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The Principles of Wireless Power Transfer for Drones and Optimization of Wireless Charging Efficiency

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Abstract: In September 2020, the Chinese government pledged at the 75th United Nations General Assembly to achieve peak carbon emissions before 2030 and carbon neutrality before 2060. As the nation advances its carbon peaking and carbon neutrality goals, the demand for technologies supporting green and low-carbon transitions has surged, particularly in high-energy-consuming sectors like power inspection. Traditional manual inspection methods are struggling to meet the operational and maintenance demands of modern smart grids due to limitations such as low efficiency, high operational risks, and incomplete inspection coverage. While unmanned aerial vehicle (UAV) inspection offers significant advantages, its limited flight time remains a major challenge to its widespread adoption. This paper focuses on analyzing and optimizing the endurance of UAVs in power line inspection based on wireless power transfer (WPT) technology. The aim is to provide a more efficient charging solution for UAVs by proposing strategies to maximize channel gain, thereby overcoming endurance limitations and promoting the extensive application of UAV technology in smart grid inspection to support the national strategy for green and low-carbon transition.

Keywords: Unmanned Aerial Vehicle, Wireless Power Transfer, Energy Transfer Efficiency

1. Introduction

The integration of unmanned aerial vehicle (UAV) technology within smart grid inspection is expanding, offering crucial technical support for the efficient operation and maintenance of contemporary power systems and aligning with national "dual carbon" objectives. However, the operational constraints of UAVs, particularly their limited endurance, impede their application in intricate inspection scenarios [1]. This study centers on the development of a system that incorporates radio frequency (RF) wireless power transfer technology to augment UAV flight duration through the collaborative optimization of dynamic RF energy provisioning, thereby enhancing task coverage and operational efficacy. The system's architecture leverages reconfigurable intelligent surfaces (RIS) as the energy transfer medium. RIS, a programmable metasurface material, facilitates the optimization of wireless signal propagation, mitigating path loss in RF energy transmission, and improving energy utilization efficiency. This research not only addresses the current limitations of UAV inspection technology but also contributes significantly to advancements in green energy technology, smart grid infrastructure, and efficient energy management. By optimizing energy supply-demand dynamics and intelligent task allocation, this research aims to reduce operational and maintenance expenditures and provide technical support for UAV collaborative operations in complex environments. Driven by

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both academic and industrial imperatives, this study establishes a theoretical and technical framework for the advanced application of UAV technology in power systems.

2. Current applications of unmanned aerial vehicles (UAVs) in smart grid inspection

As the scale and complexity of power systems increase, traditional manual inspection methods are struggling to meet the demands of modern power operation and maintenance. These methods are inefficient, costly, and time-consuming, and they also pose safety risks in complex and high-altitude operating environments. Unmanned aerial vehicles (UAVs), with their high maneuverability, rapid response capabilities, and adaptability to complex environments, have become a key tool for power inspection. By carrying high-precision sensors such as infrared thermal imagers, LiDAR, and high-definition cameras, UAVs can monitor transmission lines in real-time, accurately identify faults and damage, and significantly improve inspection efficiency and accuracy [2].

As a core component of the smart grid, substations rely on traditional inspection methods that are labor-intensive and pose safety risks. UAVs utilize thermal imaging and optical imaging sensors to remotely monitor substation equipment, especially in high-voltage and high-temperature environments, effectively avoiding the risks of manual inspection. They can also detect and analyze equipment status, identifying electrical faults and potential hazards. With the development of smart sensor technology, UAVs equipped with fault diagnosis technology can automatically identify abnormal equipment operation and make preliminary judgments. High-voltage transmission lines are located in complex terrain and harsh weather conditions, making manual inspection costly and risky. UAVs, with their flexibility and ease of operation, are equipped with high-definition cameras, infrared sensors, LiDAR, and other devices to efficiently complete inspection tasks, obtain real-time line status information, and identify faults and hazards. The advantages of UAVs are particularly significant in areas that are difficult to access, such as mountainous regions.

Field deployments underscore the substantial effectiveness of Unmanned Aerial Vehicles (UAVs) in smart grid inspection protocols. A German utility's adoption of UAVs for transmission line assessments yielded an efficiency gain surpassing 30% and a cost reduction of 20%. China Southern Power Grid has leveraged UAVs for comprehensive power grid inspections, surveying over 3,000 kilometers of lines in 2019, achieving a time cost reduction of approximately 40% while maintaining operational efficacy and safety during nocturnal operations and under adverse weather conditions [3].

Nevertheless, UAV endurance constitutes a critical constraint in their application within grid inspection scenarios. Flight duration and range limitations impede large-scale deployment. Contemporary commercial UAVs typically exhibit a flight time of 30-40 minutes, which is inadequate for the requirements of extended inspection missions. This is particularly pertinent in remote or expansive grid infrastructure, where frequent charging or battery replacement escalates time costs, thereby limiting the widespread adoption of UAVs.

