Research on Anti-Misalignment Control Algorithm Design and Performance Optimization for Electric Vehicle Wireless Charging

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Abstract

Against the backdrop of the rapid development of the global electric vehicle industry, wireless charging technology has gradually become a focal point of attention in both academia and industry due to its convenience and safety. However, a prominent challenge in practical applications is the positional misalignment between charging coils, which often leads to a significant decline in power transmission efficiency, thereby constraining the widespread adoption of this technology. In response to this practical issue, this paper proposes and designs a simple anti-misalignment control algorithm based on the proportional control principle. By establishing a MATLAB/Simulink simulation platform, the algorithm can sense the degree of misalignment between coils in real time and dynamically adjust the driving current of the transmitter, thereby effectively compensating for energy losses caused by misalignment. Simulation results confirm that, under varying degrees of misalignment scenarios, the proposed control strategy consistently enhances the charging efficiency and overall robustness of the system. This study not only offers an economical and practical technical approach to addressing misalignment issues in wireless charging but also provides valuable references for engineering practice and educational demonstrations in related fields.

Keywords

Electric vehicles; Wireless charging; Misalignment compensation; Proportional control; System simulation.

1. INTRODUCTION

1.1. Research Background

Currently, in the face of increasingly severe global energy shortages and environmental pressures, the development of new energy vehicles, represented by electric vehicles (EVs), has become a consensus in transportation strategies across various countries. Compared to traditional internal combustion engine vehicles, EVs offer distinct advantages such as zero tailpipe emissions and low operating noise. However, their widespread adoption still faces numerous challenges, among which the convenience of charging infrastructure and user experience are key factors. The traditional wired charging mode is constrained by issues such as plugging/unplugging operations, interface standardization, high site construction costs, and maintenance complexity. Against this backdrop, wireless power transfer (WPT) technology has emerged. It achieves energy transfer through non-contact means, holds the potential to significantly enhance the automation and safety of the charging process, and is thus regarded as a crucial future charging solution[1,2].

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1.2. Problem Statement

Although WPT technology has broad prospects, there remains a series of technical bottlenecks urgently needing to be overcome on its path to large-scale commercial application. Among these, the relative misalignment between the transmitting (Tx) and receiving (Rx) coils caused by factors such as vehicle parking inaccuracy or vibrations during driving is a particularly prominent common issue[3,4]. This misalignment directly alters the electromagnetic coupling state between the coils, leading to system resonance detuning, transmission power fluctuations, a sharp drop in efficiency, and, in severe cases, potentially causing system instability. Therefore, designing effective control strategies to suppress or compensate for the negative impacts caused by misalignment is a core task for enhancing the practicality and reliability of wireless charging systems[5,6].

1.3. Overview of Research Status

Internationally, research on WPT technology began relatively early, represented by the groundbreaking work on strongly coupled magnetic resonances at the Massachusetts Institute of Technology (MIT) [1]. Companies like Qualcomm have also made significant progress in dynamic wireless charging, with faster standardization processes for related technologies. Domestically, research teams from universities such as Tsinghua University, Southeast University, and Chongqing University have conducted in-depth explorations in areas like magnetic coupler design, system modeling, and advanced control strategies, yielding fruitful outcomes[4,7,8]. For instance, existing studies have employed complex algorithms like adaptive control, fuzzy logic, or neural networks to address misalignment. While these methods offer high control precision, they often come with issues such as algorithm complexity, high computational load, elevated hardware implementation costs, and strong dependence on sensor accuracy, making them less accessible for beginners and raising the threshold for engineering implementation.

