Polyphase Couplers for Small Airgap Wireless Power Transfer to Electric Drones

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***Abstract*—Wireless power transfer (WPT) has been proposed for charging of electric cars, robots, and drones to increase battery capacity factor, charging reliability, and autonomous functionality. Multiphase WPT systems using large-diameter coils have been explored to increase specific power transferred, enhance tolerance to misalignment, and reduce stray-field emissions. Stationary drone-charging inductive coils are assumed to operate with minimal airgaps (10-30 mm) compared to airgaps for electric vehicles, which may enable different coil-design tradeoffs. This paper investigates single- and multiphase wireless charging coil geometries, specifically targeting small airgap drone charging conditions. Parametric electromagnetic studies are conducted using ANSYS Maxwell 3D FEA to evaluate coupling and power delivery across multiple single- and multiphase coil geometries. Inductance matrices, current requirements, and power-delivery are then used to compare geometries to observe potential advantages. Results indicate flux-path segmentation in multiphase configurations alters coupling behavior, necessary excitation current, and switching frequency requirements. Electromagnetic simulations are validated through experimental prototype Litz and PCB coil inductance measurements that are consistent with FEA results. Results indicate trade-offs in alternative geometry and multiphase configurations that affects coil performance at small airgaps for WPT couplers in drone-charging systems.**

***Index Terms*—Wireless power transfer, inductive coupler, multiphase systems, wireless charging, unmanned aerial vehicle**

I. Introduction

Wireless power transfer (WPT) systems transfer energy over an airgap using the electromagnetic field created by inductive coils linked at a resonant frequency. Stationary wireless chargers may enable battery operated vehicles, such as electric vehicles, drones, and robotics, to operate autonomously for long periods of time, increase battery capacity factor, and improve reliability and safety. Previous literature has extensively explored varied coil geometries for large wireless charging coils (300-450 mm OD) in electric vehicle applications [1]–[3]. Electromagnetic coil studies for wireless charging of electric drones, as depicted in Fig. 1, are limited compared to literature for high power charging of EVs.

Challenges for unmanned aerial vehicles (UAVs) charging include coil volume and weight limitations on the drone side, electromagnetic interference, efficiency, and misalignment tolerances. Gravimetric power density-based optimizations have been proposed for fast charging to maximize efficiency to weight ratios [4], [5]. Investigations to reduce coil misalignment between primary and secondary coils are of interest to maximize power transfer and reduce stray fields [2], [6]. Asymmetric inductive coupler pairs are of interest for more efficient and reliable solutions [7], [8].

Design constraints and rated power differ significantly between EV and UAV applications. For UAV charging applications, power ratings for fast charging range from 0.3-0.7 kW [9]–[11], while EV applications are substantially higher between 100-250 kW [12], [13]. Wireless power transfer (WPT) coil analysis for UAVs is focused on maximizing power density, misalignment tolerance, and minimizing coil size and weight. The receiving coils for UAV application are heavily restricted in volume and weight to prevent impacting flight performance. The primary coil size is assumed to be unrestricted, enabling larger ODs to generate a large electromagnetic field with fewer turns or current.

Conventional coils typically utilize Litz wire conductors due to their high fill factor and reduced individual strand cross-sections, mitigating AC losses at high frequency. Multiphase inductive couplers have been explored to increase surface power densities while providing constant output power, reduced voltage stress, and reduced resonant compensation size. Complex design configurations at small ODs previously unconsidered due to Litz wire bend radius, are feasible through PCB-type coils using parallel paths and trace transposition. This paper analyzes various coil configurations for fast drone charging applications, assuming a small airgap between coils and restricted coil OD.

