WIRELESS POWER TRANSFER FOR UAV APPLICATIONS: A PARAMETRIC APPROACH FOR COUPLER DESIGN

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This paper explores Wireless Power Transfer (WPT) for Unmanned Aerial Vehicles (UAVs) battery recharging. To enhance the performance of WPT various parameters such as frequency, compensation topology, and the number of coils turns are examined. The objective is to identify the most suitable combination in terms of efficiency, weight, and feasibility. The aim of this procedure is to ensure a maximum WPT efficiency while having a minimum additional weight, thereby providing autonomous recharging processes, and extending the duration of the UAV mission. The analysis is carried out through simulations and measurements, taking into account the variations of the coupling factor due to potential lateral misalignment of the parallel coils.

DOI
https://doi.org/10.18690/um.feri.4.2025.15

ISBN
978-961-286-986-1

Keywords:
wireless power transfer,
unmanned aerial vehicle,
compensation topology,
frequency,
efficiency,
FEM modelling,
misalignment

University of Maribor Press

I Introduction

UAVs have quickly become essential and versatile tools in today's world, driving innovation across numerous sectors. Among their most impactful applications is inspection [1]. Whether in infrastructure, energy, agriculture, or environmental monitoring, UAVs provide an efficient means of surveying areas that are difficult to access or pose safety risks. Outfitted with advanced technology, they can perform detailed inspections and deliver real-time data, enabling swift detection of potential issues, reducing operational costs, and enhancing safety for personnel. However, their limited battery life and the need for physical recharging often at the initial takeoff point pose constraints. These limitations significantly reduce the overall duration and effective range of their missions.

To extend the UAV's mission time and make the charging process more autonomous, this paper proposes equipping an inductive WPT system into the UAV. A number of research work have been carried out to solve this problem. In [1], researchers developed a WPT system for UAVs designed for transmission line inspection, achieving 100 W of power with an efficiency of 83%. In [2], a buck converter was added before the battery to boost charging current and reduce power losses, resulting in a 9% improvement in overall efficiency. Another approach in [3] introduced a 70 W WPT system, using landing gear made from aluminum tubing as the receiver. In [4], the authors investigated Series-Series (SS) and Series-Parallel (SP) compensation topologies to improve efficiency while reducing mass. Also, in [5], various coupler designs were tested to determine which offered the best performance for dynamic WPT.

New perspectives can be explored to enhance the current approaches. Studying the WPT efficiency as a function of various parameters is necessary to minimize the UAV downtime during recharging. Analyzing the size of the additional components may provide relevant insights, considering the potential significant increase in weight to the UAV and its potential impact on aerodynamic performances.

The goal of this paper is to design a lightweight WPT system that that targets maximum efficiency despite misalignment (d_x), which can occur during the landing of the UAV. To achieve this, a new parametric approach is proposed, considering key factors such as resonance frequency, compensation topology, and the number of coil turns. The study is divided into two main parts: modeling and simulation, followed by experimental validation. For the modeling phase, COMSOL Multiphysics is used to determine the electrical parameters of the magnetic coupler, while MATLAB Simulink is used to simulate the entire electrical circuit to evaluate the WPT system efficiency. The experimental validation focuses on the validation of the coupler's electrical parameters using a mechanical test bench, allowing for an in-depth analysis of the effects of misalignment.

II WPT system setup

The WPT system is conceived to be integrated into the DJI F450 drone model, which operates without landing skids (Fig. 1). Adding landing skids could increase the overall weight of the UAV and likely cause aerodynamic issues if not properly integrated [6].

The WPT system configuration, shown in Fig. 1, is composed of two main sections: the transmitting and receiving units. The transmitting (primary) side includes an AC power source, a transmitting coil T_x, and a compensation capacitor C_1. On the receiving (secondary) side, the system features a receiving coil R_x, a compensation capacitor C_2, a rectifier to convert AC to DC, and a battery. To enhance magnetic coupling and shield the onboard electronics, a ferrite plate is positioned above the receiving coil.