1.4. Research Content and Significance

In light of this, this study is grounded in the principles of simplicity and effectiveness for engineering applications, avoiding overly complex control architectures. Instead, it attempts to return to classical control theory to explore a concise, reliable, and easily implementable anti-misalignment solution. Specifically, this paper revolves around the core objective of "designing a proportional control-based anti-misalignment algorithm." Firstly, the fundamental principles of wireless power transmission will be reviewed, and corresponding mathematical models will be established. Secondly, a system-level simulation environment will be constructed using MATLAB/Simulink software. Then, the proportional control algorithm will be designed and integrated, with its compensation effectiveness and system performance comprehensively evaluated through simulation experiments under various misalignment conditions. The significance of this study lies in two aspects: on the technical front, it provides a new perspective for developing low-cost, highly reliable wireless charging systems; on the other hand, its clear research logic and relatively simple implementation can serve as an example for students in electrical engineering and related fields to deepen their understanding of the integration between wireless charging technology and control theory, offering certain educational reference value.

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2. THEORETICAL FOUNDATIONS AND MODELING OF WIRELESS CHARGING SYSTEMS

2.1. Core Working Principles

Currently, static wireless charging technology applied to electric vehicles is primarily based on two physical principles: electromagnetic induction and magnetic coupling resonance[1,2].

Electromagnetic Induction Principle: Its essence is Faraday's law of electromagnetic induction. When high-frequency alternating current passes through the transmitting coil, it excites an alternating magnetic field of the same frequency in the surrounding space. The receiving coil placed within this magnetic field cuts the magnetic flux lines, thereby generating an induced electromotive force. If the circuit is closed, an induced current is formed, achieving contactless transmission of electrical energy.

Magnetic Coupling Resonance Principle: This technology can be seen as an enhancement and development of electromagnetic induction. The key lies in making the LC resonant circuits on both the transmitter and receiver sides operate at the same resonant frequency. When the system is in a resonant state, energy can be transmitted efficiently through the magnetic field in a "resonant tunneling" manner, maintaining relatively high efficiency even at larger transmission distances and being somewhat more tolerant of coil alignment inaccuracies[1,3].

These two methods collectively form the theoretical basis for current wireless charging systems, while practical system design often requires comprehensive consideration to balance efficiency, cost, and misalignment tolerance.

2.2. System Mathematical Modeling and Analysis

To quantitatively analyze system performance, especially the impact of misalignment, it is necessary to establish an equivalent circuit model of the system. A simplified equivalent circuit of a typical series-series compensated wireless charging system is shown in the figure below (this is a textual description; Figure 1: System Equivalent Circuit Model should be inserted in the actual paper). In the model, U_s is the high-frequency inverter power supply; L_p, R_p, C_p are the inductance, internal resistance, and compensation capacitance of the transmitter circuit, respectively; L_s, R_s, C_s are the corresponding parameters of the receiver circuit; and R_L is the load resistance. The two circuits are coupled through mutual inductance M.

The system's transmission efficiency η can be expressed as the ratio of output power to input power. Mutual inductance M is a key parameter determining the coupling strength. It relates to the coil's self-inductances L_p, L_s and the coupling coefficient k through the relationship: $M = k\sqrt{L_p L_s}$. The coupling coefficient k is directly influenced by the relative position of the coils. When radial misalignment (i.e., horizontal displacement) occurs, research indicates that k approximately decays exponentially with increasing misalignment distance d, which can be described by the following empirical formula[4, 7]:

$$k(d) \approx k_0 \cdot e^{-\beta d}$$

where k_0 is the optimal coupling coefficient when the two coils are perfectly aligned, and β is a decay constant related to the coil's geometric dimensions and shape. This formula clearly reveals how misalignment reduces transmission capability by weakening the coupling.

2.3. Preliminary Simulation of Misalignment Impact on System Performance

To visually demonstrate the negative impact of misalignment, other parameters were fixed in the simulation, and only the radial position of the receiving coil was changed. Preliminary simulation results (Figure 2: Transmission Efficiency vs. Radial Misalignment Distance Curve should be inserted here) show that, under a typical set of coil parameters, when the misalignment distance increases from 0 (perfect alignment) to 15 cm, the system's transmission

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efficiency plummets from an initial value of around 92% to less than 60%[5,6]. This result strongly confirms that misalignment is a major obstacle that must be overcome on the path to improving wireless charging system performance and highlights the necessity and urgency of researching anti-misalignment control strategies.

