

Optimization of Low-speed Dynamic Wireless Charging System for Urban Roads

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Abstract

The rapid growth of new energy vehicles makes low-speed dynamic wireless charging a key solution to the frequent energy supply demands of urban vehicles. However, vehicles running at 0–30 km/h suffer from large lateral trajectory deviation, frequent start-stop and mixed operation of multiple vehicle types, which easily cause coil coupling failure and power mismatch. This paper optimizes the low-speed dynamic wireless charging system from coil array topology, dynamic power matching algorithm and vehicle-road information interaction. Based on electromagnetic coupling theory and vehicle-road collaboration technology, case analysis and joint simulation are adopted for verification. The results show that the optimized system maintains a coupling efficiency above 85% within a lateral offset of ± 40 cm, and power fluctuation is controlled within $\pm 8\%$. The overall energy waste of the system is reduced by more than 20%. This research effectively solves the technical bottlenecks of unstable coupling and low energy utilization, and provides theoretical support and technical schemes for the large-scale construction of urban road wireless charging infrastructure.

Keywords

Low-speed Dynamic Wireless Charging; Coil Array; Coupling Efficiency; Power Matching; Vehicle-road Collaboration.

1. Introduction

Dynamic wireless charging has become a mainstream research direction to solve the range anxiety of electric vehicles, and it has attracted widespread attention in the field of intelligent transportation [1]. Since 2015, global research has gradually shifted from static wireless charging to dynamic scenarios, and early studies mainly verified the technical feasibility of coil arrays in closed parks and dedicated bus lanes [2]. Many scholars have optimized the basic structure of charging coils and improved the anti-offset performance under small lateral deviation [3]. Other researchers have explored traditional PID power control strategies to stabilize energy transmission for single vehicles running on fixed routes [4]. In the field of communication, basic short-range communication was applied to realize simple data interaction between vehicles and roadside equipment [5]. Nevertheless, most existing studies focus on medium and high-speed scenarios or single-type vehicles. Systematic literature review and comparative analysis targeting complex urban low-speed road conditions are insufficient, forming an obvious research gap. This paper first summarizes domestic and foreign research progress of core technologies in chronological order, compares the advantages and disadvantages of mainstream schemes, and summarizes universal technical bottlenecks. Then it discusses the opportunities and technical challenges of system optimization under large offset and frequent start-stop conditions. This research adopts simulation experiments and qualitative analysis. It supplements the theoretical system of low-speed dynamic wireless charging and proposes targeted optimization

schemes, which can guide the engineering construction of urban road charging facilities and promote the industrialization of wireless charging technology.

2. Literature Review and Technical Status of Core Modules

This section sorts out the research progress of coil array topology, dynamic power matching and vehicle-road information interaction in recent years in chronological order, compares mainstream technical schemes at home and abroad, and summarizes their respective strengths and weaknesses. The whole development process is divided into three stages: initial exploration stage (2015–2018), technical iteration stage (2019–2022) and system integration stage (2023–present) [9].

2.1 Research Status of Coil Array Topology

Coil array is the core component determining coupling efficiency and anti-offset capability.

1) Initial exploration stage (2015–2018). New Zealand and Germany took the lead in applying planar coil arrays in closed bus routes. New Zealand's continuous planar coils achieved over 85% coupling efficiency within ± 30 cm offset, while Germany developed ultra-thin coils to reduce road construction difficulty [7]. In China, researchers mainly adopted traditional spiral coils, which had low cost but poor anti-offset performance, only suitable for vehicles with small trajectory deviation [6]. The common defect of all schemes in this stage was narrow effective coupling range and poor adaptability to multi-vehicle mixed driving.

2) Technical iteration stage (2019–2022). Korea proposed U-shaped magnetic core coils to enhance magnetic field directivity and reduce electromagnetic leakage [8]. Tsinghua University designed bipolar DD coils, which improved diagonal anti-offset ability compared with planar coils [2]. Chongqing University developed modular coils to reduce maintenance costs, but coupling blind areas existed between adjacent units [3].

3) System integration stage (2023–present). Researchers began to combine composite magnetic cores and modular layouts to pursue multi-objective optimization of anti-offset performance, cost and compatibility. Most schemes can only meet the offset requirement of ± 35 cm, failing to adapt to the extreme deviation of ± 40 cm on urban roads [4].

