Proceedings of the 4th International Conference on Mathematical Physics and Computational Simulation
DOI: 10.54254/2753-8818/2026.33885

The Impact of Magnetic Coupling Resonant Wireless Charging on Inspection Drones

Zekai Huang[1], Yujie Mao[2], Zimu Wang[3*]

[1]Suzhou Foreign Language School, Suzhou, China
[2]Business School, Shandong University of Technology, Zibo, China
[3]School of Electrical Engineering, Southeast University, Nanjing, China
**Corresponding Author. Email: 213241662@seu.edu.cn*

Abstract. With the widespread use of drones and wireless communication in production and daily life, the traditional charging mode of drones - returning to fixed charging stations for recharging - has increasingly prominent limitations and energy security issues. Wireless charging technology can solve many practical application problems. Through wireless energy transmission and rational scheduling of mobile energy, appropriate design of the magnetic coupling structure and control strategies tailored to the flight scenarios of unmanned aerial vehicles (UAVs), etc. Wireless charging technology can ensure the stability, environmental adaptability and anti-offset performance of unmanned aerial vehicles during wireless charging, there has been a significant improvement in battery life and operational capabilities. However, the wireless charging mode also brings about issues such as a heavier drone body, changes in payload, heat dissipation problems, and electromagnetic interference. This article will conduct an in-depth study on the impact of magnetic resonance wireless charging on the performance of unmanned aerial vehicles from four aspects: the principle of magnetic resonance wireless charging, different methods for improving the efficiency of wireless charging, the comparison of the advantages and disadvantages of wireless charging and traditional charging for unmanned aerial vehicles working in outdoor scenarios, and the influence of magnetic resonance wireless charging on unmanned aerial vehicles and the corresponding optimization solutions.

Keywords: Magnetic resonance wireless charging mode, Unmanned aerial vehicle endurance, Power line inspection, Magnetic coupling coil, Mobile charging scheduling strategy

1. Introduction

As the power loss in China continues to increase and the transmission lines become increasingly complex, traditional manual inspections require inspectors to traverse complex geographical environments to record data, which makes it difficult to ensure the personal safety of the inspectors [1]. Thanks to the rapid development of wireless charging technology and drone technology, unmanned aerial vehicle (UAV) inspection has become a new method for industrial inspection due to its low maintenance costs, high line inspection efficiency, and high detection accuracy [2].

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2026.33885

Although the use of drones in conjunction with inspections is beneficial for conducting work in complex geographical environments, how to increase the inspection time and endurance remains a challenge for the new inspection mode. Applying wireless charging technology can effectively solve these problems. Compared with the traditional plug-and-play charging method, by establishing a wireless charging platform to charge the inspection drones, it can not only enhance the intelligence level of the inspection work, but also optimize the charging mode to achieve safer and more timely rapid charging. This article will be divided into four aspects for discussion: the principle of magnetic resonance wireless charging technology, different methods for improving the efficiency of wireless charging, the comparison of the advantages and disadvantages of wireless charging and traditional charging for inspection drones in outdoor working scenarios, and the impact of magnetic resonance wireless charging on inspection drones and the corresponding optimization solutions. It will summarize the possible ways for drones to achieve efficient charging in line inspection work, and propose specific optimization methods for different working scenarios. This has both theoretical significance and application value.

2. Principle of magnetically coupled resonant wireless charging technology

2.1. Working mechanism of magnetically coupled resonant wireless power transfer

Magnetically Coupled Resonant Wireless Power Transfer(MCR-WPT) is a contactless power transfer technology, which is based on electromagnetic induction. It achieves efficient energy transmission through strong magnetic coupling between the transmitting and receiving coils operating at the same resonant frequency [3]. MCR-WPT can charge the load from a distance of several centimetres to several meters, allowing misalignment between the transmitting and receiving coils. This basic structure of the wireless charging system is to use two coupled coils, matched with corresponding capacitors to unify the resonant frequency of the transmitting and receiving ends to realize energy conversion between alternating electric and magnetic fields [4].

The natural resonant frequency of the LC resonant tank satisfies Equation(1):

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Magnetic resonance occurs in the system when the resonant frequencies of the two ends are perfectly matched. The coupling strength is presented by coupling coefficient k, which reflects the tightness of the magnetic coupling between the transmitting and receiving coils. The value of k only depend on the geometrical structure, relative position, distance and angel of the coils, satisfying Equation(2):

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{2}$$

2.2. Internal charging structure and power transfer model of inspection UAVs

The charging system for UAVs consists of two parts including the transmitting circuit at the ground base station and the on-board receiving circuit on the UAV. The Series-Series (SS) compensation topology (as shown in Figure 1) is widely adopted in UAV charging systems since the value of compensation capacitor is only related to the matching inductor, rather than the mutual inductance, operating frequency and load. This feature ensures the transmission stability and easy matching performance of the system [5]. The SS topology can reduce the reactive power loss and improve the

DOI: 10.54254/2753-8818/2026.33885

transmission efficiency, offsetting the possible impact of the coil distance variation or horizontal misalignment. Meanwhile, the series capacitor has small volume with simple circuit structure, making it suitable for on-board installation and meeting the lightweight requirements of UAV.

