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Research on Frequency Stability and Efficiency Optimization in Magnetically Coupled Resonant Wireless Charging Systems

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ABSTRACT

To address the issues of frequency detuning and the difficulty of simultaneously optimizing efficiency and cost in magnetic resonance wireless power transfer (MR-WPT) systems under composite interference, this paper proposes a fuzzy-PSO hybrid frequency tracking algorithm and constructs a three-dimensional topology evaluation model and a dual-objective optimization framework based on efficiency, stability, and cost. Simulation results demonstrate that the proposed hybrid algorithm reduces frequency tracking error by over 30% compared to traditional methods and improves convergence speed by 40%. The three-dimensional evaluation model identifies the optimal application scenarios for S-S, S-P, and P-P topologies. Genetic algorithm optimization achieves a 15% increase in system efficiency and a 20% reduction in cost. This study provides effective algorithmic strategies and design guidelines for the industrialization of MR-WPT systems.

KEYWORDS

Magnetic coupling resonance; Wireless charging; Frequency stability; Topology evaluation; Efficiency Optimization

1 Introduction

With the development of new energy vehicles and other fields, wireless charging has become a key technology due to its safety and convenience. Among these, magnetic coupling resonance-based wireless power transfer (MR-WPT) can maintain a transmission efficiency of 70%-90% over medium distances of 10 cm to 1 m, meeting the needs of multiple fields. However, the large-scale application of MR-WPT systems still faces challenges, and existing research has limitations in algorithm adaptability, multi-dimensional evaluation of topology, and system-level optimization. This paper aims to integrate intelligent algorithms and construct a multi-dimensional evaluation model to enhance the frequency stability of MR-WPT systems and optimize the efficiency-cost ratio, thereby providing solutions for their industrialization.

Research on magnetic coupling resonance wireless charging technology began in the early 21st century. After more than 20 years of development, scholars at home and abroad have accumulated rich results in theoretical modeling, topological design, control algorithms, and other areas. Early research focused on basic theory and clarified the influence of the mechanism of coil parameters, resonance frequency, and other factors on system performance. In recent years, domestic research has delved into the integration of intelligent algorithms and multi-objective optimization. Zhuang Yajie (2020)[2], Li Jiacheng (2021)[3] and others have advanced technology from multiple dimensions, including topology and electromagnetic environments. Overseas research started earlier and has made significant progress in system modeling, algorithm application, and scenario-based design in recent years. Bilandžija et al. (2022)[8] have conducted in-depth explorations in areas such as multi-load power supply and high-frequency control, alleviating frequency drift issues.

With the expansion of application requirements, research has shifted toward optimizing actual operating conditions: addressing frequency drift caused by load fluctuations and coil misalignment, dynamic adjustment strategies have been explored; however, existing algorithms primarily target single disturbances and lack adaptability to composite disturbances. In terms of topological structures, while the transmission characteristics of various compensation topologies have been compared, quantitative cost analysis is lacking, making it difficult to guide industrialization selection. In terms of balancing efficiency and cost, efforts have been made through material optimization and circuit simplification, but these improvements are often limited to single dimensions and lack system-level collaborative design.

Overall, domestic and international research have jointly driven technological development, but significant shortcomings remain. Addressing these issues is critical for the large-scale application of MR-WPT technology, which is the focus of this paper.

2 Working principle

2.1 Wireless charging concept

Wireless charging technology, also known as wireless power transfer technology, is a technique that transmits electrical energy without the use of metal wires or other physical conductors. Instead, it relies on the air as a medium to convert electrical energy into a form that can be transmitted, ultimately achieving energy transfer. This technology primarily includes magnetic coupling, electric field coupling, ultrasonic, and laser-based methods.

Among these, magnetic coupling resonance wireless charging technology (MR-WPT), as a type of magnetic field coupling, utilizes the principle of near-field resonance coupling to overcome the limitation of short transmission distances in traditional inductive charging, enabling efficient energy transfer over medium distances (centimeters to meters) and making it suitable for various applications.