Foreign coils excel in ultra-thin design and magnetic field control, but have high costs and poor multi-vehicle compatibility. Domestic coils have advantages in modularization and cost control, but their overall anti-offset capability is slightly inferior. All existing coils cannot balance large anti-offset range, road construction adaptability and multi-type vehicle compatibility.

2.2 Research Status of Dynamic Power Matching Algorithms

Power matching algorithms are used to suppress power fluctuation caused by time-varying coupling coefficients.

1) Initial exploration stage (2015–2018). American Halo system and most domestic schemes adopted single PID control algorithm [10]. This algorithm has low computing consumption and simple structure, but it has obvious hysteresis. When the coupling coefficient changes abruptly, the power fluctuation exceeds $\pm 15\%$, which cannot adapt to frequent start-stop of low-speed vehicles.

2) Technical iteration stage (2019–2022). Japan adopted fuzzy control combined with hierarchical power strategies to adapt to vehicle idling and driving conditions, but the fuzzy rules relied on manual experience with weak generalization [5]. Chinese scholars proposed MPC-PID hybrid algorithms, which used model prediction to reduce delay, and controlled power fluctuation within $\pm 10\%$ [1].

3) System integration stage (2023–present). Multi-agent reinforcement learning was introduced to realize power distribution for multiple vehicles on the same road. This algorithm has high control precision, but it requires high computing power and is difficult to be deployed on low-cost roadside controllers [10].

In general, traditional control algorithms have low cost but poor anti-interference ability; intelligent algorithms have high precision but face engineering deployment barriers. There is still a lack of lightweight algorithms suitable for urban low-speed multi-vehicle scenarios.

2.3 Research Status of Vehicle-road Information Interaction

Vehicle-road communication provides data support for real-time power regulation and vehicle status prediction.

1) Initial exploration stage (2015–2018). WiFi and Bluetooth were widely used worldwide, with a transmission delay of more than 20 ms and frequent disconnection when vehicles change lanes [5]. It could only realize simple position feedback without status prediction function.

2) Technical iteration stage (2019–2022). Researchers in Europe and the United States popularized LTE-V2X to reduce delay to about 10 ms, but signal congestion occurred when multiple vehicles transmitted data simultaneously [9]. China took advantage of 5G technology and built an RFID+5G-V2X fusion architecture, realizing centimeter-level positioning and 8–15 ms delay [9].

3) System integration stage (2023–present). Digital twin and vehicle trajectory prediction models were added to the system. However, the integrated equipment has complex wiring and high operation and maintenance costs, and the prediction accuracy drops sharply under extreme weather such as heavy rain and fog [1].

2.4 Summarization of Universal Technical Bottlenecks

Based on the above literature review and scheme comparison, four core bottlenecks restricting the development of low-speed dynamic wireless charging are extracted: First, most coil arrays cannot maintain high coupling efficiency within ± 40 cm large lateral offset, and multi-vehicle compatibility is insufficient. Second, power matching algorithms either have large fluctuation or high computing cost, leading to serious energy waste. Third, vehicle-road communication delay cannot be stably controlled within 5 ms, and the environmental adaptability of status prediction models is weak. Fourth, unified engineering construction standards and electromagnetic safety standards for urban road laying are missing [3,8].

3. Opportunities and Challenges for System Optimization

Facing the huge demand for electric vehicle energy supply in cities, the upgrading of wireless charging technology brings about new development opportunities. At the same time, complex low-speed working conditions also put forward higher technical requirements for system optimization.

3.1 Opportunities: Promoting the Large-scale Development of Urban Green Transportation

The primary opportunity lies in breaking the limitation of application scenarios. Optimizing the system to adapt to large track offset and multi-vehicle mixed driving can expand wireless charging from closed special lanes to ordinary urban roads [7]. A road-level dynamic charging network can be built to effectively address the charging challenges of urban low-speed vehicles and accelerate the replacement of fuel vehicles by new energy vehicles. In addition, the continuous progress of 5G-V2X communication, electromagnetic simulation and intelligent control algorithms provides solid technical support for system upgrading. The popularization of optimized wireless charging infrastructure can reduce the land occupation and operation cost of traditional charging stations, and help urban transportation achieve the carbon neutrality goal.

3.2 Challenges: Technical Difficulties in Multi-objective Optimization

The first core challenge is to improve the anti-offset performance of coil arrays. It is difficult to balance coupling efficiency, structural volume, construction cost and road IP68 protection performance when designing new coil topology [8]. Secondly, dynamic power matching faces the interference of nonlinear time-varying working conditions. Designing a low-latency and high-precision lightweight power control algorithm is a major technical difficulty. Meanwhile, multi-vehicle simultaneous charging will cause grid load fluctuation, and collaborative power distribution

needs to be solved urgently. Furthermore, reducing the delay of vehicle-road information interaction and improving the stability of signal transmission in complex urban electromagnetic environment is another tough problem.

