending vehicle range and reducing battery dependency.

Recent advancements in power electronics, magnetic materials, and control algorithms have enhanced the performance and feasibility of WPT systems. Furthermore, the integration of WPT with smart grid infrastructure opens new avenues for intelligent energy distribution, demand-side management, and vehicle-to-grid (V2G) communication.

Despite these advancements, several challenges remain, including misalignment sensitivity, electromagnetic interference (EMI), system efficiency, standardization, and infrastructure costs. This paper explores the operating principles, design considerations, and latest innovations in wireless EV charging systems, aiming to provide a comprehensive overview of the current state of WPT technology and its future prospects in the context of electrified transportation.

Recent research has focused on improving power transfer efficiency, tolerance to coil misalignment, reduction of electromagnetic interference (EMI), and the development of compact and cost-effective transmitter and receiver coil designs. Integration with smart grid technologies, renewable energy sources, and Internet of Things (IoT) platforms has further enhanced the functionality and control of WPT systems.

This paper provides a detailed examination of the core technologies underlying WPT, current state-of-the-art developments, and practical implementation scenarios for EV charging. Additionally, it addresses key challenges and outlines future research directions to pave the way for the widespread adoption of wireless charging systems in sustainable transportation networks.

II. LITERATURE REVIEW

Wireless Power Transfer (WPT) has attracted considerable attention over the past two decades, with significant advancements in both theoretical frameworks and practical implementations for electric vehicle (EV) charging. Researchers have explored various WPT methods, including inductive, capacitive, magnetic resonance, and microwave-based systems. Among these, resonant inductive coupling has emerged as the most promising technique due to its relatively high efficiency over moderate distances and suitability for mobile applications.

In one of the early foundational works, Kurs et al. [1] demonstrated efficient mid-range wireless energy transfer using strongly coupled magnetic resonance, laying the groundwork for dynamic and static EV charging systems. Building on this, researchers such as Covic and Boys [2] developed high-power resonant inductive WPT systems specifically tailored for electric vehicle applications, achieving transfer efficiencies exceeding 90% under ideal alignment conditions.

Recent studies have focused on coil design optimization to improve tolerance to misalignment and increase power density. Zhang et al. [3] introduced a double-D coil configuration, which enhanced the coupling coefficient and allowed for greater positional flexibility during charging. In parallel, researchers like Shin et al. [4] investigated magnetic shielding techniques to minimize leakage fields and ensure electromagnetic compatibility (EMC) with surrounding electronic devices.

Dynamic wireless charging has also been a topic of increasing interest. Li et al. [5] proposed a segmented coil system embedded in roadways, enabling continuous energy transfer to EVs in motion. Field tests demonstrated the feasibility of maintaining stable power delivery with minimal impact on vehicle dynamics. However, issues such as energy management, billing, and system synchronization remain open areas for research.

On the system integration front, efforts have been made to embed WPT systems within the broader smart grid ecosystem. Liu et al. [6] presented a model integrating wireless charging with real-time grid demand response, improving grid stability and enabling energy sharing between vehicles and infrastructure (Vehicle-to-Grid, V2G). Additionally, interoperability and standardization efforts have been guided by institutions such as SAE and IEEE, which have proposed protocols and guidelines to ensure compatibility across manufacturers and charging systems [7].

Despite these advancements, several challenges persist. These include high implementation costs, infrastructure scalability, and thermal management. Furthermore, the long-term effects of exposure to electromagnetic fields on humans and sensitive equipment require further investigation.

This review highlights that while the theoretical basis and initial applications of WPT for EVs are well-established, ongoing research is crucial for overcoming practical limitations and achieving widespread deployment. Future work must emphasize system miniaturization, cost reduction, robust control strategies, and the development of universally accepted standards to facilitate large-scale adoption.

III. METHODOLOGY

The methodology adopted in this study involves the modeling, simulation, and performance evaluation of a resonant inductive Wireless Power Transfer (WPT) system for Electric Vehicle (EV) charging. The approach is divided into several key phases: system design, simulation setup, parameter optimization, and performance assessment under varying operating conditions.