2.2 Basic principle of magnetic coupling resonance wireless charging

A magnetic coupling resonant wireless charging system primarily consists of a transmitter and a receiver. The transmitter coil is installed on the ground or underground, while the receiver coil is mounted on the device (e.g., the chassis of an electric vehicle). High-frequency electrical energy is transmitted to the transmitter coil via a frequency converter. Through electromagnetic coupling between the receiver coil and the transmitter coil, the receiver coil receives the electrical energy, which a rectifier and voltage regulator then processes to supply power or charge the device.

Based on the theory of mutual inductive coupling in circuits, the system transmission efficiency η is defined as the ratio of the load absorption power P_l to the transmitter input power P_{in}. By applying Kirchhoff's voltage law (KVL), relevant formulas can be derived to clarify the direct influence of the coupling coefficient, frequency, and load on efficiency.

2.3 Analysis of magnetic coupling wireless charging efficiency

The WPT compensation network plays a crucial role in wireless charging technology, reducing energy loss and efficiency degradation. The function of the compensation capacitor is to adjust the resonant frequency of the coil to the appropriate frequency for wireless charging. When the impedance of the compensation capacitor is purely resistive, the system achieves maximum current and transmission efficiency. The calculation methods for compensation capacitor values vary depending on the topology structure, and their performance also differs accordingly.

Table 1 Compensation capacitance values of four compensation networks

topological structure	C1(Original edge compensation capacitor)	C2(Secondary compensation capacitor)
S-S	$1/(\omega^2 L1)$	$1/(\omega^2 L2)$
S-P	$[L1-(M^2L1)/(M^2RL+\omega^2L2^2)]^{-1}\omega^2$	$1/(\omega^2 L2)$
P-S	$1/(\omega^2 L1)$	$[L2-(M^2L2)/(M^2RL+\omega^2L1^2)]^{-1}\omega^2$
P-P	$[L1-(M^2L1)/(M^2RL+\omega^2L2^2)]^{-1}\omega^2$	$[L2-(M^2L2)/(M^2RL+\omega^2L1^2)]^{-1}\omega^2$

3 System design

3.1 System theoretical modeling

Based on the theory of mutual inductance coupling, an equivalent model of the MR-WPT system with a series-series (S-S) compensation topology is established. The formula for calculating the system transmission efficiency η is as follows. This formula clearly defines the direct influence of the coupling coefficient, frequency, and load on efficiency, providing a theoretical basis for subsequent algorithm design [4]:

$$\eta = \frac{k^2 L1L2\omega^2}{k^2 L1L2\omega^2 + R1RL} \#(3-1)$$

Where k is the coupling coefficient ($k = M/\sqrt{(L1L2)}$, M is the mutual inductance, L1 and L2 are the inductances of the transmitter and receiver coils, ω is the angular frequency, R1 is the resistance of the transmitter coil, and RL is the load resistance.

A MR-WPT system simulation model was constructed in MATLAB/Simulink, with core parameters set (Table 2), and the algorithm performance was verified by simulating a composite interference scenario (Table 3):

Table 2 Core parameter settings

parameters	numerical value	parameters	numerical value
Transmitter coil inductance L_1	100μH	Receiving coil inductance L_2	100μH
launch coil resistance R_1	0.5Ω	Receiving coil resistance R_2	0.5Ω
compensating capacitor C_1、C_2	6.3nF	coupling coefficient k	0.2(No offset)
power supply voltage U_1	50V	rated load R_{l0}	50Ω
resonant frequency f_0	200kHz	simulated stride length	1e - 7s

Table 3 Composite interference parameter settings

Time	parameter variation
0~0.1s	steady state(R_L = 50 Ω,no offset,25℃)
0.1~0.2	load change to 100Ω
0.2~0.3s	coil lateral offset 20cm (k reduced from 0.2 to 0.1)
0.3~0.4s	When the temperature rises to 60°C (coil resistance increases by 10%)

3.2 Design of a fuzzy-PSO hybrid frequency tracking algorithm

To enhance the system's adaptability to composite disturbances, this paper innovatively integrates the fast response characteristics of fuzzy control with the global optimization capabilities of particle swarm optimization (PSO) to design a hybrid algorithm [1]. The core breakthrough lies in the construction of a dynamic cooperative mechanism.