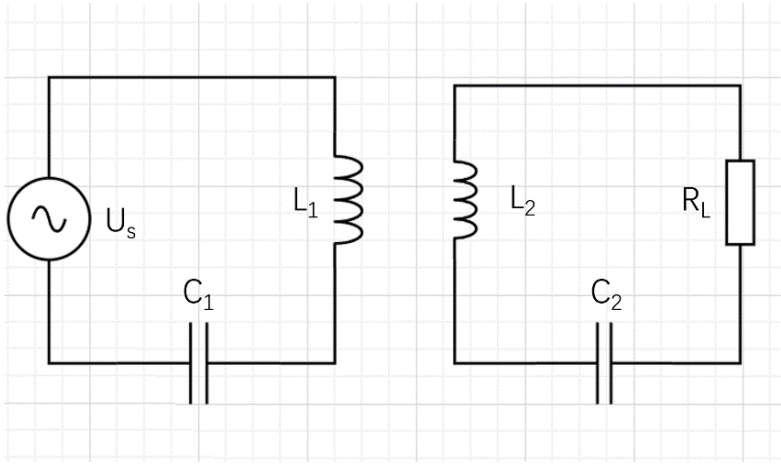


Figure 1. Circuit diagram of SS-type compensation topology (picture credit: original)

2.3. Factors affecting charging efficiency

For the practical application of the inspection UAV, the charging efficiency of the MCR-WPT system is manly limited by the following four parts: first is the positioning error during UAV landing will lead to the angular and distance misalignment between the transmitting and receiving coils, which reduces the coupling coefficient k and make the charging efficiency decrease further; second is the increased self-impedance of the primary and secondary circuits caused by the ohmic loss and radiation loss of the coils in the circuit; the third is the efficiency is affected by the fluctuations of the loads resulted from the change in current and voltage when charging; the forth is other electromagnetic interference factors in the actual operating environment may disrupt the matched resonant frequency [2].

3. Various optimization methods for improving wireless charging efficiency and multi-dimensional comparison

3.1. Overview of four core methods

The coupling structure, as the core component of the wireless charging system, is optimized for the scenario of close-range fixed-point charging and is the key link determining the upper limit of the system's energy transmission efficiency. The coupling coefficient, leakage magnetic level, and losses of the coil and magnetic core directly determine the effective proportion of energy transmission. From this perspective of optimization, the coupling ability can be directly enhanced and transmission losses can be reduced at the physical source of energy transmission. Currently, the mainstream optimization methods include coil structure optimization, magnetic core optimization, and adaptation optimization. Among them, adaptation optimization achieves the improvement of wireless charging efficiency by matching and adapting the coupling mechanism and magnetic coupling resonant topology [6, 7].

Resonance topology is the core of energy transmission in wireless charging systems. The system can achieve the minimization of reactive power and efficient transmission of active power only

DOI: 10.54254/2753-8818/2026.33885

when the transmitting and receiving ends have precise resonance matching. This optimization method is applicable to medium and long-distance wireless charging and is suitable for the hovering dynamic charging scenarios of inspection drones. Optimizing the resonance topology can solve the problems of dynamic offset and resonance mismatch in medium and long-distance transmission, significantly reduce reactive power loss, and improve transmission stability. The current mainstream optimization methods include basic topology selection, composite topology optimization, and anti-interference optimization. Basic topology selection includes, for example, SS/SP/PP basic resonant topologies, which are suitable for short-distance low-cost scenarios. Composite topology selection includes, for example, LCC-S/LCL-S composite resonant topologies, which can improve the transmission performance in medium and long distances after being introduced into the compensation network. The principle of anti-interference optimization is to add electromagnetic shielding units to suppress the influence of strong electromagnetic interference on the resonance state [8].