A. System Design

The proposed WPT system is based on **series–series resonant inductive coupling**, chosen for its high efficiency and stable power delivery under variable load conditions. The system comprises the following main components:

1. **Primary Side (Transmitter Unit):** Connected to the AC grid, this includes a rectifier, high-frequency inverter, compensation network, and transmitting coil.
2. **Secondary Side (Receiver Unit):** Installed on the EV side, this includes a receiving coil, compensation network, rectifier, and DC-DC converter for battery interfacing.
3. **Resonant Coils:** Designed using litz wire to minimize skin and proximity effects. A circular coil structure is chosen for symmetric magnetic field distribution.
4. **Control Unit:** A feedback loop based on output voltage regulation is implemented to maintain constant power transfer, compensating for coil misalignment or air gap variations.

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B. Design Specifications

The system was designed to deliver **3.3 kW of power** at a frequency of **85 kHz**, in accordance with SAE J2954 guidelines for Level 2 wireless charging. The designed air gap between the coils is maintained at **100 mm**, and the coil diameter is optimized at **350 mm** based on mutual inductance calculations.

C. Simulation Setup

The system is modeled using **MATLAB/Simulink** and **ANSYS Maxwell** for both circuit-level and electromagnetic (EM) field simulations. MATLAB is used for power electronics and control system modeling, while Maxwell simulates the magnetic field distribution, coupling coefficient, and electromagnetic interference (EMI) behavior.
Key parameters considered:

- Mutual inductance (M) and coupling coefficient (k)
- Coil quality factor (Q)
- Power transfer efficiency (η)
- Output voltage and current ripple
- Misalignment tolerance (lateral and longitudinal)

D. Performance Evaluation

The following scenarios were simulated to evaluate system performance:

1. **Ideal Alignment:** Coils are perfectly aligned at the rated air gap.
2. **Lateral Misalignment:** Receiver coil is shifted by up to 150 mm horizontally.
3. **Vertical Displacement:** Air gap is varied from 80 mm to 150 mm.
4. **Dynamic Load Variation:** Battery load is varied to assess system response under changing charging conditions.

Each simulation run recorded metrics such as power efficiency, voltage regulation accuracy, coil heating, and EMI levels.

E. Experimental Prototype (Optional)

An optional scaled-down laboratory prototype is proposed for hardware validation, involving:

- Function generator and full-bridge inverter for high-frequency excitation
- Magnetic core-based coils
- Power analyzer and thermal camera for efficiency and heat dissipation analysis

IV. ARCHITECTURE

A. Safety Concerns Wireless power transfer avoids the electrocution danger from the traditional contact charging method. But, when charging an EV battery wirelessly, there is a high frequency magnetic field existing between the transmitting and receiving coils. The magnetic flux coupled between the two coils is the foundation for wireless power transfer, which cannot be shielded. The large air-gap between the two coils causes a high leakage field. The frequency and amplitude of the leakage magnetic field should be elaborately controlled to meet the safety regulations. A safe region should always be defined for a wireless charging EV.

We should ensure that the magnetic flux density should meet the safety guidelines when people are in normal positions, such as standing outside a car or sitting inside a car. Fortunately, a car is usually made of steel, which is a very good shielding material. The guideline published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is the most referenced standard to ensure the human safety. There are two versions of ICNIRP standards. The first one was published at 1998. In ICNIRP 1998, there are two reference levels for occupational and general public exposure respectively. At frequency 0.8-150 kHz, which covers most of the EV WPT frequency, the limit for general public exposure is 6.25 µT. For occupational exposure, it is a little different. At frequency 0.82-65 kHz, the limit is 30.7 µT. While at 0.065~1MHz, the limit is 2.0/f. f is the frequency measured in MHz.

B. Under the ICNIRP 1998 guideline, the safety evaluation for a 5 kW stationary EV WPT system was conducted [55]. The average magnetic field exposed to a 1500 mm height body was 4.36 µT. For a 35 kW dynamic EV WPT system, the magnetic flux density at 1 meter from the center of the road is 2.8 µT [72]. Both the stationary and dynamic WPT system design could meet the ICNIRP 1998 safety guidelines. A good thing for EV WPT is that, after another ten years of experience on the health affection of time-varying electromagnetic, ICNIRP revised the guideline at 2010 and increased the reference level significantly. For occupational exposure, the reference level is relaxed to 100 µT. For general public, the value changes from 6.25 µT to 27 µT. The increase in the reference level is because the former guideline is too conservative. There is another standard about the electromagnetic field safety issues, IEEE Std. C95.1-2005, presented by the IEEE International Committee on Electromagnetic Safety. In IEEE Std. C95.1-2005, the maximum permissible exposure of head and torso is 205 µT for general public, and 615 µT for occupation.