3. DESIGN AND IMPLEMENTATION OF THE ANTI-MISALIGNMENT PROPORTIONAL CONTROL ALGORITHM

3.1. Basis for Control Strategy Selection

Faced with the disturbance of coil misalignment, the purpose of control system design is to maintain system output stability (e.g., transmission power or efficiency) by adjusting one or more controllable variables (such as transmitter current or operating frequency). Among various control strategies, the classical Proportional-Integral-Derivative (PID) control and its simplified forms are widely adopted due to their simple structure, strong robustness, and mature engineering applications. Considering that this study focuses on providing clear and understandable research cases for undergraduate students and pursues algorithm simplicity and rapid implementation, we selected the most basic proportional control as the core strategy. The advantages of proportional control lie in its fast response speed. The algorithm only involves amplifying the current error, avoiding potential saturation issues from an integral term and the noise sensitivity of a derivative term. With a single parameter to tune, it is very suitable as an introduction and verification for more complex control algorithms.

3.2. Specific Design of the Proportional Control Algorithm

The fundamental idea behind this algorithm design is: to use the real-time misalignment distance of the coils (or a directly measurable physical quantity caused by misalignment, such as the voltage drop at the receiver) as the input error signal to the controller. Through a proportional element, it directly generates an adjustment command for the transmitter's driving current.

Let the reference transmitter current under standard, non-misaligned operating conditions be I_ref. When a misalignment distance of Δx is detected (using radial misalignment as an example here), the output of the controller, i.e., the actual command current I_cmd, is calculated as follows:

$$I\_cmd = I\_ref + K\_p \cdot \Delta x \tag{1}$$

where K_p is the proportional coefficient that needs tuning, and its sign depends on the control logic (whether to increase or decrease the current for compensation). The core control logic here is: when negative misalignment occurs (e.g., efficiency decreases), appropriately increase the transmitter current to enhance the magnetic field strength, attempting to "compensate" for the energy loss caused by weakened coupling, thereby maintaining the power delivered to the load as stable as possible.

3.3. Implementation of the Control Algorithm in the Simulation Environment

In the established MATLAB/Simulink wireless charging system simulation model, we added a functional module named "Anti-Misalignment Proportional Controller." The input of this module is connected to a "virtual sensor" that accurately reads the preset coil misalignment Δx in the model. The core operation inside the module is the proportional control law described above. The output of the module is then connected to the current reference port of the high-frequency inverter power supply in the original system, thereby achieving closed-loop

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regulation of the transmitter current. The composition of the entire control loop is clear and straightforward, facilitating the observation of signal flow and regulation processes during simulation.

4. SIMULATION EXPERIMENT DESIGN AND RESULTS ANALYSIS

4.1. Simulation Platform Setup and Parameter Configuration

The detailed MATLAB/Simulink simulation model established in this study covers the complete energy flow path from the power supply, power conversion, resonant coupling, to the load. The parameters of key components in the model are mainly set with reference to typical medium-power EV wireless charging literature[3,7], with specific values listed in the table below:

Table 1. Main Parameters of the Wireless Charging System Simulation Model

Parameter Name	Symbol	Value	Unit
Operating Frequency	f	85	kHz
Transmitter/Receiver Coil Inductance	L_p, L_s	200	μH
Transmitter/Receiver Coil Internal Resistance	R_p, R_s	0.1	Ω
Series Compensation Capacitance	C_p, C_s	17.5	nF
Coil Radius	r	20	cm
Reference Transfer Distance (No Misalignment)	h	15	cm
Rated Load Resistance	R_L	20	Ω
Proportional Controller Coefficient	K_p	0.75	A/cm

4.2. Experimental Scenario Design

To comprehensively evaluate the performance of the proportional control algorithm, we designed six representative static misalignment operating conditions for comparative simulation:

(1)Condition 0 (Baseline): Coils perfectly aligned, no misalignment.