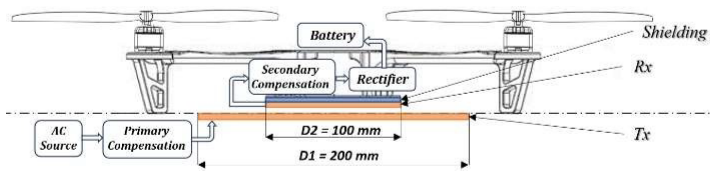


Figure 1: Representation of a WPT system for UAV

III WPT system analysis

For the electrical circuit, SP compensation topology is accounted (Fig. 2) due to its ability to provide high coupling efficiency while requiring fewer turns on the receiving coil [4]. The number of turns for the coils was determined through electromagnetic modeling, resulting in $N_1 = 8$ for the transmitting coil and $N_2 = 2$ for the receiving coil. This configuration achieves an efficiency of over 90% while keeping the receiving coil R_x lightweight.

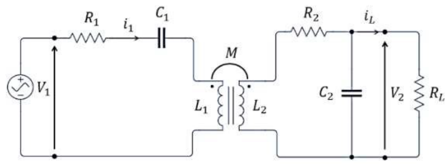


Figure 2:Electrical circuit of the WPT system

The electromagnetic modeling is carried out by Finite Element Method (FEM) as shown in Fig. 3 to obtain the self-inductances L_1, L_2 and the mutual inductance M as a function of misalignment. These values are then used in the electrical circuit to evaluate the system's power efficiency both at resonance and off-resonance, as the efficiency is directly affected by the coils misalignment.

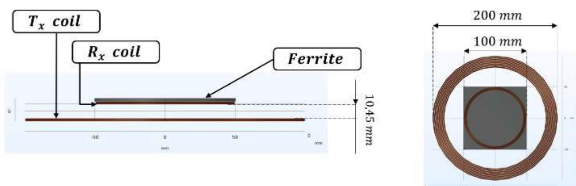
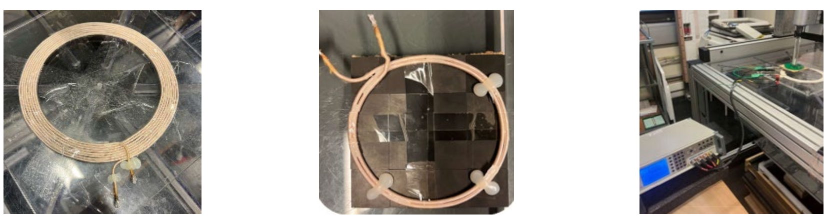


Figure 3: Coil geometries modeled by finite element method

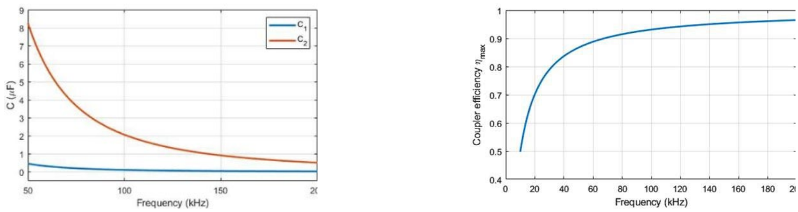
To validate the model experimentally, the inductances $L1$, $L2$, and M are measured across different cases of misalignment d_x using an RLC meter at different frequencies (Fig. 4). The measured inductances are then compared to the results of the FEM model to assess accuracy.



a) Transmitter coil (8 turns coil) | b) Receiving coil (2 turns coil) + ferrite measurements | c) RLC meter

Figure 4: Magnetic coupler prototype and validation

Following the validation of the FEM model, the maximum efficiency of the coupler (Fig. 5.b) and the values of capacitors C_1 and C_2 (Fig. 5.a) are assessed at perfect alignment for different operating frequencies.



a) Compensation capacitors values versus frequency b) Coupler efficiency versus frequency

Figure 5: Results of the frequency study

Fig. 5a demonstrates that the value of the secondary compensation capacitor decreases significantly as the operating frequency increases. Meanwhile, Fig. 5b shows that maximum coupling efficiency improves with higher frequencies. To achieve at least 90 % efficiency, the system must operate at a minimum of 65 kHz. Selecting 150 kHz strikes a good balance, offering both high efficiency and a reduced capacitor size, an important consideration for onboard UAV applications.

