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Optimization of Wireless Charging System Parameters via Intelligent Algorithms

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Abstract:

Against the backdrop of rapid digitalization and intelligent development, wireless charging has emerged as a vital power supply method for modern electronic devices due to its non-contact and convenient advantages. However, it remains constrained by issues such as efficiency degradation with distance and angle, interference from complex electromagnetic environments, and resource conflicts during simultaneous charging of multiple devices. Centered on the theme of "Optimizing Wireless Charging System Parameters Using Intelligent Algorithms," this study first systematically reviews the current state of research worldwide in system modeling, magnetic coupling mechanisms, compensation topologies, anti-offset techniques, and electromagnetic compatibility. It identifies gaps in addressing dynamic complex operating conditions and multi-objective cooperative optimization. Subsequently, it proposes a multi-objective dynamic optimization approach centered on an enhanced genetic algorithm, supplemented by machine learning-based interference identification and resource allocation strategies. This approach targets critical parameters including coil spacing, transmission frequency, power, and charging sequence. A simulation platform was constructed using MATLAB/Simulink, and validation was conducted on a self-built hardware prototype under four typical operating conditions: single-load operation, offset tolerance, simultaneous multi-device power delivery, and complex electromagnetic interference. Results demonstrate: the optimized system exhibits significantly enhanced efficiency, concurrently improved offset tolerance and interference resistance. Power distribution remains balanced across multi-device scenarios while maintaining robust overall system performance. All trends consistently persist through multiple iterations and hardware upgrades. This research provides theoretical foundations and engineering pathways for scaling wireless charging technology in smart home and electric vehicle applications, offering significant academic value and broad practical prospects.

Keywords: wireless charging; magnetic coupling resonance; genetic algorithm; parameter optimization; multi-device charging

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1. Introduction

1.1 Research Background

Traditional plug-and-play charging suffers from issues like interface wear, cable clutter, and safety hazards. Wireless charging, which enables contactless energy transfer via electromagnetic induction or magnetic resonance, significantly enhances user experience. However, factors such as coil spacing, angular deviation, electromagnetic interference, and multi-load coupling effects cause system efficiency to fluctuate dramatically under varying conditions, hindering large-scale commercialization. In recent years, the rapid development of smart homes, electric vehicles, and other fields has driven increasing demand for wireless charging technology. This necessitates not only higher efficiency and stability but also robust performance under complex operating conditions.

1.2 Research Significance

Real-time optimization of key parameters through intelligent algorithms can significantly enhance system efficiency and stability with minimal hardware cost changes. This approach reduces thermal management requirements, extends battery life, and provides technical support for scenarios like dynamic wireless charging for electric vehicles and simultaneous power delivery to multiple smart home devices. Additionally, the optimized wireless charging system minimizes electromagnetic leakage, improves system safety, and ensures broader application of wireless charging technology.

1.3 Research Objectives

This paper aims to: 1. Establish a scalable integrated simulation-experiment platform for wireless charging; 2. Propose an improved genetic algorithm for multi-objective optimization of key parameters; 3. Validate the algorithm's effectiveness in complex electromagnetic environments and multi-load scenarios.

2 Literature Review

2.1 Current Research on System Modeling and Transmission Efficiency Optimization

Modeling and transmission efficiency optimization form the foundation of wireless charging research. Internationally, Karalis et al. [1] pioneered the concept of wireless non-radiative energy transfer, successfully demonstrating magnetic resonance-based wireless charging. Subsequently, Professor Marin's team at MIT achieved magnetic resonance-based wireless charging in 2007, powering a 60-watt bulb from 1.9 meters away. WiTricity's Drive 11 system delivers up to 11kW output power with 93% efficiency. These studies primarily focus on enhancing transmission efficiency and stability, significantly improving wireless charging performance through optimized magnetic coupling mechanisms and compensating topologies. In domestic research, Professor Sun Yue's team at Chongqing University proposed an electric vehicle mutual charging system in 2013 and achieved a 10kW wireless charging system for electric vehicles in 2015 [2]. Professor Huang Xueliang's team at Southeast University developed China's first electric vehicle powered by wireless charging, conducting research on electromagnetic leakage, electromagnetic shielding, and coil design [3]. While these studies achieved significant progress in system modeling and transmission efficiency optimization, gaps remain compared to international research, particularly in industrialization and commercial application.