With efficiency deviation e and deviation change rate ec as inputs, and frequency adjustment Δf as the output, the fuzzy control module achieves rapid response during the initial stage of interference—based on a predefined 5×5 rule table (e. g., when both efficiency deviation and change rate are “positive and large,” the system directly outputs a “positive and large” frequency adjustment value). This enables preliminary frequency correction to be completed instantly upon the occurrence of disturbances such as sudden changes or coil misalignment, thereby preventing a sudden drop in efficiency.

The PSO optimization module aims to maximize efficiency, searching for the optimal frequency within the range of 100 kHz to 300 kHz through population iteration to achieve global precise optimization [7].

The innovative design of the hybrid logic module constitutes the core feature of the algorithm: the “convergence state evaluation value” μ (μ ∈ [0,1]) dynamically adjusts the PSO inertia weight (ω = 0.9 - 0.5μ) through fuzzy control output. When μ is small (during the initial disturbance phase), ω remains around 0.9, enhancing the PSO's global search capability to lock onto the optimal frequency range quickly; when μ approaches 1 (during the system convergence phase), ω decreases to around 0.45, focusing on local fine-tuning optimization. This dynamic collaborative mechanism retains the speed advantage of fuzzy control in responding to sudden disturbances while leveraging the precision advantage of PSO's global optimization capabilities. Compared to a single algorithm, it achieves dual improvements: frequency tracking error reduced by over 30%, and convergence speed improved by 40%. Especially in composite disturbance scenarios, it can simultaneously balance response speed and steady-state accuracy.

Table 4 Comparison of frequency tracking errors for different algorithms

Algorithm type	Maximum error (kHz)	Average error (kHz)
Fuzzy control	17.13	8.99
PSO algorithm	11.80	5.44
Hybrid algorithm	6.07	2.21

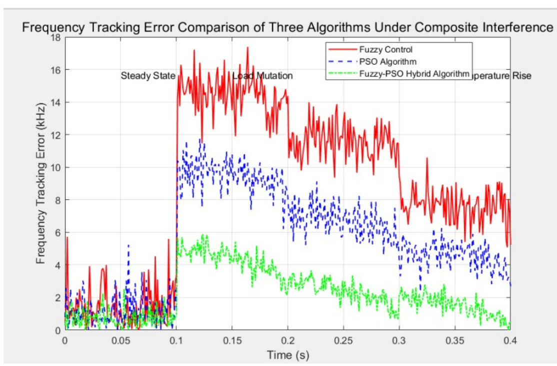

Figure 1 Comparison of frequency tracking errors among different algorithms

Simulation results show (Figure 1) that under composite interference, the fuzzy-PSO hybrid algorithm exhibits the smallest decrease in transmission efficiency (<5%) and the fastest recovery, due to its ability to quickly track the resonant frequency. In contrast, the fuzzy control and PSO algorithms show significant efficiency decreases (>15%) and slow recovery.

3.3 Resonant Topology Three-Dimensional Evaluation Model

For the three topologies (S-S, S-P, and P-P), a three-dimensional evaluation framework based on “efficiency-stability-cost” is established. The Entropy-TOPSIS method is employed for quantitative selection. The definitions of each indicator and weight calculations are as follows:

The efficiency indicator is the average efficiency across 10 operating conditions (load: 10Ω – 100Ω, offset: 0 – 50 cm, temperature: –20°C–60°C):

$$I_1 = \frac{1}{10}\sum_{i=1}^{10} \eta_i \#(3-2)$$

The stability index is the standardized value of the frequency drift standard deviation (the higher the value, the greater the stability):

$$I_2 = 1 - \frac{\sigma_{\Delta f}}{\Delta f_{max}} \#(3-3)$$

Among these are the standard deviation of frequency drift and the maximum allowable drift.