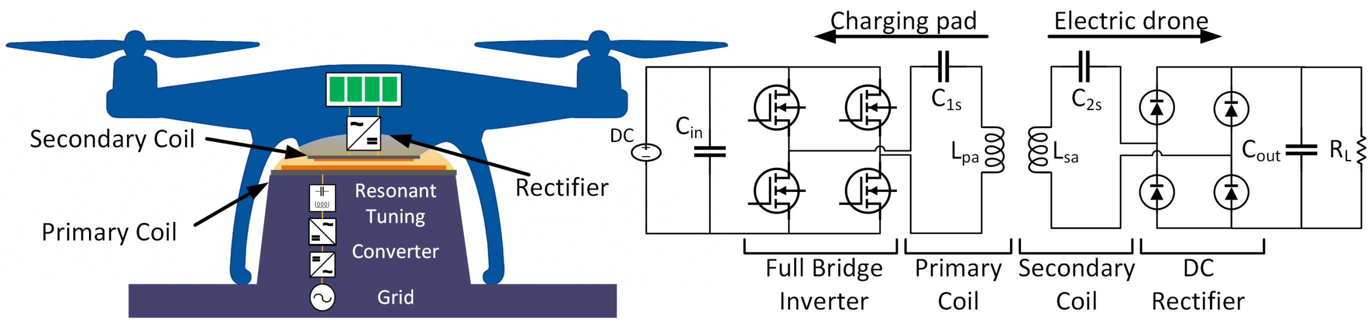

Fig. 1. Example application of stationary wireless charging of an electric drone using a single phase inductive coil pair. The secondary coil in this application is restricted by the available area on the underside of the drone. Power electronics for the example system are depicted and labeled, showing series-series resonant tuning with a full bridge high frequency inverter.

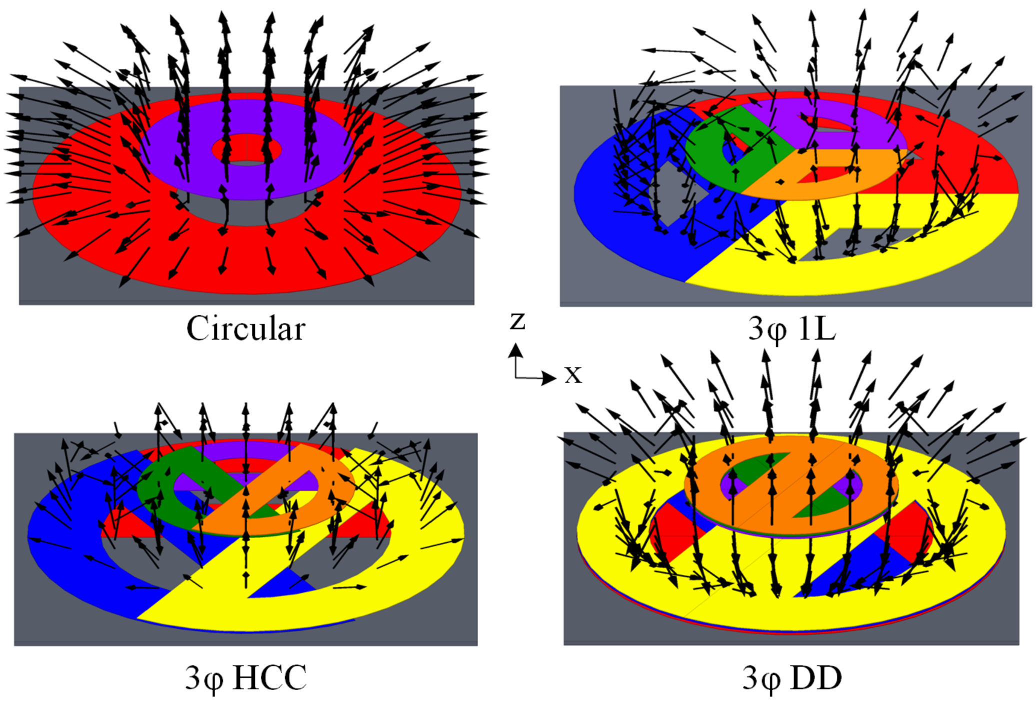

Fig. 2. Wireless charging coil configurations: circular, three-phase half coil, three-phase single layer, and three-phase three layer macro coil models with each coil colored by phase. The secondary side coils are smaller to minimize volume while considering maximal coupling with the primary. Example vector B-field plots simulated with 3D electromagnetic FEA are shown for each model.

