



A Novel Solenoid-Based Magnetic Coupler for Achieving High Misalignment Tolerance in UAV Wireless Charging

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ABSTRACT

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Unmanned aerial vehicle (UAV) charging is one of the wireless charging applications, and charging their batteries can be challenging because they have short flight times and are frequently charged. Autonomous wireless charging of UAVs requires a magnetic coupler that can tolerate landing-position errors while avoiding obstruction of onboard payload sensors. This paper proposes a solenoid-based inductive power transfer (IPT) coupler consisting of eight ferrite-core solenoid coils on the ground transmitter and two solenoid receiver coils integrated into the UAV landing gear. A three-dimensional finite-element model developed in ANSYS Maxwell is used to evaluate the self-inductances, mutual inductance, coupling coefficient, misalignment sensitivity, and magnetic-field distribution. The coupler is then incorporated into a 350 W LCC-LCC compensated charging system simulated in MATLAB/Simulink at 100 kHz. At nominal alignment, the coupling coefficient is 0.313, and the mutual inductance is 21.26 μ H. Within ± 50 mm horizontal displacement, the coupling coefficient decreases by approximately 4.7% and 1.9% along the X and Y axes, respectively, while a 25° rotation produces a 9.8% reduction. The simulated DC-to-DC efficiency reaches 91.96%. At a height of 145 mm, corresponding to the UAV-body level, the simulated magnetic flux density is below 1.7 μ T. The results indicate that the proposed geometry maintains relatively stable coupling over the evaluated landing region while keeping the central under-body camera path free from direct coil obstruction. The present study is simulation-based; experimental validation and detailed frequency-dependent coil-loss characterization remain subjects for future work.

1. INTRODUCTION

Wireless power transfer (WPT) systems can be divided into two main types: inductive power transfer (IPT) and capacitive power transfer (CPT), which are based on a magnetic field and an electric field, respectively, for energy transfer [1, 2]. IPT technology demonstrates a clear advantage over CPT technology in its ability to efficiently transmit high power levels across larger air gaps [3]. This technology is used widely in main industries, such as portable electric vehicles (EVs) [4], unmanned aerial vehicles (UAVs) [5], and so forth. UAV technology is rapidly developing in several applications, with ongoing improvements in performance. Due to their many advantages, such as their basic structure, compact size, low cost, exceptional adaptability, and operational flexibility, UAVs are widely used in the commercial, military, and governmental sectors [6]. UAVs are predicted to become a common delivery method by 2040 in order to meet the increasing needs for parcel logistics [7, 8]. But because of size and payload restrictions, the battery capacity of UAVs is still limited, limiting flight time and requiring regular return to charging stations. Thus, it is essential to develop wireless charging methods to save time and human resources. Because WPT technology offers an effective, cable-free recharging

mechanism, it has become a strategic solution to enable continuous and autonomous UAV operations [9]. The most important design parameter for an IPT system is the coil design, since a strong magnetic coupling between the primary and secondary charging pads mounted on the UAV can be used to achieve efficient power transfer [6, 10]. WPT systems encounter specific technical problems, especially 'misalignment' between the transmitter and receiver pads, either laterally or rotationally, as the positioning and landing of UAVs is dynamic. Therefore, the main technical obstacle to implementing wireless charging systems on UAVs is the misalignment issue. When UAVs hover over or land on the wireless charging stations, misalignments between transmitters and receivers are inevitable due to the complex environment and limited algorithm accuracy, consequently resulting in a sharp decline in coupling, low efficiency and unstable power transfer [11, 12]. Meanwhile, the challenge is getting worse due to the limited space on the UAV's body, requiring a sophisticated electromagnetic design for the magnetic coupler that balances spatial constraints with high performance without obstructing the field of view [13]. Therefore, high misalignment tolerance and the UAV structure must be considered when designing the magnetic pads. Concerning this phenomenon, the authors in studies [14-17]

proposed various designs of charging pads, including circular, square, solenoid, and DD coils, among others, to improve the system's tolerance to horizontal and rotational misalignment.

The research on UAV-IPT couplers in recent years can be considered to be moving in three complementary design directions. First, geometry-based approaches are used to enhance the translational or rotational tolerance by employing cross/DDD, circular, or DD structures [6, 9, 12]. These geometries can increase the space for the usable charging region, but the location of the receiver and the footprint of the coil might limit the space available for a downward-looking payload. Second, multi-winding, dynamic-field, integrated free-positioning, and reconfigurable transmitter approaches have been developed to broaden the effective charging region [14, 15, 17, 18]. Such approaches can improve coverage, although additional windings, switching states, or control functions may increase implementation complexity. Third, receiver-integration strategies seek to use the UAV structure more effectively, including multichannel conformal receivers [13], landing-gear-integrated receivers [16], and solenoid-based receivers [11]. Taken together, these studies show a recurring trade-off among coupling magnitude, coupling stability under misalignment, charging-pad area, receiver placement, control complexity, and camera/payload clearance.

Thus, the research gap of this study is not just to get the maximum nominal coupling coefficient. The goal is to keep the magnetic coupling relatively constant across the UAV landing area while avoiding direct obstruction of the coils and a reconfigurable receiver/transmitter switching scheme. A comparison of representative previous designs, including their reported coupling coefficients, misalignment characteristics, and receiver placement/FOV implications, is provided later in this paper. The unavailable numerical values are indicated as NR (not reported).