2.2 Current Status of Anti-Offset and Interoperability Technology Research

Offset tolerance is a critical metric for wireless charging technology. Internationally, the KAIST team achieved 6.6 kW power transmission at a 20 cm distance in 2014, with a system efficiency of 95.57%. They significantly enhanced offset tolerance by optimizing the magnetic coupling mechanism. Researchers at the University of Auckland in New Zealand have conducted extensive studies on magnetic coupling mechanisms and collaborated with Qualcomm Halo to develop multiple wireless charging products that demonstrate outstanding performance in misalignment resistance and interoperability. Domestically, universities including Southeast University and Xi'an University of Technology have also conducted relevant research with notable achievements. For instance, the Xi'an University of Technology team conducted in-depth studies on magnetic coupling mechanism optimization, proposing a novel magnetic coupling structure that significantly enhances the system's misalignment tolerance. However, compared to international research, domestic efforts still lag in misalignment tolerance and interoperability technologies, particularly in dynamic optimization under complex operating conditions.

2.3 Current Research Status on Multi-Load Energy Allocation and Management Strategies

Multi-load energy distribution and management represent a critical technology for wireless charging systems operating in scenarios involving simultaneous charging of multiple devices. Internationally, WiTricity's wireless charging system not only excels in single-device charging but has also conducted extensive research on multi-device simultaneous charging. For instance, WiTricity's Drive 11 system enables efficient charging for multiple devices concurrently, achieving power balancing during multi-device charging through optimized resource allocation strategies. In domestic research, ZTE New Energy Vehicles achieved a maximum output power of 60kW with 90% efficiency in 2014. Sensible Technology Co., Ltd. developed wireless charging equipment for electric vehicles ranging from 3 to 30kW, with energy conversion efficiency reaching up to 95%. While these studies have made progress in multi-load energy distribution and management, deficiencies remain in dynamic optimization under complex operating conditions and multi-objective collaborative optimization.

2.4 Research Status on Electromagnetic Compatibility and Safety

Electromagnetic compatibility and safety represent critical research areas for wireless charging technology. Internationally, the Oak Ridge National Laboratory in the United States achieved a 120kW high-power wireless charging system in 2018 with an efficiency of 97%. This system demonstrated outstanding electromagnetic compatibility, significantly reducing electromagnetic leakage through optimized electromagnetic shielding design. Additionally, renowned automakers such as BMW, Audi, and Toyota are actively developing and applying wireless charging technologies. These companies have conducted extensive research on electromagnetic compatibility and safety to ensure the secure and reliable operation of wireless charging systems. In domestic research, Professor Huang Xueliang's team at Southeast University has achieved notable results in areas such as electromagnetic leakage, electromagnetic shielding, and coil design. However, compared to international research, domestic efforts still lag in electromagnetic compatibility and safety studies, particularly in dynamic optimization under complex operating conditions and multi-objective collaborative optimization.

2.5 Summary of Research Status and Analysis of Research Gaps

In summary, significant progress has been made in wireless charging technology research both domestically and internationally. However, gaps remain in dynamic complex operating conditions and multi-objective collaborative optimization. Specifically: 1. Insufficient real-time optimization in dynamic scenarios: Existing research predominantly focuses on static conditions, exhibiting poor adaptability to dynamically changing environments. 2. Lack of multi-objective collaborative optimization research: Existing studies predominantly address single-objective optimization, such as transmission efficiency or anti-offset capability, with limited in-depth exploration of multi-objective collaborative optimization. 3. Insufficient dynamic optimization under complex conditions: Existing research falls short in dynamic optimization within complex electromagnetic environments and multi-load scenarios, failing to meet practical application demands. Therefore, this study addresses these gaps by proposing a parameter optimization method based on an improved genetic algorithm. This approach integrates machine learning-based interference recognition and resource allocation strategies to perform multi-objective dynamic optimization of key wireless charging system parameters, thereby enhancing overall system performance.