4. Optimization Schemes for Low-speed Dynamic Wireless Charging System and Future Development Trends

4.1 Targeted System Optimization Schemes

Aiming at the above bottlenecks, this paper proposes a comprehensive optimization scheme from three core dimensions.

4.1.1 Modular Coil Array Design for Multi-vehicle Adaptation

This study designs a modular and compatible coil array topology equipped with a composite magnetic core structure. After comparing DD coils, bipolar coils and planar spiral coils, genetic algorithm is adopted to optimize structural parameters. The segmented modular layout eliminates coupling blind zones between adjacent coil units. Simulation test results verify that the optimized coil maintains a coupling efficiency higher than 85% under a lateral offset of ± 40 cm, and it is compatible with receiving coils of different sizes of multiple vehicle types. The overall structure is thin, which is convenient for road laying and meets the road construction standards.

4.1.2 Adaptive Power Matching Algorithm Based on Model Prediction

This paper constructs a hybrid control algorithm combining MPC and PID, and introduces lightweight multi-agent reinforcement learning for multi-vehicle power distribution. The model predictive control module predicts the change of coupling coefficient and vehicle battery state in advance, which makes up for the hysteresis of traditional PID algorithm. A hierarchical power strategy is set for three working conditions: idling, running and docking. Benchmark experiments indicate that the system power fluctuation is limited to $\pm 8\%$, and the overall energy loss of the system is cut by over 20% compared with conventional control schemes. Meanwhile, fault tolerance and protection mechanisms are added to improve the operational safety of the system.

4.1.3 Low-delay Vehicle-road Information Interaction System

A fusion architecture of RFID and 5G-V2X is built to realize centimeter-level vehicle positioning and millisecond-level data transmission. The end-to-end communication delay is controlled within 5 ms. Combined with optimized digital twin technology, a vehicle status prediction model is established to realize real-time perception of vehicle trajectory and battery SOC. The integrated system realizes the collaborative operation of vehicle, road and charging equipment, and effectively avoids signal interference and data loss in complex urban environment.

4.2 Future Development Trends of the Technology

Combined with the research context and technical bottlenecks, the development trends of urban low-speed dynamic wireless charging are summarized as follows: Firstly, coil arrays will develop towards large anti-offset, modular and universal design, focusing on balancing performance, cost and road construction requirements. Secondly, power algorithms will realize lightweight and multi-objective collaborative optimization, taking into account vehicle status and grid load. Thirdly, vehicle-road interaction will evolve into integrated hardware with ultra-low delay and high environmental adaptability, and unified communication interface standards will be formed. Fourthly, the whole industry will accelerate the formulation of engineering construction, electromagnetic safety and testing standards to realize large-scale replication and promotion. Finally, dynamic wireless charging will be deeply integrated with autonomous driving and road energy storage to build an integrated vehicle-road-energy network [9,11].

5. Conclusion

This paper takes the low-speed dynamic wireless charging system for urban roads as the research object. It systematically combs the domestic and foreign research progress of coil array, power matching and vehicle-road interaction in chronological order, compares the advantages and disadvantages of various mainstream technical schemes, and summarizes four core technical bottlenecks restricting industrial development. This paper also discusses the opportunities brought by technological development and the technical challenges faced by system optimization. Targeting the problems of insufficient offset resistance, unstable power output and high communication delay, this paper puts forward a complete optimization scheme covering coil array, power control and vehicle-road collaboration. Simulation and experimental verification prove that the optimized modular coil array has excellent anti-offset performance and multi-vehicle compatibility. The hybrid power algorithm greatly improves power matching accuracy and energy utilization efficiency. The low-delay vehicle-road interaction system provides reliable data support for the whole charging process. The integrated scheme can effectively solve the key technical bottlenecks restricting the development of urban low-speed wireless charging.

This research only focuses on the basic performance optimization of the system under conventional urban road conditions, and does not carry out in-depth research on extreme environments such as heavy rain, low temperature and road frost. In follow-up studies, researchers can explore the environmental adaptability of the system. Besides, this paper mainly analyzes the performance of coil and control modules, and subsequent research can further explore the economic benefit model and unified engineering standards of wireless charging infrastructure.

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