This paper proposes a solenoid-based magnetic coupler consisting of eight ferrite-core solenoid elements on the charging-station side and two ferrite-core solenoid receivers mounted on the UAV landing gear. The coupler is evaluated in ANSYS Maxwell and incorporated into a 350 W LCC-LCC compensated MATLAB/Simulink model. Within the investigated region, the design is evaluated for horizontal displacement up to ± 50 mm and rotational misalignment up to 25° . At the nominal operating point, the simulated DC-to-DC efficiency reaches 91.96%. The intended contribution is the relatively small variation in coupling over the landing area of interest and the avoidance of direct obstruction of the central downward-looking camera path; the study does not claim the highest absolute coupling coefficient or experimental validation. The main contributions of this study are summarized as follows:

- A solenoid-based primary/secondary magnetic coupler is proposed for UAV IPT charging. The simulated coupling coefficient decreases by only 4.7% and 1.9% along the X and Y axes, respectively, at ± 50 mm displacement, and by 9.8% at 25° rotational misalignment.
- The two receiver solenoids are integrated into the landing gear rather than placed directly beneath the UAV body, thereby avoiding direct obstruction of the central downward-looking camera path. Aerodynamic neutrality is not claimed because no CFD or flight test was performed.
- The coupler is integrated with an LCC-LCC compensated 350 W model operating at 100 kHz. The complete simulated system reaches 91.96% DC-to-DC efficiency under the nominal model parameters, while the limitations associated

with fixed-load operation and lumped loss modeling are explicitly discussed.

2. DESIGN AND SIMULATION OF THE PROPOSED MAGNETIC COUPLER

This section presents the electromagnetic design of the proposed magnetic coupler and the corresponding 350 W compensated charging model. Finite-element analysis is used to extract the magnetic parameters required by the MATLAB/Simulink circuit model, after which the effect of misalignment on the simulated charging performance is examined.

2.1 Magnetic coupler design

The useful flux path, leakage field, mutual inductance, and sensitivity to displacement of an IPT coupler depend on the geometry of the coupler. A high nominal coupling coefficient is desirable for UAV charging, but stability of the coupling over the landing region is also important since sudden changes in mutual inductance may cause detuning of the compensated system. Conventional circular pads are simple and rotationally symmetric; DD- and cross-type pads can increase the effective charging region but can also have null-coupling positions depending on the relative geometry [6, 9, 12]. The present design thus employs distributed solenoid elements to provide a wide area where the receiver overlaps a similar magnetic-flux pattern.

The proposed primary charging pad on the station side consists of eight ferrite-core solenoid coils connected in series and wound with the same polarity. The secondary pad consists of two ferrite-core solenoid coils mounted on the UAV landing gear, as illustrated in Figure 1.

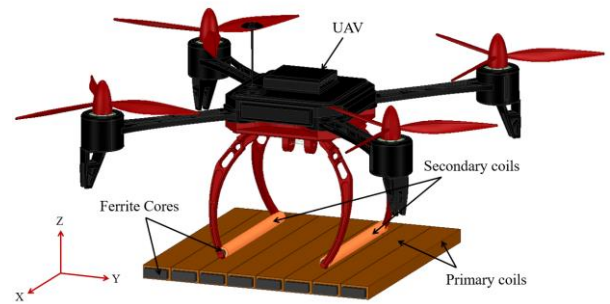


Figure 1. General overview of the presented magnetic coupler of the unmanned aerial vehicle (UAV)

In the present equivalent model, the two secondary solenoid coils are geometrically symmetric and are connected in parallel. When mounted on the landing gear, they are away from the central under-body area where downward-looking payloads are mounted, and distribute the extra electromagnetic components on the two sides of the airframe. This geometric configuration does not imply that the aerodynamic characteristics have remained the same: added mass, frontal area, wiring, and drag were not measured in the present simulation-only study. The primary charging pad is made up of eight symmetric coils connected in series, as shown in Figure 2. The coupler was modeled using ANSYS Maxwell 3D. The equivalent litz-wire diameter (d_c) is 2.5 mm. L_{PP} and W_{PP} denote the primary-pad length and width; W_f and h_f denote

the ferrite-bar width and thickness; S is the spacing between adjacent primary coils; and N_P and N_S denote the number of turns per primary and secondary bar, respectively.