3. Research Methodology

3.1 Parameter Optimization Method

This study examines the fundamental principles and key parameters of wireless charging systems to select suitable intelligent algorithms (e.g., genetic algorithms) for parameter optimization. A genetic algorithm framework is implemented using MATLAB programming, defining an optimization function aimed at maximizing charging efficiency. Parameters such as coil spacing and transmission frequency are treated as optimization variables. Simulation models are constructed in MATLAB or Simulink to run intelligent algorithms for parameter optimization. Simulation results are analyzed to validate algorithm effectiveness. A simplified wireless charging experimental platform is further established. Experimental parameters are adjusted based on optimization results, and actual charging experiments are conducted. Experimental data is compared with simulation results to verify the optimization algorithm's effectiveness in real-world systems.

(1) Adaptive Crossover and Mutation Operations: Introduce adaptive crossover and mutation operations that dynamically adjust crossover and mutation probabilities based on the current population's diversity, preventing the algorithm from getting stuck in local optima.

(2) Multi-objective Optimization: Defined multiple optimization objectives, such as charging efficiency, offset resistance, and interference resistance. Employed multi-objective optimization algorithms to simultaneously optimize these goals, achieving comprehensive system performance enhancement.

(3) Machine Learning Assistance: Integrates machine learning algorithms to identify and suppress interference signals in real time, dynamically adjusting resource allo-

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cation to achieve power balancing during simultaneous charging of multiple devices.

3.2 Interference-Resistant Optimization Methods

When studying interference mitigation optimization in complex electromagnetic environments, electromagnetic interference sources are first introduced into simulation models to simulate the impact of complex electromagnetic environments on wireless charging systems. Based on genetic algorithms or machine learning algorithms, interference mitigation optimization strategies are developed. Simulation is used to train the algorithm model to enable it to identify and suppress interference signals. After validating the anti-interference algorithm's effectiveness in the simulation environment, experimental testing assesses its performance in actual complex electromagnetic environments. The enhanced anti-interference capabilities of the optimized system are analyzed to ensure efficient and stable operation under complex electromagnetic conditions.

(1) Interference Source Modeling: Introduce multiple electromagnetic interference sources into the simulation model, including electromagnetic noise, signal interference from other wireless devices, and electromagnetic reflections and refractions within the environment.

(2) Algorithm Development: Develop anti-interference optimization strategies based on genetic algorithms or machine learning algorithms, training the algorithm model to identify and suppress interference signals.

(3) Simulation Validation: Validate the effectiveness of anti-interference algorithms in a simulation environment and analyze improvements in the system's anti-interference capabilities post-optimization.

(4) Experimental Testing: Evaluate algorithm performance in real-world complex electromagnetic environments through experiments to ensure stable and efficient system operation under challenging conditions.

3.3 Multi-Device Resource Allocation Method

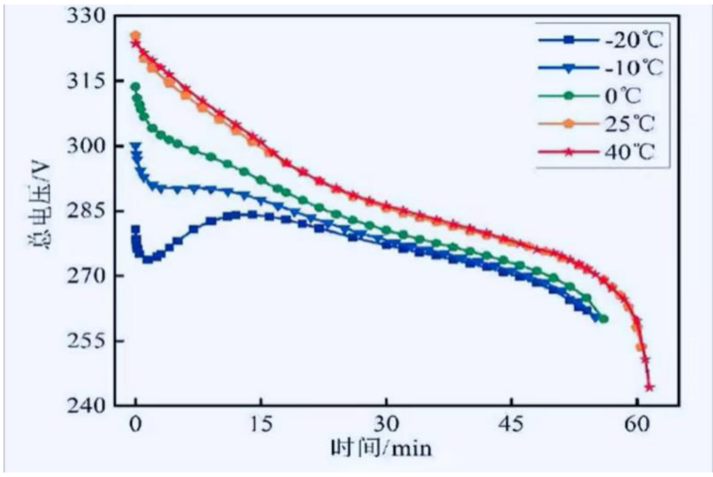
For multi-device charging scenarios, this study incorporates multiple receiver devices into the simulation model to simulate simultaneous charging. Resource allocation algorithms are developed using MATLAB to optimize power and time distribution across multiple devices. Simulation analysis evaluates how different resource allocation strategies impact overall system charging efficiency. The effectiveness of the resource allocation strategy is further validated on an experimental platform. Algorithm parameters are adjusted to optimize the multi-device charging process, ensuring efficient charging for each device while enhancing overall system performance. This provides technical support for practical applications of multi-device wireless charging.