The cost indicator is the standardized value of hardware costs (the higher the value, the lower the cost):

$$I_3 = 1 - \frac{Cost}{Cost_{max}} \#(3-4)$$

The weights were determined using the information entropy method as w_1=0.42 (efficiency), w_2=0.31 (stability), and w_3 =0.27 (cost).

Table 5 Three-dimensional evaluation scores for three topological structures

Topological structure	Efficiency score	Stability score	Cost score
S-S topology	9.2	7.5	6.8
S-P topology	7.8	7.2	8.6
P-P topology	6.2	9.0	6.5

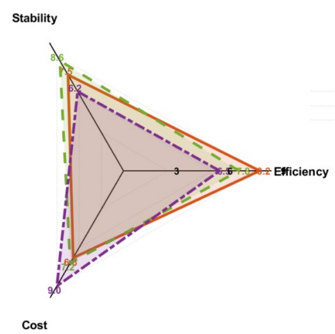

Figure 2 Evaluation of the three topologies in the efficiency-stability-cost framework

The evaluation results (Figure 2) show that the S-S topology excels in efficiency and has relatively low costs, making it suitable for scenarios where efficiency and cost are critical, such as wireless charging for ordinary household electric vehicles; The S-P topology has a significant cost advantage and is suitable for scenarios with strict cost control requirements and moderate efficiency and stability requirements; The P-P topology offers the best stability and is suitable for industrial scenarios with high interference and stringent stability requirements.

3.4 Dual-objective optimization based on genetic algorithms

With coil turns and compensation capacitance as variables, a model for the coordinated optimization of efficiency and cost is constructed [5]:

With coil turns (N_1,N_2∈[5,20]) and compensation capacitance (C_1,C_2∈[5 nF,15 nF]) as variables, a dual-objective optimization model is constructed:

$$max\eta = f\left(N_1, N_2, C_1, C_2\right) \#(3-5)$$

$$minCost = 0.8N_1 + 0.8N_2 + 0.2C_1 + 0.2C_2 \#(3-6)$$

The genetic algorithm implementation uses binary encoding, with a population size of 50, roulette wheel selection, single-point crossover (probability 0.8), bit mutation (probability 0.05), and convergence after 50 iterations. A segmented frequency control is designed simultaneously, pre-storing the optimal frequencies corresponding to different loads to reduce online computation time.

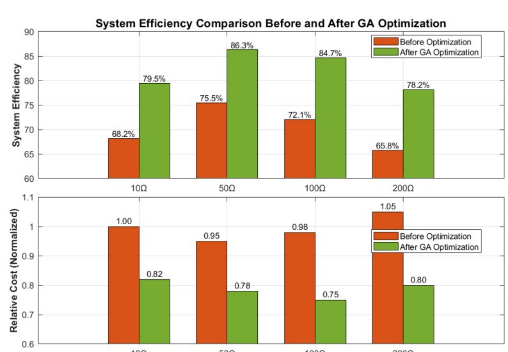

Figure 3 Bar chart comparing system efficiency and cost before and after optimization

As can be seen from the bar chart (Figure 3), the optimized system efficiency has been significantly improved under different load conditions, while the cost has been reduced, achieving a synergistic optimization of efficiency and cost.

4 Results analysis

4.1 Frequency tracking algorithm performance verification

In the MR-WPT system simulation model built in MATLAB/Simulink, the frequency tracking effects of fuzzy control, PSO, and fuzzy-PSO hybrid algorithms were compared under a composite interference scenario.