The core of the power control strategy is the dynamic regulation core of the wireless charging system. An excellent control strategy can improve the accuracy of power matching and achieve efficient and stable charging over the entire distance and in all scenarios. From this perspective, optimization can enable precise matching between the input and the load, and synergistically enhance the optimization effects of the coupling mechanism and resonant topology. This is the core guarantee for stable and efficient charging in all scenarios. The mainstream optimization methods include intelligent algorithm upgrades, dynamic power regulation, and multi-module collaborative optimization. Among them, the principle of multi-module collaborative optimization is to deeply link the power control strategy with the coupling mechanism and resonant topology optimization to achieve maximum efficiency throughout the entire chain [9].

Environmentally adaptive regulation takes into account that inspection drones often work in complex and variable outdoor environments, where factors such as temperature, humidity, and electromagnetic interference may all lead to a decrease in charging efficiency. This method can monitor the real-time parameter data of the environment and dynamically adjust the key working parameters of the wireless charging system, such as resonant frequency, power, charging time, coupling position, etc., to promptly reduce the efficiency loss caused by environmental interference, and is suitable for outdoor complex inspections.

3.2. Comparative analysis of various optimization methods for improving charging efficiency

The working scenarios of inspection drones are diverse. Considering that different scenarios require different charging optimization strategies, it is necessary to compare and analyze the advantages and disadvantages of various optimization methods, and compare these different methods from four aspects: efficiency improvement effect, technical complexity, cost investment, and applicable inspection scenarios.

By comparing the efficiency improvement effects of the four optimization methods, the study found that the coupling structure optimization had a significant improvement in efficiency for short distances (mm to cm level). In practical working scenarios, the small volume and lightweight characteristics of the receiving end of the load-limited inspection unmanned aerial vehicle determine that rectification and BMS charging management losses need to be considered, and the overall efficiency of the entire system can reach 88% to 93% [10]. The leakage magnetic intensity in key areas was reduced by 30% to 50% compared to the unoptimized structure, effectively suppressing spatial electromagnetic interference and significantly improving electromagnetic compatibility.

DOI: 10.54254/2753-8818/2026.33885

The improvement of resonant topology has a significant effect on medium and long-distance as well as anti-offset scenarios. The LCC-S/LCC-P compensation topology can improve the stability of constant current/constant voltage output mode; the improved SP/S topology can enhance the anti-offset ability [11], and the transmission efficiency in medium and long distances can reach 85% to 90%.

The upgrade of power control strategy has a significant improvement in the adaptability to all load ranges. The environmental adaptive adjustment can significantly enhance the robustness of the system in complex environments. The efficiency attenuation caused by temperature drift/electromagnetic interference is ≤ 8% [12].

To better distinguish the technical complexity of the four methods, we divide the difficulty levels into three categories: low, medium, and high. Coupling structure optimization belongs to medium difficulty. The technical challenges mainly lie in the reasonable design of coils and magnetic core structures, and the combination of simulation and experimental verification, among which the design of the NEU matrix requires complex algorithm support [13].

Resonance topology optimization is of high difficulty. It requires the design of new topological structures, high-order resonant networks and wide-band resonant structures, as well as the integration of multi-coil collaborative control. The driving technology for wide bandgap devices is also demanding.

The upgrade of power control strategies is of high difficulty. It requires the design and optimization of the maximum efficiency tracking (MEPT) algorithm, real-time multi-parameter detection, and the software architecture for multi-mode (CC/CV/MPPT) collaborative control [14].

Environmental adaptive regulation is of medium difficulty. It requires the construction of a multi-physical field monitoring module (temperature/humidity/magnetism).

To more clearly compare the cost investment of the four types of methods, we divide the cost investment into low, medium, and high categories.

Coupling structure optimization is of medium cost investment. The main cost is the cost of the Leeds wire, coil consumables, and high-frequency magnetic core materials. If an array layout is adopted, the cost will increase slightly, and the increase in copper and magnetic material usage will lead to a slight increase in cost.

Resonance topology optimization is a high investment project. The main investment is in GaN/SiC wide bandgap power devices and high-order resonant capacitors and inductors [15]. In medium power scenarios, the LCC topology integration can help reduce some costs.

The upgrade of power control strategies is a low investment project. The main cost is the algorithm development and the upgrade of embedded control software. No additional BOM hardware costs need to be increased.

Environmental adaptive regulation is a low investment project. The core cost is the high-precision sensing module and the anti-interference shielding packaging [16].

In application scenarios such as inspection, coupling structure optimization is suitable for power point charging at power stations, oil pipeline point replenishment, and close-range charging of small unmanned aircraft; resonance topology optimization is suitable for precise hovering charging of unmanned aircraft, pole station charging, and multi-unmanned aircraft formation charging; the upgrade of power control strategies is adaptable to various inspection scenarios, especially suitable for inspection tasks with dynamic load changes; environmental adaptive regulation is suitable for high-altitude power inspection, polar research, and near-sea/high-humidity salt spray oil work point inspection.