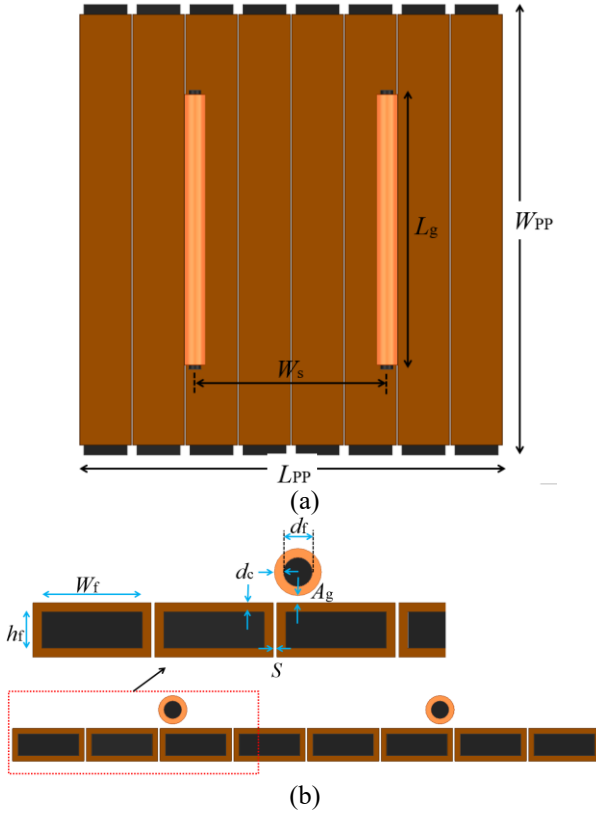


Figure 2. Magnetic coupler structure: (a) top view and (b) side view

S_P and S_S refer to the spacing between the turns of the primary and secondary coils, respectively. A_g refers to the air gap between the primary and secondary magnetic coupler. d_t refers to the diameter of the ferrite bar in the secondary charging pad. The secondary magnetic coupler is mounted on its two landing gears. W_s refers to the spacing between the two UAV landing gears, and L_g refers to the length of the secondary charging pad.

2.2 Charging system simulation

The coupler parameters were obtained from ANSYS

Maxwell and then the wireless charging system was modeled in MATLAB/Simulink with the circuit shown in Figure 3. In the present model, the battery is represented by a nominal resistive load ($R_L = 9 \Omega$) and the output voltage is about 56 V, which results in an operating point of about 350 W. This representation is appropriate for a nominal-point study, but it is not a representation of the varying equivalent load of a battery under constant-current/constant-voltage charging.

A double-sided LCC compensation network is connected between the inverter, magnetic coupler, rectifier, and load. The compensation network is selected because its additional tuning inductors provide design flexibility and can reduce sensitivity to coupling and load variation compared with simpler resonant structures [19]. The rectifier converts the received high-frequency AC power to DC power for the load. For the present design, the filter and resonant capacitors are selected at the operating frequency $f_r = 100 \text{ kHz}$ using Eqs. (1) and (2), while the mutual inductance is obtained from Eq. (3).

$$C_{f1} = \frac{1}{\omega_r^2 L_{f1}}, \quad C_p = \frac{1}{\omega_r^2 (L_p - L_{f1})} \quad (1)$$

$$C_{f2} = \frac{1}{\omega_r^2 L_{f2}}, \quad C_s = \frac{1}{\omega_r^2 (L_s - L_{f2})} \quad (2)$$

Here, L_P and L_S are the primary and secondary self-inductances, respectively; L_{f1} and C_{f1} are the primary-side filter elements; L_{f2} and C_{f2} are the secondary-side filter elements; C_P and C_S are the coil-side compensation capacitors; M is the mutual inductance between the magnetic pads; and $\omega_r = 2\pi f_r$ is the resonant angular frequency. The mutual inductance is related to the coupling coefficient by Eq. (3).

$$M = k \sqrt{L_P L_S} \quad (3)$$

For transparency, the component values in Section 3.2 are produced directly from the extracted coil parameters. At $f_r = 100 \text{ kHz}$, $\omega_r = 6.283 \times 10^5 \text{ rad/s}$. Using $C_{f1} = 1/(\omega_r^2 L_{f1})$ with $L_{f1} = 15 \mu\text{H}$ gives $C_{f1} = 169 \text{ nF}$, and $C_{f2} = 1/(\omega_r^2 L_{f2})$ with $L_{f2} = 12 \mu\text{H}$ gives $C_{f2} = 211 \text{ nF}$. The coil-side capacitors are obtained from $C_P = 1/[\omega_r^2 (L_P - L_{f1})] = 67.35 \text{ nF}$ and $C_S = 1/[\omega_r^2 (L_S - L_{f2})] = 33.66 \text{ nF}$, which round to 67.4 nF and 33.7 nF, respectively. Similarly, from Eq. (3) $M = 21.2 \mu\text{H}$, consistent with the 21.26 μH FEA value after rounding. The values $L_{f1} = 15 \mu\text{H}$ and $L_{f2} = 12 \mu\text{H}$ are design-selected tuning inductances; once fixed, the corresponding capacitors follow from the resonance conditions.

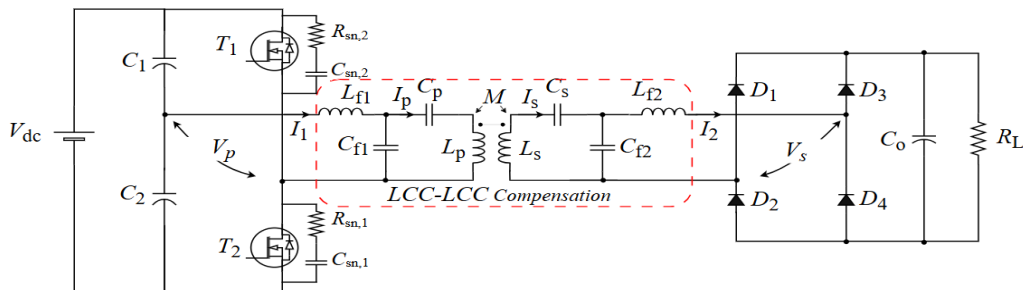


Figure 3. Inductive power transfer (IPT) system circuit diagram of unmanned aerial vehicle (UAV)

3. RESULT AND DISCUSSION

This section presents the simulated magnetic-coupler

behavior, magnetic-field leakage, compensated-system performance, and the practical limitations associated with the present simulation-only model.