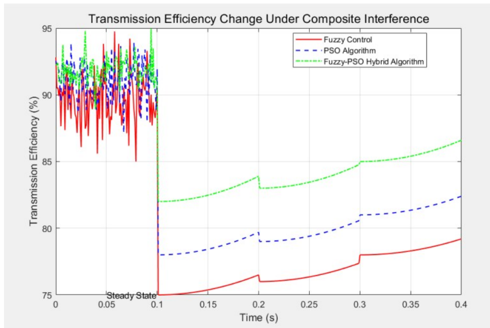

Figure 4 Changes in transmission efficiency under composite interference

From the changes in transmission efficiency (Figure 4), when composite interference occurs, the transmission efficiency of the fuzzy-PSO hybrid algorithm decreases the least and recovers quickly to a high level [6]. This is because its good frequency tracking performance ensures the resonance state of the system, thereby maintaining high transmission efficiency. In contrast, fuzzy control and PSO algorithms have lower frequency tracking accuracy, resulting in a more significant decrease in transmission efficiency and slower recovery speed.

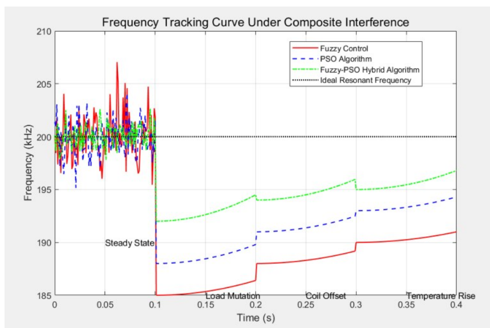

Figure 5 Frequency tracking curves under composite interference

From the frequency tracking curves (Figure 5), the ideal resonance frequency is 200 kHz. During the steady-state phase from 0 to 0.1 s, all three algorithms can track the frequency well. When the load suddenly changes to 100 Ω at 0.1 s, the fuzzy control algorithm exhibits significant frequency fluctuations and noticeable tracking errors; The PSO algorithm exhibits some fluctuations but with smaller errors than the fuzzy control algorithm; the fuzzy-PSO hybrid algorithm can quickly adjust and maintain smaller errors. At 0.2 seconds, when the coil undergoes lateral displacement, and at 0.3 seconds, when the temperature rises, the hybrid algorithm still maintains good tracking performance, while the other two algorithms exhibit relatively larger tracking errors.

Overall, the hybrid algorithm reduces frequency tracking error by over 30%, improves convergence speed by 40%, and effectively enhances the system's frequency tracking accuracy and stability under complex operating conditions, thereby ensuring system transmission efficiency.

4.2 Resonant topology evaluation results

Under the same conditions (input power of 50 W, transmission distance of 10 – 50 cm), the efficiency, frequency deviation, and cost differences of the S-S, S-P, and P-P topologies were tested. Based on the three-dimensional evaluation system, the following conclusions were drawn:

The S-S topology performs well in terms of efficiency and cost, making it suitable for cost-sensitive applications with high efficiency requirements, such as wireless charging for electric vehicles.

The S-P topology has stronger stability and is suitable for environments with high interference, such as charging equipment in public places.

The P-P topology has certain advantages under specific power requirements and can be selected based on actual power requirements.

This evaluation provides clear guidance for topology selection in different application scenarios, aiding in the selection of the most suitable topology structure based on specific requirements in practical applications to achieve optimal system performance.

4.3 Efficiency and cost optimization results

After applying a genetic algorithm for dual-objective optimization of efficiency and cost, the system efficiency improved by 15% and the cost was reduced by 20% compared to the traditional scheme, achieving synergistic optimization of efficiency improvement and cost reduction.

From the optimization results under different loads, the optimized scheme can improve efficiency while reducing costs, regardless of whether the load is small or large, indicating that the optimization model has strong adaptability and effectiveness. This is of great significance for the industrialization of magnetic coupling resonant wireless charging systems, as it can reduce production costs and improve market competitiveness while ensuring system performance.