SP compensation topology, and M varies with misalignment. Three different cases are identified :

1. $V_1 = 12$ V and C_1 adapted for each "d_x"
2. $V_1 = 12$ V, $i_1 \leq 10$A and C_1 adapted for each "d_x"
3. $P_1 \leq 120$ W ($V_1 = 12$ V, $i_1 \leq 10$A) & fixed capacitor C_1

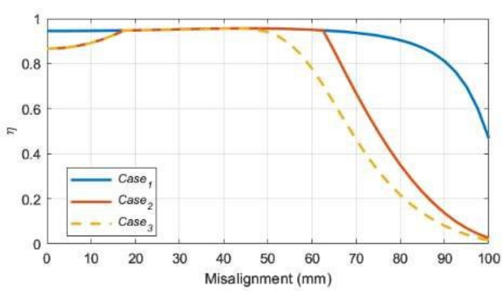


Figure 6: System efficiency versus misalignment

Fig. 6 shows the impact of constraints on the coupler efficiency. In Case 1, the efficiency remains above 80% up to $90\ mm$ misalignment. However, in Case 2, where the power source is limited to $120\ W$, the efficiency drops under 80% at $68\ mm$ of misalignment, which affect the receiving current. With a fixed primary capacitor C_1 (Case 3), the efficiency falls under 80% at approximately $60\ mm$ misalignment, leading to insufficient source power for wireless transfer. This prompts a further study of various compensation topologies to optimize the WPT system for the DJI F450.

IV Conclusion

This paper explores the impact of key parameters, specifically the frequency and compensation topology, on the performance of a WPT system. The results reveal a potential reduction in value (size) of the secondary capacitor's by increasing the frequency, leading to an optimal selection of the capacitor and frequency. However, constraints on the source power and the primary compensation capacitor may reduce the system's tolerance misalignment. These results require more studies on compensation topologies and coil turns.

Experimental validation supports the finite element model for optimizing the coupler dimensions, which will be described in the extended version. Additional factors, such as the weight of the receiving parts, will also be taken into account. The comprehensive analysis aims to determine optimal coupler dimensions, enhancing misalignment tolerance while maintaining high WPT efficiency.

References

[1] S. Duan, X. Lu, H. Wu, H. Zhang, Z. Zhang and G. Wang, "Unmanned Aerial Vehicle Wireless Power Transfer System for Long-Distance Transmission Line Patrol", in *2022 IEEE International Power Electronics and Application Conference and Exposition (PEAC)*, 2022.
[2] X. Gao, C. Liu, Y. Huang and Z. Song "Design of An UAV-Oriented Wireless Power Transfer System with Energy-Efficient Receiver" in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 2020.
[3] T. Campi, S. Cruciani, F. Maradei and M. Feliziani "Innovative Design of Drone Landing Gear Used as a Receiving Coil in Wireless Charging Application" *Energies*, vol. 12, nº 18, 2019.
[4] T. Campi, F. Dionisi, S. Cruciani, V. De Santis, M. Feliziani and F. Maradei "Magnetic field levels in drones equipped with Wireless Power Transfer technology" in *Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC)*, 2016.

[5] K. Kadem, M. Bensetti, Y. Le Bihan, E. Labouré and M. Debbou, "Optimal Coupler Topology for Dynamic Wireless Power Transfer for Electric Vehicle" *Energies*, vol. 14, nᵒ 13, janv. 2021.

[6] S. Pang, J. Xu, Z. Xie, J. Lu, H. Li, and X. Li and Lightweight UAV's Wireless Power Transfer System for Constant Current Charging Without Secondary Feedback Control" *IEEE Trans. Veh. Technol.*, vol. 72, nᵒ 12, p. 15611-15621, 2023.