3.1 Magnetic coupler analysis

The coupler geometry was analyzed in ANSYS Maxwell using the magnetostatics solver to obtain the inductive parameters listed in Tables 1 and 2. Magnetostatic analysis can be used to extract the nominal inductance and coupling trends that can be used in the circuit model, but it cannot be used to quantify the frequency-dependent copper losses due to skin and proximity effects at 100 kHz.

Table 1. Design parameters of the magnetic coupler

Symbol	Value
$L_{PP} \times W_{PP}$	272.6×290 mm
W_f	28 mm
h_f	10 mm
S	1 mm
S_p	25 mm
L_g	180 mm
W_s	124 mm
S_s	1 mm
N_p/bar	11
N_s/bar	50
A_g	2 mm
d_f	8 mm

Table 2. Parameters of the magnetic coupler

Parameter	Value
L_P	52.61 μH
L_S	87.24 μH
k	0.313

The resulting nominal parameters are $L_P = 52.61 \mu\text{H}$, $L_S = 87.24 \mu\text{H}$, and $k = 0.313$. Although this value of k is moderate rather than exceptionally high, the design objective is to limit its variation over the expected landing region. The geometric values used in the FEA model are summarized in Table 1, and the extracted inductive parameters are listed in Table 2.

Figure 4 shows the simulated sensitivity of the coupling coefficient to horizontal and rotational misalignment. At ± 50 mm horizontal displacement, k decreases by approximately 4.7% along the X axis and 1.9% along the Y axis. A 25° rotation about the Z axis produces a 9.8% reduction. These results indicate that the principal benefit of the proposed geometry is coupling stability rather than a large absolute value of k .

The variation of M with the rotational misalignment angle is shown in Figure 4(c). The M values are taken from the results of the available electromagnetic analysis at the respective rotational positions.

This result provides a more direct assessment of the effect of rotational misalignment on the magnetic coupling. The rotational misalignment analysis is considered within a range of $\pm 25^\circ$. Due to the geometrical symmetry of the proposed coupler, the rotational response is symmetric with respect to the aligned position. Therefore, positive and negative rotational misalignments of the same magnitude produce essentially the same magnetic coupling behavior. The results shown in Figure 4(c) therefore characterize the rotational behavior over the considered $\pm 25^\circ$ range without requiring separate interpretation of the positive and negative directions. Mutual inductance can also be interpreted from Eq. (3). At nominal alignment, $M(0) = 21.26 \mu\text{H}$.

Figure 5 presents the variation of the primary and secondary self-inductances as the receiver is displaced by up to 50 mm

along the X and Y axes. The maximum change in L_P is $0.47 \mu\text{H}$ along X and $0.24 \mu\text{H}$ along Y, while the corresponding maximum changes in L_S are $0.43 \mu\text{H}$ and $0.51 \mu\text{H}$. Relative to the nominal inductances, these variations are small, supporting the observation that the resonance condition is less sensitive to horizontal displacement than the mutual coupling.