DOI: 10.54254/2753-8818/2026.33885

4. The impact of magnetic resonance wireless charging on inspection drones and corresponding optimization solutions

4.1. Optimization of transmission distance

The transmission distance of magnetic resonance wireless charging determines the tolerance margin for drone takeoff and landing as well as the flexibility of the deployment of the charging platform. Compared with electromagnetic induction charging, magnetic resonance wireless charging can achieve a medium-distance transmission ranging from 5cm to 50cm. Compared with radio frequency wireless charging at the same distance, the efficiency of the magnetic resonance wireless charging system can reach 70% - 90%, while that of radio frequency wireless charging is usually 20%.However, the efficiency of magnetic resonance wireless charging will decrease exponentially with the increase in transmission distance. To meet the charging requirements of inspection drones for medium distances, existing research mainly proposes optimization solutions based on the coil structure. Compared with the traditional circular coil design, which generally encounters the bottleneck problem of the coupling coefficient sharply decaying with distance in long-range energy transmission scenarios, the new rectangular coil architecture, by adopting an asymmetric winding strategy (for example, implementing a low-number-of-turns sparse winding layout at the transmitting end and a high-number-of-turns dense winding structure at the receiving end), can reconfigure the three-dimensional distribution characteristics of the magnetic field at the physical level, significantly expanding the effective flux's operational space range. A three-layer orthogonal bidirectional anti-offset coil structure can effectively suppress the fluctuation of coupling coefficient under large lateral misalignment, which provides a reliable guarantee for stable energy transmission of drones [17]. In addition, a novel high-misalignment-tolerance coil structure has been verified to maintain stable output under offset conditions, further improving the spatial robustness of the wireless charging system [18]. This structural optimization not only significantly reduces the reliance of unmanned aerial vehicles on precise positioning during takeoff and landing phases, but also enhances the spatial freedom of the system, enabling it to accommodate larger deviations in attitude and position. This provides key technical support for the reliability of unmanned aerial vehicle autonomous charging systems in complex environments.

4.2. Efficiency transmission optimization

Transmission efficiency is the key indicator of the performance of a wireless charging system. It directly determines the duration of time required for the unmanned aerial vehicle to complete the power replenishment and the effectiveness of energy conversion. Taking into account the actual situation where the power demand of the inspection drones changes significantly during operation and the tolerance for charging connection positions is limited, the proposed systematic optimization approach focuses on the aspect of adjusting the capacitance of the power supply. Due to the differences in the landing posture and position of the drones each time, the wireless charging system is prone to experiencing circuit disharmony during operation. To solve this problem, relevant studies have proposed adaptive tuning schemes based on capacitance adjustment, which can adjust circuit parameters in real time according to drone position deviation and load change, ensuring the stable operation of the resonant circuit [18]. A systematic review of UAV wireless charging has summarized the key factors affecting efficiency and the mainstream optimization routes, providing a theoretical basis for scheme design [19].

DOI: 10.54254/2753-8818/2026.33885

5. Conclusion

This article conducts a systematic review on the application of magnetic coupling resonant wireless power transfer (MCR-WPT) technology in inspection drones. This technology is based on electromagnetic induction and resonance principles, and can achieve non-contact power transmission within a range of 5 to 50 centimeters. Among them, due to the simple structure and easy matching feature of the SS compensation structure, it is particularly suitable for the weight-sensitive application requirements of unmanned aerial vehicles. The research has found that the main factors affecting the charging efficiency include four aspects: the deviation of the coil's relative position, the loss of circuit components, the change of load, and external electromagnetic interference. In terms of technical optimization, this article summarizes the following aspects: Firstly, by optimizing the coil and using high-performance magnetic core materials, the material loss can be reduced and the efficiency can be improved. Then, by introducing intelligent control algorithms and combining multiple charging modes, it can better meet the energy replenishment requirements in actual operations. Finally, through environmental perception and anti-interference design, stable efficiency can be maintained in complex working conditions. Compared with the traditional charging method, this technology has advantages in wireless charging due to its non-contact nature and the ability to transmit at different distances. However, it also faces issues such as limited transmission distance and fluctuating efficiency. The asymmetric coil design and adaptive tuning scheme proposed in the article provide feasible solutions to these problems. In the future, the magnetic resonance wireless charging technology needs to continuously develop and improve in multiple aspects. In terms of basic research, it is necessary to break through the limitations of core technologies, extend the transmission distance, and solve the key performance issues in the system operation; in terms of engineering applications, it is necessary to establish technical standards, reduce production costs, and enhance the operational reliability of the equipment in harsh environments; in terms of system architecture, it is necessary to create a diversified charging network to promote the deep integration of technology and digitalization. The advancement of these efforts will provide a more complete energy guarantee for inspection drones, ensuring their efficient performance in various tasks.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Wang, Y., Ji, L., & Zhang, M. (2025). Method for multi-target wireless charging for oil field inspection drones. Drones, 9(5), 381.
[2] Almohammedi, A., Alshammari, B., & Abo-Khalil, A. G. (2025). Comparative analysis of contact-based and contactless charging systems for industrial inspection UAVs. Energies, 18(11), 5015.
[3] Xu, M. Q., He, Z. W., & Nie, Z. S. (2021). Wireless charging solution for unmanned aerial vehicles based on magnetic coupling resonant radio energy transmission technology. Electronic Technology and Software Engineering, (8), 234-236.
[4] Shi, W. (2021). Design of Autonomous Wireless Charging System for Power Line Inspection Drones. Harbin University of Science and Technology.
[5] Liu, D. (2023). Design and Control Strategy Research of Autonomous Wireless Charging System for Electric Power Inspection Unmanned Aerial Vehicles. Shenyang University of Technology.
[6] Wu, S., Cai, C. W., Chen, Y., et al. (2022). Research Progress and Development Trends of Wireless Charging Technology for Multi-rotor Unmanned Aerial Vehicles Transactions of China Electrotechnical Society, 37(3), 11.