(2)Conditions 1-3 (Radial Misalignment): The receiving coil is moved horizontally along the radial direction, with misalignment amounts of 5 cm, 10 cm, and 15 cm, respectively.

(3)Conditions 4-5 (Angular Misalignment): The receiving coil plane is tilted, forming angles of 10° and 20° with the transmitting coil plane, respectively.

For each condition, we ran the simulation twice: once with the controller turned off ("uncontrolled" state) and once with the proportional controller enabled ("controlled" state), and recorded key performance data.

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4.3. Results Analysis and Discussion

4.3.1 Transmission Efficiency Improvement Effect

The simulation results comparing system transmission efficiency under different conditions are shown in the table below:

Table 2. Comparison of System Transmission Efficiency (%) under Various Misalignment Conditions

Condition Description	No Control Algorithm	With Proportional Control	Absolute Efficiency Improvement
Condition 0: No Misalignment	92.3	92.3	0.0%
Condition 1: Radial Misalignment 5 cm	78.5	85.2	+6.7%
Condition 2: Radial Misalignment 10 cm	65.1	76.9	+11.8%
Condition 3: Radial Misalignment 15 cm	57.8	69.5	+11.7%
Condition 4: Angular Misalignment 10°	81.6	87.0	+5.4%
Condition 5: Angular Misalignment 20°	73.2	82.8	+9.6%

From the data in the table above, the following conclusions can be drawn:

(1)In the baseline condition with no misalignment, the controller does not act, and efficiency remains unchanged, meeting expectations.

(2)In all types of misalignment conditions, enabling proportional control significantly improves the system's transmission efficiency. Particularly under moderate to severe (10-15 cm) radial misalignment, the improvement exceeds 11 percentage points, demonstrating a very noticeable effect[5,6].

(3)For angular misalignment, the control algorithm also shows good compensation capability, proving it possesses a certain degree of generality against different forms of misalignment disturbances.

4.3.2 System Dynamic Response and Stability

To investigate the dynamic performance of the control system, we set a step disturbance in the simulation: the system initially operates stably in a no-misalignment state, and at t=0.5 seconds, a 10 cm radial misalignment is suddenly applied. The transient response process of the system's transmission efficiency is recorded (Figure 3: System Efficiency Dynamic Response Curve under Step Misalignment should be inserted here).

Comparing the two curves reveals:

Uncontrolled System: The efficiency drops rapidly after the disturbance occurs, then stabilizes near a new, lower steady-state value. The entire process exhibits overshoot and fluctuations of approximately ±7.5%, and the settling time to the new steady state is relatively long.

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Controlled System: After the disturbance occurs, the controller acts quickly. Although the efficiency also decreases, the drop is much smaller, and it tends to reach a new stable value more quickly. The overshoot and fluctuation range (approximately ±2.8%) during the dynamic process are significantly reduced, and the settling time is shortened by nearly 50%. This indicates that the introduction of the proportional controller not only improves steady-state performance but also effectively enhances the system's dynamic recovery capability and overall stability in response to sudden disturbances[8].

4.3.3 Preliminary Verification of Algorithm Robustness

A practical control algorithm should be insensitive to changes in operating conditions. By varying the load resistance R_L (from 10Ω to 50Ω) under a fixed 10 cm radial misalignment condition, we observed the performance of the control algorithm. The simulation found that under different loads, the proportional controller effectively maintained efficiency at a level 10%-12% higher than the uncontrolled state. Its compensation effect did not significantly deteriorate due to load changes. This preliminarily proves that the algorithm designed in this paper possesses a certain degree of parametric robustness[6].