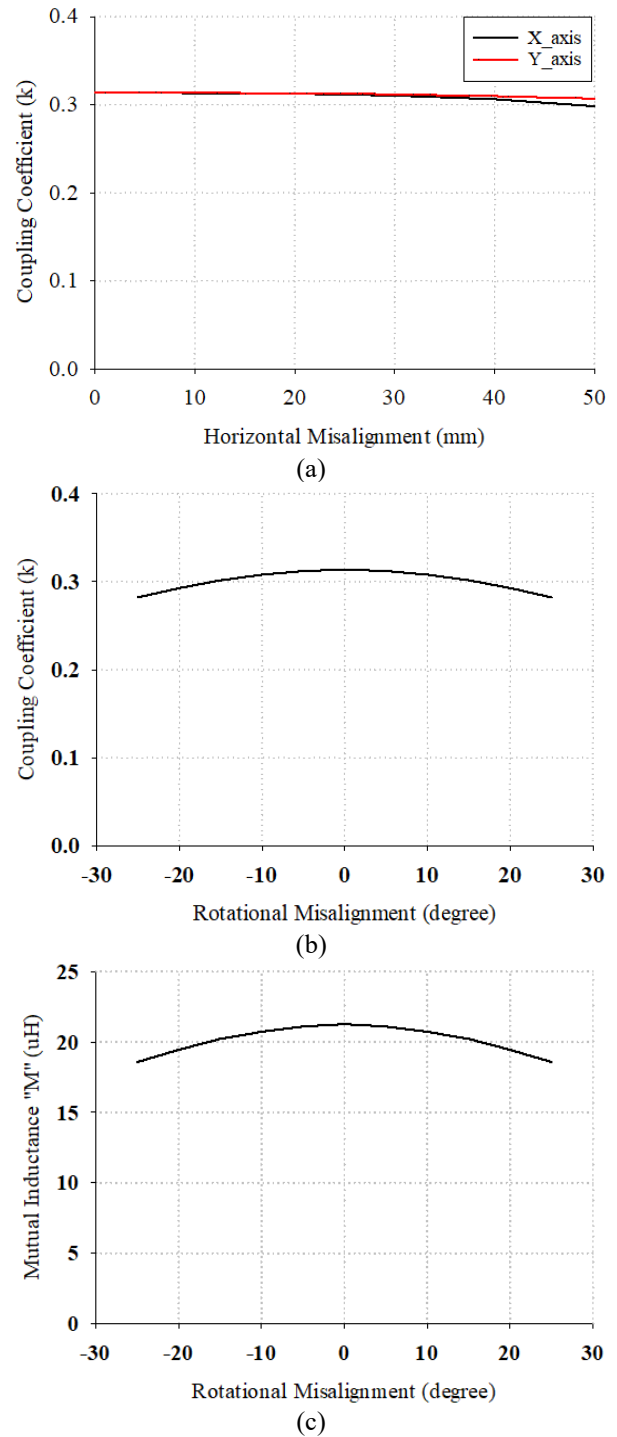


Figure 4. Misalignment effects: (a) horizontal misalignment on k (b) rotational misalignment on k (c) rotational misalignment on M

Figure 6 shows the simulated magnetic-flux-density distribution. At a height of 145 mm, corresponding to the UAV-body level, the reported magnetic flux density is below $1.7 \mu\text{T}$. For context, the ICNIRP 2020 guidelines for 100 kHz–300 GHz give a general-public whole-body incident magnetic-field reference level of $H = 2.2/\text{fM}$ A/m for 0.1–30 MHz,

where fM is the frequency in MHz [20]. At 100 kHz (0.1 MHz), this is 22 A/m, corresponding in air to approximately 27.6 μ T. Thus, the simulated 1.7 μ T point value is about 6% of this magnetic-field reference level. This comparison is indicative rather than a formal compliance assessment since the manuscript reports a simulated point magnitude and does not establish the RMS temporal/spatial averaging conditions prescribed by ICNIRP. Additionally, the simulated field level at the evaluated UAV-body height indicates limited exposure concerns to operators; however, electromagnetic exposure limits are not an EMC test for onboard sensors or electronics, and hardware EMC evaluation is still needed for practical deployment.

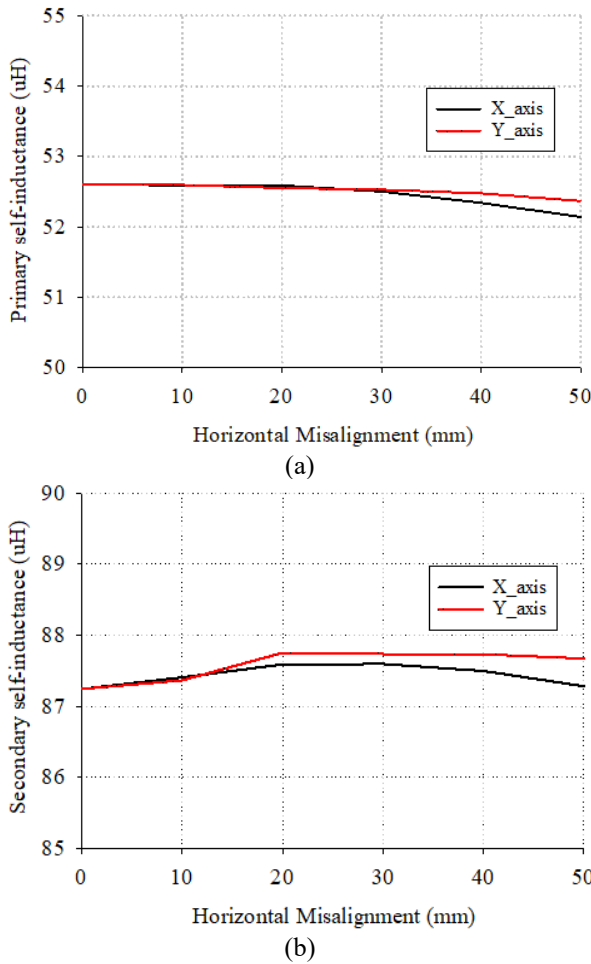


Figure 5. Self-inductance variation with misalignment: (a) primary self-inductance; (b) secondary self-inductance

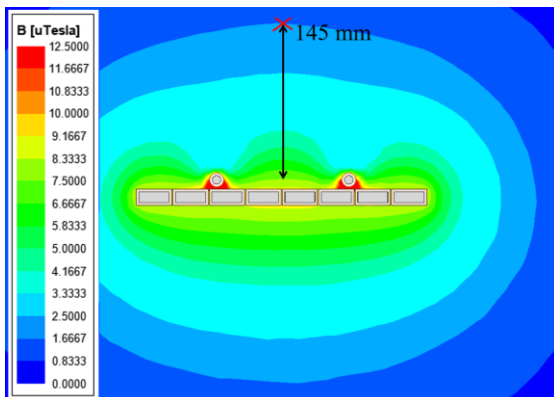


Figure 6. Simulated magnetic flux density distribution

The horizontal coupling surface obtained from the FEA data is shown in Figure 7. Within the evaluated region $(-50 \text{ mm}, -50 \text{ mm}) \leq (x, y) \leq (50 \text{ mm}, 50 \text{ mm})$, the coupling coefficient varies only modestly. This indicates that the proposed geometry can provide a comparatively uniform magnetic-coupling region over the simulated landing area. The statement is limited to the modeled coordinates and should not be extrapolated to arbitrary landing positions outside this range.