II. UAV Coupler Characteristics and Design

For stationary UAV wireless charging applications, the airgap between the transmitter and receiver coils is assumed to be very small, typically between 10-30 mm, with the coils operating in close proximity for charging. The coupling coefficient for a wireless charger is often used to size the airgap, with a common heuristic being one-third of the outer diameter of the receiver coil depending on the fundamental flux path between the two coils. Under small-airgap conditions, the magnetic flux linkage will significantly increase, resulting in enhanced electromagnetic coupling and performance. Elevated coupling at small airgaps relaxes design constraints that dominate large-airgap systems, allowing for special coil geometries and phase configurations not previously considered. Alternative coil geometries may provide distinct advantages in power density, magnetic field utilization, and rated currents necessary for UAV wireless charging systems.

Inductive wireless charging coil configurations are characterized by their impedance, specific power output, and current per phase. Multiple single and polyphase coil geometries macro models were developed using ANSYS 3D finite element analysis (FEA) tool [14], as seen in Fig. 2, including half circular coils, two phase two layer, three-phase single layer, and three-phase three layer double-D (DD) coils. As part of an initial study comparing coil geometries, only coil pairs with the same topology are employed in all explored models. Macro models simulate overall electromagnetic performance without modeling individual conductors by grouping turns and layers together into one bulk conductor, which reduces mesh size and computation times common with modeling of very thin conductor with a large surface. Electromagnetic simulation results from macro modeling have been validated previously in literature through experimentation and resulted in less than 10% error [13].

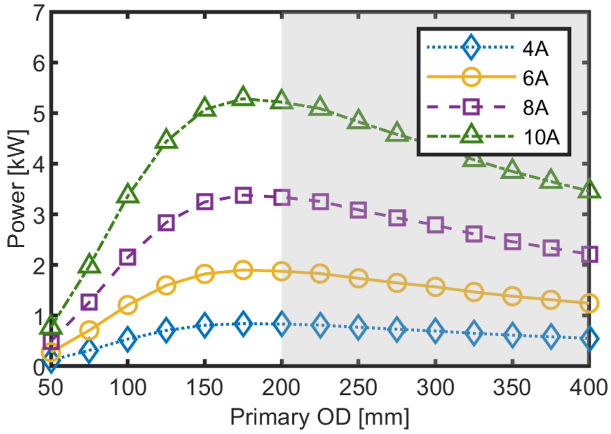

Fig. 3. Output power consistent between each geometry at 100 mm secondary outer diameter (OD) with a constant 30 mm airgap. Larger coils may have increased efficiency and allow larger airgaps, but are limited by the area under the drone (200 mm OD). At the same outer diameter, doubling the primary coil excitation more than doubles the power.

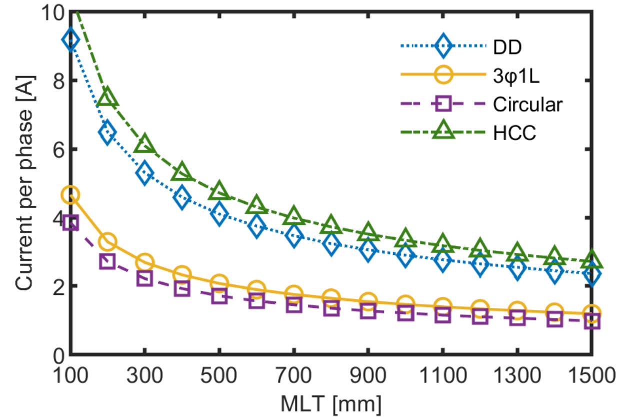

Fig. 5. Required current per phase to reach 700 W rated power for different coil configurations based on mean length per turn (MLT). Geometries are the same on primary and secondary sides. With the same conductor length, HCC coils require a higher current excitation.