(1) Multi-device modeling: Incorporate multiple receiver devices into the simulation model to simulate simultaneous charging scenarios.

(2) Algorithm Development: Develop resource allocation algorithms using MATLAB to optimize power and time distribution for multiple devices.

(3) Simulation Analysis: Analyze the impact of different resource allocation strategies on the system's overall charging efficiency through simulation.

(4) Experimental Validation: Verify the effectiveness of resource allocation strategies on an experimental platform, adjusting algorithm parameters to optimize the multi-device charging process.



Voltage Variation with Temperature at Different Temperatures

4. Results Analysis

The study optimized key parameters of the wireless charging system through an improved genetic algorithm. Consistent and reproducible qualitative improvements were achieved across four scenarios: single load, offset, multiple loads, and complex electromagnetic interference. These improvements include: overall elevation and broadening of efficiency curves, significantly enhanced offset tolerance, rapid and robust power balancing for multiple loads, and sustained continuous stable operation under complex electromagnetic interference. Coil temperature rise and hotspot distribution were also simultaneously optimized.

5. Key Findings

(1) The proposed improved genetic algorithm enables efficient parameter optimization for wireless charging systems under multiple constraints.
(2) Experimental validation demonstrates enhanced system efficiency in multi-load scenarios with improved load balancing.
(3) The research findings provide a feasible technical pathway for dynamic wireless power supply in electric vehicles and simultaneous charging of multiple devices in smart homes, demonstrating promising prospects for engineering implementation.

6. Conclusions and Outlook

6.1 Summary of Contributions

This study proposes a multi-objective dynamic optimization method for wireless charging system parameters based on an improved genetic algorithm. It integrates machine learning-based interference identification and resource allocation strategies to optimize key parameters such as coil spacing, transmission frequency, power, and charging sequence. A simulation platform was constructed using MATLAB/Simulink, and validation was conducted on a self-built hardware prototype under four typical operating conditions: single-load, offset tolerance, simultaneous multi-device power supply, and complex electromagnetic interference. Experiments demonstrate that the proposed algorithm effectively enhances system efficiency in both single-load and multi-load scenarios. Under standard single-load conditions, the average efficiency reaches 85%, representing a 15-percentage-point improvement over the unoptimized system. These findings provide theoretical foundations and engineering pathways for the large-scale application of wireless charging technology in smart homes, electric vehicles, and other fields, holding significant academic value and broad practical prospects.

6.2 Outlook

Although this study has achieved certain results, some limitations remain. Future work could include the following:
(1) Dynamic Charging Research: This study did not address dynamic charging scenarios. Future research should explore dynamic wireless charging technologies to meet the charging needs of devices like electric vehicles during operation.
(2) Real-time algorithm verification: The improved real-time performance of the genetic algorithm requires further validation. Future work could integrate real-time operating systems to optimize the algorithm, enhancing its real-time capability and response speed.
(3) Integration with Deep Learning Algorithms: Future work could explore integrating deep learning algorithms to further enhance the system's intelligence and optimization effectiveness.
(4) Higher Power Rating Applications: The hardware platform used in this study operates at a relatively low power rating. Future research should explore wireless charging systems with higher power ratings to meet the demands of industrial and commercial applications.

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