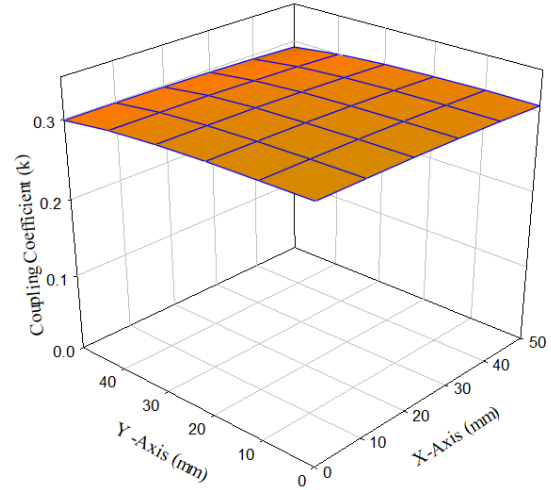


Figure 7. Coupling coefficient between primary and secondary pads under horizontal misalignment

3.2 Simulation results

The magnetic parameters extracted from the FEA were incorporated into the MATLAB/Simulink model of the double-sided LCC-compensated system shown in Figure 3. The compensation values were calculated following the procedure described in Section 2.2 and are summarized in Table 3. Under the nominal 9Ω load, the model produces approximately 350 W with a simulated DC-to-DC efficiency of 91.96%, as reported in Table 4.

Table 3. Inductive power transfer (IPT) system's particular parameters for UAVs

Parameter	Value
M	21.26 μ H
f_r	100 kHz
C_P	67.4 nF
C_S	33.7 nF
L_{f1}	15 μ H
C_{f1}	169 nF
L_{f2}	12 μ H
C_{f2}	211 nF
V_{dc}	110 V
R_P	125 m Ω
R_S	100 m Ω
R_L	9 Ω

Table 4. Simulation results of the IPT system

Parameter	Value
Load power: P_L	350 W
Simulated DC-to-DC efficiency: η_{DC-DC}	91.96 %
Simulated power-transfer efficiency: PTE	98.88 %

Note: Power transfer efficiency (PTE); inductive power transfer (IPT).

Figure 8 shows the steady-state simulated voltage (V_P & V_S)

and current (I_1 & I_2) waveforms at the input and output ports of the compensation network. Figure 9 shows an output voltage of approximately 56 V and a load power close to 350 W, which is consistent with the nominal resistive load $R_L = 9 \Omega$.

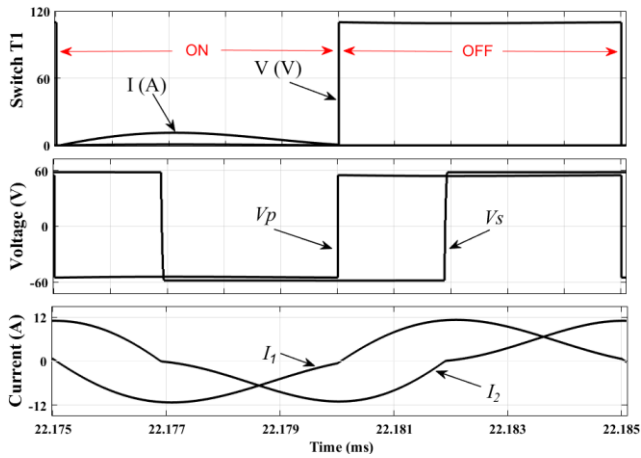


Figure 8. Simulated waveforms

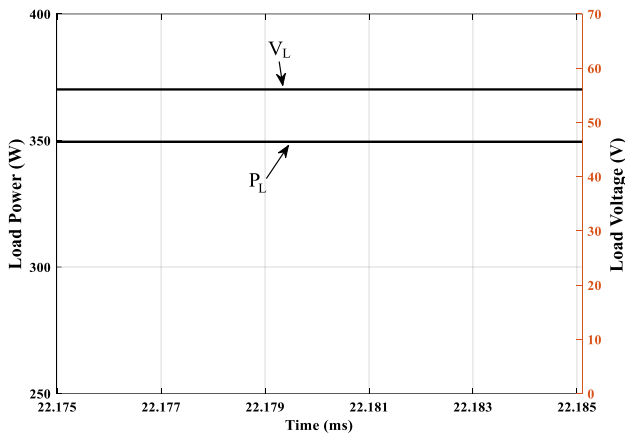


Figure 9. Load power and load voltage of the unmanned aerial vehicle (UAV) charging system