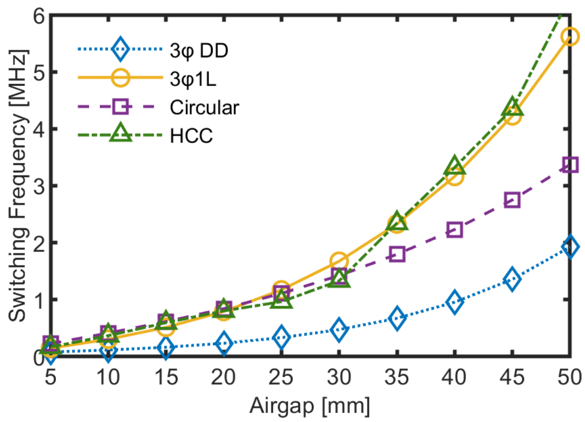

Fig. 4. Switching frequency to reach rated power at the same current for dual geometries of the same size with varying airgap sizes. Flux paths are smaller for higher phase geometries, affecting performance at larger airgaps.

Parametric studies were conducted to simulate the electromagnetic performance of different geometries. Coil macro models were simulated at 85kHz, 100 mm secondary OD, 32 turns per phase, with a 15 mm airgap and 3 mm thick square ferrite plates at 106 mm width. Inductance matrices and coupling coefficients are simulated and utilized to calculate the performance of numerous design candidates. Studies were focused on isolating conditions that persist between geometries and differentiating the advantages of each geometry. The electromagnetic behavior of one, two, and three-phase models with varying geometry are simulated over a range of airgaps and coil ODs. A combination of FEA and analytical equations are used to derive results based on the simulated inductance and output power.

Design and comparison of coil configurations requires detailed studies of delivered power. Power transferred between the transmitter and receiver coils can be generalized between geometries as:

$$P = |j\omega \overline{I_p^T} M_{ps} I_s|, \tag{1}$$

where M_{ps} is the mutual inductance matrix between transmitter and receiver, and I_p and I_s are the complex primary and secondary currents respectively [15], [16]. The power equation is used to analytically determine the switching frequencies and per-phase current necessary to achieve a rated power of 700 W. For comparative evaluation, mutual inductance is assumed at perfect alignment for the given design candidates to isolate the effect of coil geometry and phase configuration on calculated performance. Under these assumptions, maximizing the power transferred over a fixed airgap focuses on increasing max conductor current and then the mutual inductance through geometric optimization, providing a framework for comparison of single and multiphase coupler designs.

The induced voltage on the secondary scales with the frequency and current in the following analytical equation:

$$V_s = j\omega I_p M = j\omega I_p N_p (N_s \hat{L_m}), \tag{2}$$

where I_p is the primary current, L_m is the mutual inductance per turn, and N is the number of turns in the primary [16]. The analytical representation of the induced voltage allows coil selection with either a high number of turns or higher current excitation to achieve rated power. Ideally, drone couplers would have a large primary and small secondary coil pairing, so the system can operate with high current on the primary and high voltage on the secondary, reducing size and losses on the secondary side.

III. Multiphase Geometry Comparison

Under volume constraints, different sizing of primary and secondary coils enables the use of a greater number of or larger conductors, thereby increasing the maximum power transferred. As the primary coil outer diameter (OD) increases, both the flux linkage and power transferred will scale consistently across the evaluated geometries, as seen in Fig. 3. Larger coil ODs generally are beneficial for enhancing coupling capabilities, but performance becomes limited when paired to the compact 100 mm OD receiver. At very small airgaps, increased field penetration and reduced stray flux allows very