3. Advancements in wireless power transfer (WPT) technology

As a crucial method for addressing the endurance limitations of unmanned aerial vehicles (UAVs), wireless power transfer (WPT) technology has garnered significant attention in recent years, particularly demonstrating its unique advantages in scenarios involving extended operational durations and frequent task execution. Radio frequency (RF) wireless power transfer, due to its flexibility and extended transmission range, holds considerable application potential in domains such as smart grid inspection. This study will provide a detailed discussion of WPT technology, categorized into two primary modules: RF energy transfer and antenna arrays.

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3.1. RF energy harvesting

Radio frequency (RF) wireless power transfer (WPT) primarily utilizes electromagnetic induction, magnetic resonance, and radio wave technologies [4]. Magnetic resonance, a relatively recent advancement, allows for significant improvements in transmission efficiency and distance through the adjustment of resonant frequencies, thus enabling long-range wireless charging. Radio wave technology converts electrical energy into radio waves, transmitting them through the air to a receiver, where they are then converted back into electrical energy. While this method facilitates wireless charging over extended distances, it currently suffers from lower charging efficiency.

The development of RF WPT is relatively nascent, yet several companies have made notable progress. For instance, Ossia's Cota system, certified by the US FCC, can simultaneously charge up to 32 devices within a 9-meter range. Furthermore, the WattUp wireless charging system supports a maximum charging distance of 4.5 meters and is already implemented in devices such as hearing aids [5]. Concurrently, Huawei has proposed a dynamic UAV charging system based on RF energy transfer. This system employs multiple base stations to emit RF signals, providing continuous power to in-flight UAVs, thereby eliminating the need for return-to-base charging and significantly extending flight duration.

Although radio frequency (RF) wireless power transfer (WPT) offers significant potential for remote charging and real-time power delivery, its practical implementation is currently constrained by factors including signal attenuation in the millimeter-wave spectrum, propagation losses, and environmental interference. Signal attenuation is especially critical in long-range energy transfer scenarios, leading to variable energy transfer efficiency across diverse operational environments. Moreover, existing RF-WPT applications, both domestically and internationally, are predominantly static due to challenges in maintaining signal alignment and beam modulation performance in mobile RF systems. Consequently, optimizing signal modulation and beamforming strategies within RF-WPT systems to counteract environmental attenuation and enhance energy transfer efficiency constitutes a crucial research area.

3.2. Antenna array

Antenna array technology is a critical component of radio frequency (RF) energy transmission systems, particularly in the millimeter-wave (mmWave) spectrum. By deploying multiple antenna elements at both the transmitter and receiver ends, antenna arrays can effectively focus signal energy through beamforming techniques, thereby enhancing energy transmission efficiency while minimizing propagation losses. This approach improves signal coverage and transmission quality by optimizing the directionality of signal propagation [6].

Recent advancements in massive antenna array technology have significantly enhanced energy transmission capabilities in mmWave communications. Studies demonstrate that multi-antenna arrays improve the focusing accuracy of energy delivery, resulting in substantial reductions in energy attenuation. For instance, Huawei's mmWave RF energy transmission system employs a large-scale antenna array with beamforming technology to achieve over 40% improvement in RF energy transmission efficiency. The system optimizes signal direction by adjusting phase and amplitude parameters across array elements, maximizing signal strength and extending the operational endurance of unmanned aerial vehicles (UAVs) [7].

Despite these advantages, practical implementation of antenna arrays presents design challenges. System performance remains highly sensitive to array dimensions and phase control precision. Additionally, the high-frequency characteristics of mmWave frequencies necessitate careful trade-offs between antenna gain, beamwidth, and power consumption during array design. A key research focus involves maintaining system efficiency while simplifying hardware complexity.

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4. Future trends of UAV-based power grid inspection

The deployment of unmanned aerial vehicles (UAVs) in power grid inspection is poised to evolve toward higher levels of intelligence and coordination, particularly through integration with artificial intelligence (AI), the Internet of Things (IoT), and 5G communication technologies. These synergies are expected to substantially enhance UAV autonomy and intelligent operation capabilities.

Progress in millimeter-wave (mmWave) radio frequency (RF) technology provides critical support for long-range, high-efficiency wireless energy transfer. Research indicates that mmWave RF signals can achieve energy transmission efficiencies approaching 20%, offering a sustainable power source for UAVs during smart grid inspections. Furthermore, the gradual rollout of 5G and future 6G networks will enable wireless energy transmission across higher frequency bands and broader geographic areas, ensuring UAV operational continuity in complex remote environments.

Combined with Intelligent Reflecting Surfaces (IRS) technology, UAV wireless energy transfer efficiency in complex environments is projected to improve further. IRS systems intelligently regulate radio wave reflection paths, effectively reducing path loss and optimizing energy delivery. Studies suggest that IRS integration could boost energy transmission efficiency to over 40%, significantly extending UAV flight endurance and providing a technological foundation for intelligent, automated power inspection systems [8].

In summary, continuous advancements in wireless energy transmission, AI, and 5G/6G communication technologies are expanding the application horizons of UAVs in power grid inspection. These innovations will substantially enhance inspection efficiency and intelligence, offering critical technical support and safeguards for the secure, high-performance operation of power systems.