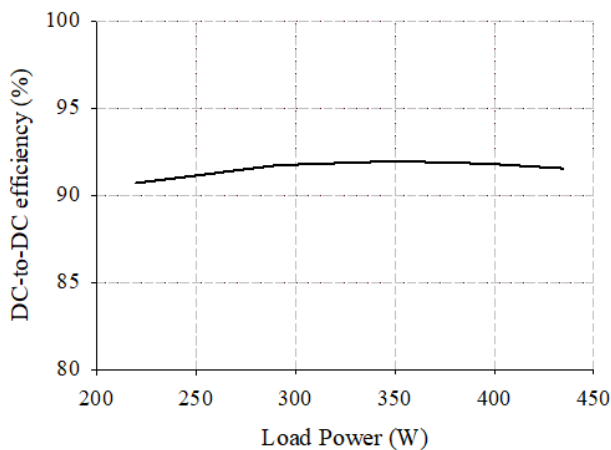


Figure 10. Simulated DC-to-DC efficiency under different output power levels

The present analysis evaluates the system over an equivalent load resistance range of $R_L = 5\text{--}13 \Omega$ at 100 kHz, corresponding to a load power range of 220–434.5 W. As shown in Figure 10, the simulated DC-to-DC efficiency

remains relatively stable over this load range, varying from 90.70% to 91.96%. The variation across the investigated range is 1.26 percentage points. The maximum efficiency of 91.96% occurs at the nominal operating point $R_L = 9 \Omega$, corresponding to an output power of 350 W. These results indicate limited efficiency variation over the investigated equivalent resistive-load range. However, the analysis does not use a complete electrochemical battery model and therefore does not reproduce the full constant-current/constant-voltage (CC-CV) charging trajectory.

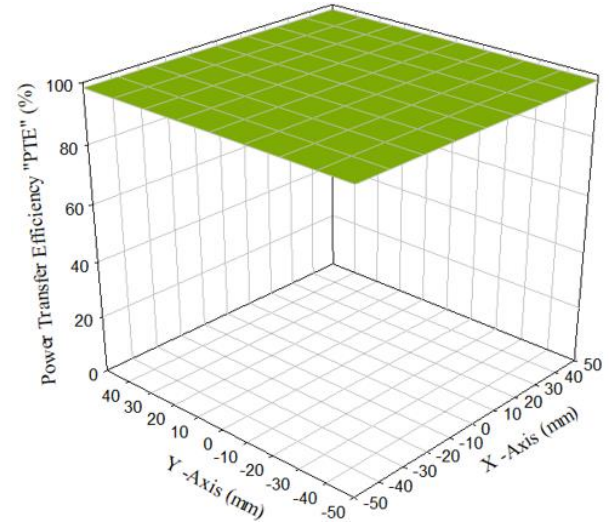


Figure 11. Power transfer efficiency (PTE) under misalignment

Figure 11 indicates that the simulated power-transfer efficiency remains nearly unchanged over the evaluated horizontal misalignment region under nominal tuning. The nominal coupling coefficient $k = 0.313$ should therefore be interpreted as moderate but relatively stable. The relatively stable coupling coefficient under misalignment helps maintain the operating resonant condition and consequently limits the variation in PTE caused by misalignment, without requiring changes to the nominal compensation component values. However, this result does not by itself establish robustness against component tolerances, temperature drift, or switching-frequency error, which were not independently evaluated in this study. The reported efficiencies are simulation-derived using the lumped loss elements included in the model and should not be interpreted as measured hardware efficiencies.

Table 5 provides a revised comparison with representative UAV-WPT couplers. The comparison includes coil topology, primary-pad size, receiver placement/FOV implications, nominal coupling coefficient where reported, coupling change under the stated misalignment condition, and DC-to-DC efficiency.

Several previous layouts place the receiving structure close to or under the central UAV body, with possible limitations on the available camera/payload region. The proposed landing-gear receiver does not directly obstruct the central downward-looking camera path. This geometric observation is not to be taken as proof of aerodynamic neutrality; no CFD analysis or flight test was performed.

The reported nominal coupling coefficients in Table 5 range from 0.16 to 0.328, while NR denotes values not reported in the cited study. The proposed nominal value $k = 0.313$ is therefore comparable with the reported range but is not the

highest value in the table. Its principal simulated advantage is the relatively small coupling change over the evaluated misalignment conditions: 4.7% at X = 50 mm, 1.9% at Y = 50 mm, and 9.8% at 25° rotation. Furthermore, the proposed design maintains a moderate and relatively stable coupling level across the evaluated charging surface. The proposed DC-to-DC efficiency of 91.96% is also within the range of the compared studies.

Another approach to further extending the misalignment tolerance is to increase the primary pad size. The main pad is situated on the ground-side charging station, so enlarging it does not add weight to the UAV, but would require more copper and ferrite, increase cost and station footprint, and could increase the spatial extent of leakage fields. Primary-pad enlargement should thus be seen as a design trade-off rather than an unconditional improvement.