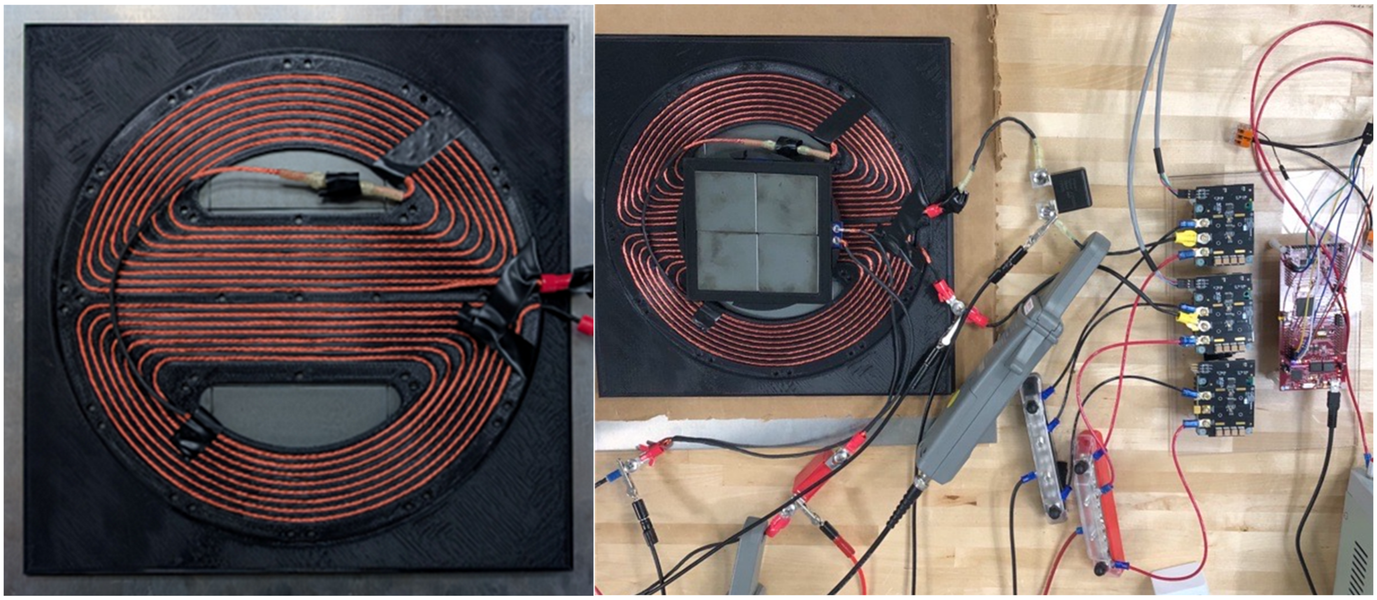

Fig. 6. Wireless power transfer prototypes and test fixture comprising a 250 mm single phase Litz DD coil and a 100 mm PCB secondary coil backed by a ferrite core. Experimental measurements were taken across the primary and secondary coils and resonant series capacitors at an airgap of 15 mm and 30 mm.

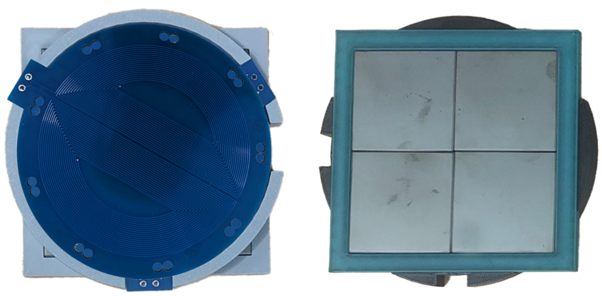

Fig. 7. Prototype DD PCB coil at 100 mm OD with ferrite core backing. PCBs allow for many turns with increased customization and manufacturability at smaller ODs through special design techniques.

high efficiency and transferred power. Each geometry exhibits distinct field emission characteristics, resulting in trade-offs between robustness and surface power density.