4.1. Model construction of UAV power grid inspection wireless power transfer system

The wireless power system transfer model shown in Figure 1 is established, where UAVs receive energy from transmitters to perform power line inspection tasks.

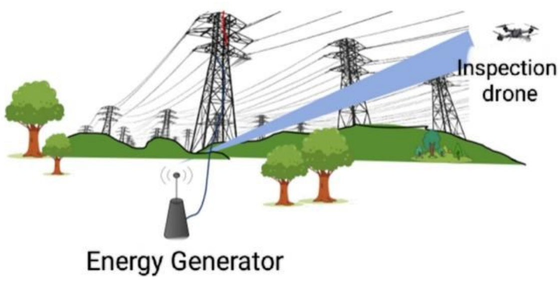

Figure 1: Wireless power transfer system model diagram

In traditional all-digital millimeter-wave systems, constructing large antenna arrays requires numerous millimeter-wave RF chains and high-speed ADCs, significantly increasing hardware costs. To improve power transfer efficiency, analog beamforming architectures with high hardware efficiency are adopted in millimeter-wave transmitters. This architecture effectively focuses beams in desired directions for single-antenna users, eliminating complex digital processing, making it suitable for wireless power transfer systems [9].

Furthermore, to reduce power consumption and hardware complexity, practical analog beamformers with limited discrete phase shifters are employed. Specifically, the analog beamformer f uses R low-resolution phase shifters, each with unit modulus and discrete phases controlled by bET bits. The possible phase set for each shifter is defined as

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$$F_B \triangleq \{\exp(j2\pi r/2^b ET)\}_{r=0}^{2^{bET}-1}, r \in \{1,\cdots,R\} \tag{1}$$

Under this structure, the base station's transmitted signal can be expressed as

$$x = \sqrt{p[t]}f[t]s \tag{2}$$

$p[t]$ represents the transmitter's power within time t; $f[t]$represents the beamforming adjustment matrix within time t; s is a 1×1 qualitative signal dedicated to wireless power transfer.

The RF signal received by the UAV receiver is as follows, $h[t]^H$ is the channel coefficient at time t, and $n0$ is additive white Gaussian noise

$$y = \sqrt{p[t]}h[t]^H f[t]s + n0 \tag{3}$$

Therefore, the power carried by the received radio frequency signal at time t can be approximated as:

$$P[t] = p[t]||h[t]^H f[t]||^2 \tag{4}$$

Here, we focus on the radio frequency (RF) signal component of the received power and neglect the noise contribution in this analysis, as the noise is negligible compared to the power of the received signal [10].

4.2. Maximization of UAV's received RF power

The method proposed in this paper focuses on maximizing the channel power gain. Assuming a fixed transmit power, this simplification allows us to concentrate on maximizing the channel gain without considering variations in the RF-to-DC power conversion efficiency, thereby simplifying the optimization process. Therefore, under the premise of a fixed transmit power, the problem of maximizing the channel power gain can be formulated as:

$$\max|h^H f|^2 \tag{5}$$

By relaxing the discrete phase shift constraints and allowing a continuous domain, a closed-form solution is derived. The optimal phase angle of h[t] (which is an integer multiple of 180° relative to the channel's argument) is calculated within the continuous domain, and then quantized to the nearest discrete value in the feasible set FB to obtain the optimized solution. The received power obtained after optimizing the algorithm is significantly higher than that of a randomly generated adjustment matrix. This approach offers lower computational complexity, and its optimization effect can almost reach optimality even in high-resolution scenarios.

5. Conclusion

This paper investigates and analyzes strategies to improve the endurance of unmanned aerial vehicles (UAVs) in power grid inspection applications, specifically addressing the challenge of limited flight duration hindering long-term, large-scale inspection tasks. Against the backdrop of China's proactive pursuit of carbon neutrality goals, UAV-based inspection emerges as a critical component of green low-carbon technologies with significant application potential. However, current endurance limitations constrain its further development.

The paper outlines the application status and advantages of UAVs in smart grid inspection, including high mobility, rapid response, and adaptability to complex environments. It highlights the primary constraint—insufficient flight time and endurance for prolonged operations. To address this, the study focuses on solutions leveraging Wireless Power Transfer (WPT) technology. Through detailed analysis of RF-based WPT and antenna array systems, the paper proposes adopting

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Reconfigurable Intelligent Surfaces (RIS) as energy transmission media. This strategy optimizes the propagation environment of wireless signals, reduces path loss, and enhances energy utilization efficiency by maximizing channel gain, thereby offering a more efficient charging solution for UAVs.

Optimizing WPT systems can significantly enhance UAV endurance, expanding their applicability in smart grid inspection. This research not only breaks existing technical barriers but also contributes to innovations in green energy technologies, smart grid development, and efficient energy utilization. Furthermore, it provides directions for future studies, such as exploring optimized WPT strategies to improve energy transfer efficiency.

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