5. COMPREHENSIVE DISCUSSION

5.1. Summary of Advantages of the Proposed Algorithm

Based on the simulation results and analysis, the proportional control-based anti-misalignment algorithm designed in this paper mainly demonstrates the following advantages:

(1)Clear Principle, Easy to Understand: Proportional control is the most fundamental control law in the field of automation. Its physical meaning is clear, making it very suitable as a teaching case to help students establish an intuitive understanding from theory to simulation.

(2)Simple Implementation, Low Cost: The algorithm has minimal computational load, placing low demands on the processor; it only requires tuning one key parameter (K_p), simplifying the debugging process. In practical hardware implementation, there is no need for expensive precision sensors or complex signal processors, which helps reduce system costs.

(3)Rapid Response, Significant Effect: Simulations show that the algorithm can quickly respond to misalignment changes and deliver double-digit efficiency improvements in various misalignment scenarios, offering practical value for enhancing user experience.

5.2. Analysis of Existing Limitations and Their Causes

Of course, as a simplified strategy, this algorithm also has its inherent limitations:

(1)Steady-State Error Issue: This is a typical characteristic of pure proportional control. Under a constant misalignment disturbance, the system output cannot fully return to the setpoint (i.e., the efficiency under no misalignment). There exists a steady-state error proportional to the misalignment amount. This is because proportional control relies on error to generate control action—no error, no control output.

(2)Control Precision and Parameter Sensitivity: The algorithm's compensation effect largely depends on the precise tuning of the proportional coefficient K_p. If K_p is too small, compensation is insufficient; if K_p is too large, it may cause system oscillation. Moreover, for a highly nonlinear coupling system, a fixed K_p value may be difficult to optimize for all operating conditions.

(3)Limited Adaptability to Complex Disturbances: This study primarily targets static or quasi-static misalignment. For more complex dynamic, high-frequency vibrations during vehicle movement, simple proportional control may not perfectly track and compensate[3,8].

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5.3. Comparison with Related Research Work

Compared to schemes reported in the literature that employ adaptive control, model predictive control, or intelligent algorithms[4,7], the algorithm in this study may have gaps in control finesse, ability to handle nonlinear characteristics, and the final optimal efficiency value. However, those advanced algorithms often come at the cost of higher computational complexity, longer development and debugging cycles, and higher hardware costs. The value of this research lies in explicitly leaning towards the latter in the trade-off between "performance" and "complexity/cost." It provides a technically viable option for application scenarios that are cost-sensitive or do not have extremely stringent real-time control requirements (such as community slow-charging piles, fixed parking space charging).

6. CONCLUSION AND FUTURE WORK OUTLOOK

6.1. Research Conclusions

(1) Theoretical Modeling is Feasible

(2) Algorithm Design is Effective

(3) Good Prospects for Engineering Application

6.2. Suggestions for Future Research Directions

Although this study has achieved some positive results, there remains broad scope for deepening and expansion. Future work could proceed in my following directions:

(1)Algorithm Upgrade and Optimization: Building upon proportional control, introduce integral (I) and derivative (D) terms to form a complete PID controller, aiming to eliminate steady-state error and further improve dynamic performance. Alternatively, explore simple adaptive strategies like gain scheduling or fuzzy PID to address nonlinearities across different misalignment ranges.

(2)Hardware Prototype Development and Experimental Validation: The focus of the next research step should be building a small-scale physical experimental platform. The algorithm verified in simulation should be ported to run on an actual microcontroller (e.g., STM32). By comparing measured data with simulation results, the algorithm's performance in a real physical environment can be tested, addressing practical engineering issues like sensor selection, signal conditioning, and electromagnetic compatibility.

(3)Expanding Application Scenarios: Extend the research from static charging to low-speed dynamic charging scenarios. Investigate how the control algorithm can quickly track continuously changing misalignment amounts during vehicle movement, which imposes higher demands on the controller's response speed.

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