DOI: 10.54254/2753-8818/2026.33885

[7] Jiang, J. C., Hong, Y., Deng, P. Q., & Fu, S. M. (2025). An evaluation method for magnetic focusing enhancement and spatial transmission capability of radio energy transmission systems based on non-centrosymmetric unit matrix coils. Transactions of China Electrotechnical Society, 40(12), 3742-3758, 17.
[8] Song, L. Y., & Jiang, J. Y. (2023). Field Effect Analysis and Optimization of Wireless Charging Coils for Electric Power Inspection Drones Manufacturing Automation, 45(3), 58-62, 69.
[9] Ma, H., Wang, T., & Xu, D. H. (2022). Cooperative Optimization of Resonant Topology and Control Strategy for Radio Energy Transmission System Proceedings of the CSEE, 42(12), 4445-4458.
[10] Budhia, M., Boys, J. T., Covic, G. A., & Huang, C. Y. (2013). Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems. IEEE Transactions on Power Electronics, 28(1), 488-500.
[11] Zhang, W., & Mi, C. C. (2016). Compensation topologies of high-power wireless power transfer systems. IEEE Transactions on Vehicular Technology, 65(6), 4768-4778.
[12] Campi, T., Cruciani, S., & Feliziani, M. (2018). Wireless power transfer system for unmanned aerial vehicles. IEEE Transactions on Electromagnetic Compatibility, 60(4), 928-936.
[13] Covic, G. A., & Boys, J. T. (2013). Modern trends in inductive power transfer for transportation applications. IEEE Journal of Emerging and Selected Topics in Power Electronics, 1(1), 28-41.
[14] Zhong, W. X., & Hui, S. Y. R. (2015). Maximum energy efficiency tracking for wireless power transfer systems. IEEE Transactions on Power Electronics, 30(7), 4025-4034.
[15] Li, S., Li, W., Deng, J., Nguyen, T. D., & Mi, C. C. (2015). A double-sided LCC compensation network and its tuning method for wireless power transfer. IEEE Transactions on Vehicular Technology, 64(6), 2261-2273.
[16] Cheng, Y., Shi, W., Xiong, X. B., Zhou, X., Gan, Z. Y., & Li, Z. Q. (2025). Design and Optimization of Three-Layer Orthogonal Bidirectional Anti-offset Coil Structure for Dynamic Radio Frequency Energy Transmission System Advanced Technology of Electrical Engineering and Energy, 44(4), 19-30.
[17] Munsi, A., Pradhan, S., & Aditya, K. (2025). Design and implementation of wireless charging infrastructure for autonomous UAV charging. IEEE Access, 13, 180462-180478.
[18] Li, Y., Zhao, J., Yang, Q., Liu, L., Ma, J., & Zhang, X. (2019). A novel coil with high misalignment tolerance for wireless power transfer. IEEE Transactions on Magnetics, 55(6), 1-4, Art no. 2800904.
[19] Chittoor, P. K., Chokkalingam, B., & Mihet-Popa, L. (2021). A review on UAV wireless charging: Fundamentals, applications, charging techniques and standards. IEEE Access, 9, 69235-69266.