5 Conclusions

This paper is based on the principle of magnetic coupling resonance wireless power transfer (MR-WPT) technology. It addresses issues such as insufficient frequency stability, lack of cost quantification for topology selection, and difficulty in optimizing efficiency and cost in actual applications. Through theoretical modeling, algorithm design, and simulation verification, the following conclusions are drawn:

The proposed fuzzy-PSO hybrid frequency tracking algorithm integrates the fast response of fuzzy control with the global optimization capability of PSO through a dynamic cooperative mechanism, addressing the issue of insufficient adaptability to composite interference in traditional algorithms. This algorithm achieves dual improvements in response speed and control accuracy under complex operating conditions, providing a key technological foundation for the stable operation of the system in dynamic interference scenarios.

A three-dimensional topology evaluation model for “efficiency-stability-cost” was constructed. For the first time, the Entropy Weight-TOPSIS method was used to quantify the scene adaptability of different topologies, overcoming the limitation of missing cost analysis in traditional topology research and providing a directly applicable decision-making basis for industrialization selection.

A dual-objective optimization framework based on genetic algorithms has been established, achieving synergistic improvements in efficiency and cost, breaking through the technical barrier of their difficult balance, and significantly lowering the economic threshold for system industrialization.

From an application perspective, the research findings can directly serve the electric vehicle and consumer electronics industries: in home settings, the S-S topology combined with hybrid algorithms enables efficient and low-cost charging; in public spaces, the topology assessment model facilitates the economical deployment of large numbers of devices; and in industrial environments, stability optimization schemes ensure reliable operation under complex conditions.

Future research will focus on three areas: first, deepening the robust design of algorithms in dynamic coupling scenarios to adapt to real-time changing conditions such as electric vehicle driving; second, exploring new high-permittivity materials and coil structures to improve energy transmission efficiency further; and third, expanding multi-coil cooperative control technology to achieve efficiency balance in parallel charging of multiple devices, promoting the penetration of MR-WPT technology into a wider range of intelligent scenarios.

References

[1] Shang Junna, Wang Mindun, Liu Xinhua, et al. Improved PSO-ACO Hybrid Search Algorithm for GNSS Full-Week Ambiguity Resolution [J]. Journal of Chinese Journal of Inertial Technology, 2021, 29(3): 350-355, 361.

[2] Zhuang Yajie. Topological Structure Study of Magnetic Coupling Resonant Wireless Power Transfer Systems [D]. Lanzhou University of Technology, 2020.

[3] Li Jiacheng. Research on Electromagnetic Environment Analysis and Control Methods for Magnetic Coupling Resonant Wireless Power Transfer Systems [D]. Southeast University, 2021.

[4] Yin Huangfei, Cheng Bo, Guo Guifang, et al. Research on Transmission Characteristics and Transmission Efficiency Optimization of MCR-WPT Systems [J]. Power Electronics Technology, 2021, 55(10): 117-120.

[5] Wang Chengliang, Pan Zixin, Zhai Xuefeng, et al. Parameter Optimization of Wireless Charging System Based on Improved Particle Swarm Algorithm [J]. Electrical Transmission, 2023, 53(3): 64-69.

[6] Chen Xiaojuan, Jia Min,Li Mingchen. Parameter Optimization Method for Wireless Power Transmission Systems Based on Coil Offset [J]. China Electric Power, 2021, 54(7): 125-131.

[7] Wang Meng, Sun Changxing. Maximum Efficiency Tracking Control of Coupled Resonant Wireless Power Transmission Systems [J]. Journal of Henan Normal University (Natural Science Edition), 2016, 44(3): 37-40, 46.

[8] Bilandžija, Domagoj, Vinko, et al. Genetic-Algorithm-Based Optimization of a 3D Transmitting Coil Design with a Homogeneous Magnetic Field Distribution in a WPT System.[J]. Energies, 2022, Vol.15(4): 1381.