Table 5. Balanced comparison with representative unmanned aerial vehicle (UAV) magnetic-coupler designs

Reference/Year	Primary Coil Secondary Coil	Primary Charging Pad Size (cm)	Receiver Placement/FOV Implication	Nominal k	Coupling Change Due to Misalignment (%)	DC-to-DC Efficiency (%)
[6]/2020	DDD coil Air-core coil	29.2 × 20.4	Near camera region; possible payload-view obstruction	0.328	65% at X = 40 mm 12% at Y = 40 mm 18% at rotate 25°	91.577
[12]/2022	Circular coil Air-core coil	Diameter = 50	Near camera region; possible payload-view obstruction	NR	6.7% at X = 20 mm 6.7% at Y = 20 mm 0% at rotate 360° (unstable)	88.64
[9]/2025	Circular coil Circular coil	Diameter = 30.8	Under-body receiver; central FOV constraint	0.20	20% at X = 50 mm 20% at Y = 50 mm 0% at rotate 360°	86.77
[16]/2025	DD coil DD coil	76 × 60	Landing-gear receiver; reduced payload-view interference	0.16	60% at X = 25 mm 30% at Y = 20 mm ---	94.5
[11]/2025	Solenoid Solenoid	14 × 9.5	FOV not quantitatively reported	NR	35% at X = 30 mm 34% at Y = 30 mm 17% at rotate 25° (unstable)	85
This Article	Solenoid Solenoid	27.26 × 29	Landing-gear receiver; no direct central camera obstruction	0.313	4.7% at X = 50 mm 1.9% at Y = 50 mm 9.8% at rotate 25°	91.96

3.3 Practical limitations and robustness considerations

Frequency-dependent coil loss: Table 3 uses lumped winding resistances $R_p = 125 \text{ m}\Omega$ and $R_s = 100 \text{ m}\Omega$. If these values are interpreted as the effective series resistances at 100 kHz, the corresponding model-based quality factors are $Q_p = \omega_r L_p / R_p = 264$ and $Q_s = \omega_r L_s / R_s = 548$. These values are not experimentally measured Q-factors. The magnetostatics FEA does not resolve skin and proximity losses, and the litz-wire strand count and individual strand diameter are not specified, so a detailed AC-resistance or copper/core-loss breakdown cannot be supported by the present data. The reported efficiency is to be understood as the efficiency of the reported lumped parameter simulation model.

Load variation and battery representation: The $R_L = 5\text{--}13 \text{ }\Omega$ sweep in Section 3.2 extends the analysis beyond the nominal 350 W point and shows a simulated DC-to-DC efficiency range of 90.70–91.96%. This addresses sensitivity to equivalent resistive loading, but it does not reproduce battery state-of-charge dynamics or the complete CC-CV charging trajectory.

Parallel receiver current sharing: The present Simulink model uses the equivalent secondary branch to model the two secondary solenoids. Geometric symmetry can support similar conditions near centered alignment but it does not guarantee equal branch currents under arbitrary lateral or rotational displacement. No quantitative current-balancing claim is made because branch-resolved mutual inductances (M_1 and M_2) and currents (I_{s1} and I_{s2}) were not calculated independently. Unequal branch coupling could lead to current imbalance and unequal thermal stress; thus, an electromagnetic/circuit model

with branch-resolved in the future work is required.

Mechanical and scaling trade-offs: Integrating the receiver with the landing gear avoids direct central-camera obstruction, but added ferrite, copper, wiring, frontal area, center-of-gravity effects, and aerodynamic drag were not quantified. Likewise, enlarging the ground-side primary pad can increase landing coverage without increasing UAV payload mass, but at the cost of additional material, station footprint, and potentially wider leakage-field distribution. These aspects require mechanical/CFD and experimental evaluation before practical deployment.

4. CONCLUSION

This study numerically evaluated a solenoid-based IPT coupler for UAV wireless charging using ANSYS Maxwell and a 350 W LCC-LCC compensated MATLAB/Simulink model at 100 kHz. At nominal alignment, the extracted coupling coefficient and mutual inductance are $k = 0.313$ and $M = 21.26 \text{ }\mu\text{H}$, respectively. Within the investigated region, k decreases by approximately 4.7% and 1.9% at 50 mm displacement along the X and Y axes, respectively, and by 9.8% at 25° rotational misalignment. The nominal simulated DC-to-DC efficiency reaches 91.96%, while the added equivalent-load sweep from 220 to 434.5 W gives efficiencies of 90.70–91.96%. The receiver placement also keeps the central downward-looking camera path free from direct coil obstruction. These results support the proposed geometry as a simulation-based approach for maintaining relatively stable coupling over the evaluated landing region; they do not

establish the highest absolute coupling coefficient or hardware-level robustness.

The main limitations are the absence of experimental validation, the use of a magnetostatics model that does not resolve frequency-dependent litz-wire losses, the equivalent representation of the two parallel receiver coils, and the use of resistive loads rather than a complete battery CC-CV model. Component-tolerance and switching-frequency detuning, branch-resolved current sharing, aerodynamic/mechanical effects, EMC behavior, and full angle-resolved mutual-inductance data also require further study. Future work should therefore prioritize prototype measurements of L_p , L_s , M , k , AC resistance/Q-factor, branch currents, output power, and DC-to-DC efficiency under aligned and misaligned conditions, followed by battery-oriented and mechanical/EMC validation.

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