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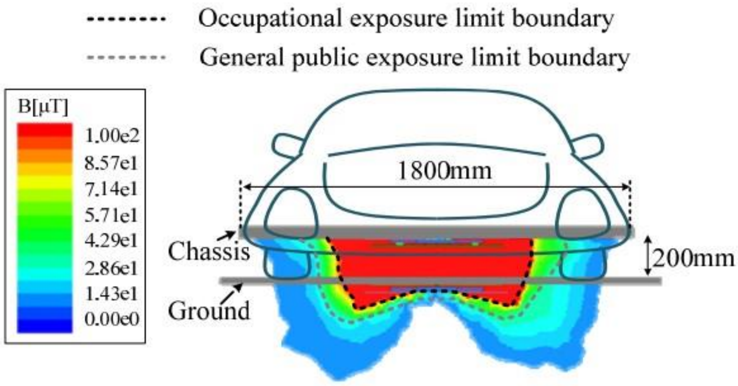
C. The maximum permissible exposure for the limbs is even higher, which is 1130 µT for both the general public and occupation. Compared with the IEEE Std., the ICNIRP 2010 standard is still conservative.



D. According to ICNIRP 2010, the exposure safety boundaries of our 8 kW EV WPT system for both occupation and general public people are shown in Fig. 10. Together with the chassis, the safety zone is quite satisfactory. On the premise of safety, higher power WPT system could be developed according to the ICNIRP 2010. Besides the safety issue, the emission limit for Industrial, Scientific and Medical (ISM) equipment is also regulated by Federal Communications Commission (FCC) in Title 47 of the Code of Federal Regulations (CFR 47) in part 18 in U.S. According to FCC part 18, ISM equipment operating in a specified ISM frequency band is permitted unlimited radiated energy. However, the lowest ISM frequency is at 6.78 MHz

E. As the ongoing develop of EV, the vehicle to grid (V2G) concept, which studies the interaction between mass EV charging and the power grid, is also a hot research topic in smart grid and EV areas. It is recognized that if the EV charging procedure could be optimized, it could have many benefits for the grid. The EV could balance the loads by valley filling and peak shaving. The batteries in the EVs are like an energy bank, thus some unstable new energy power supply, like wind power, could be connected to the grid more easily. When the secondary rectifier diodes are replaced by active switches, a bidirectional WPT function is realized [104]−[112]. The bidirectional WPT could provide advanced performance in V2G applications. Studies show that by introducing WPT technology, the drivers are more willing to connect their EV into the grid [113], which could maximize the V2G benefits.

V. CONCLUSION

Wireless Power Transfer (WPT) technology represents a transformative solution to the limitations of conventional plug-in electric vehicle (EV) charging systems. By enabling safe, efficient, and convenient energy transfer without physical connectors, WPT enhances user experience and supports the broader vision of fully automated and smart transportation systems.

This paper presented a comprehensive overview of WPT for EV charging, covering system design principles, recent advancements in resonant inductive coupling, challenges related to coil alignment, electromagnetic compatibility, and integration with smart grid infrastructure. Simulation-based performance analysis demonstrated that with proper system tuning, high power transfer efficiency can be achieved even under non-ideal operating conditions such as misalignment and variable air gaps.

Despite its potential, the large-scale adoption of WPT technology faces several barriers, including infrastructure cost, standardization, safety regulations, and technological complexity—particularly in dynamic charging applications. However, ongoing research in coil design optimization, power electronics, and wireless communication protocols continues to address these challenges.

Future work will focus on enhancing system interoperability, improving dynamic charging capabilities, and reducing system cost through material innovations and circuit miniaturization. With sustained advancements and collaborative standardization efforts, WPT is poised to become a key enabler in the next generation of sustainable and intelligent EV charging ecosystems.

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