Multiphase wireless charging systems balance transmitting distance with achievable power density and magnetic field intensity. Each coil geometry produces a distinct flux path, with certain topologies performing more efficiently at small airgaps while others maintain stronger coupling at larger separation distances. As additional phases are introduced, the flux path of the WPT systems is segmented, effectively reducing the usable airgap but increasing coupling. The switching frequency requirements for the studied geometries at a rated power of 700 W are shown in Fig. 4, depicting how the airgap effects the coupling of different topologies. Geometry selection fundamentally governs trade-offs between coil-to-coil efficiency, misalignment tolerances, volume, weight, and power density over varying transmission distances.

Rated current requirements for dual coil configurations to reach a rated power of 700 W are summarized in Fig. 5. Under matching constant mutual inductance produced for each

TABLE I

COIL-TO-COIL EXPERIMENTAL RESULTS BETWEEN 250 MM LITZ WIRE COIL AND 100 MM PCB-TYPE COIL AT DIFFERENT EXCITATIONS.

Airgap [mm]	Vin [Vrms]	Power [W]	Efficiency [%]
15	12.5	9.4	90.4
15	25.0	39.2	87.7
15	50.0	160.6	86.3
15	75.0	366.0	85.7
30	12.5	16.8	84.4
30	25.0	68.0	83.9
30	50.0	279.7	83.9

mean turn per length (MLT), the half circular coil (HCC) requires a higher current to reach the rated power. Multiphase configurations may require larger excitations as a trade-off to increasing power density and reducing stray field losses. Experimental power and inductance measurements conducted on the prototype hardware shown in Fig. 6 were consistent with macro coil model FEA simulations.

IV. CASE STUDY RESULTS AND DISCUSSION

Polyphase couplers for UAVs are heavily restricted by conductor bend radii, volumetric limits, and weight mechanical constraints. Inductive coils rely on having many conductors to increase the strength of the magnetic field and determines induced voltage on the secondary. Litz wire conductor bend radii restricts the applicability of more complex geometries. Printed circuit board (PCB) type coils, as seen in Fig. 7, have been explored as an alternative to Litz wire conductors by using copper traces to form coils [17].

Conventional circular coils are the simplest and have the largest range due to the unipolar fundamental flux, however, power transfer is not continuous resulting in waveform pulses compared to multiphase alternatives. Circular and three-phase one-layer coils require similar current per phase for the same MLT, in part due to the single layer implementation.

Skin and proximity effect losses are the dominant loss mechanism in small-OD PCB coils, making frequency selection critical for high efficiency operation.Coil configurations that fundamentally require lower frequencies for rated power, such as the studied DD coils, reduce AC losses across the airgap. Multi-layer coil stacking significantly increases AC resistance, attributed to interlayer proximity losses. These results suggest that optimal implementation of WPT in UAVs would incorporate a large, multi-layer Litz wire transmitter coil paired with a single-layer PCB receiver coil optimized for low volume and higher power density.

Increases to coil OD past a certain limit result in diminishing and even reduced returns. This is due to variation in the flux path between the primary and secondary coils, resulting flux linkage, and the geometry of the compact receiver. High efficiency with limited airgap is demonstrated through the test results, with near zero gaps between coils being ideal for even higher efficiencies.

V. Conclusion

In this paper, single and multiphase wireless charging coil electromagnetic properties are characterized using ANSYS Maxwell 3D FEA and analytical equations for small-airgap wireless charging of electric drones. Ranges of designs for single phase to three-phase systems of varying geometry are evaluated based on their mutual inductance matrices, required excitation currents, switching-frequency behavior, and output power delivered. Results of parametric studies and power electronic simulations indicate that complex multiphase models exhibit distinct advantages for very small airgap conditions compared to conventional coils, including reduced current requirements, improved magnetic coupling, and higher power density. A DD Litz wire transmitter and PCB-type receiver coil pair are developed and tested to validate simulation results and evaluate performance under two different airgaps.

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