Article

Design and Optimization of a Lightweight, Aerodynamic, and Misalignment-Tolerant Wireless Charging System for Unmanned Aerial Vehicles

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**Abstract:** This paper presents the design and development of a lightweight, aerodynamic, and misalignment-tolerant wireless charging system for Unmanned Aerial Vehicles (UAVs). To improve system performance and efficiency, a novel receiver coil design is proposed to be integrated with the UAV's landing gear. The rectangular helical coil configuration has been chosen on the receiver side for reducing weight, improving aerodynamics, and achieving a high coupling coefficient. The proposed design of a coil is analyzed in detail using the Finite Element Simulation platform, with a focus on key parameters such as power transfer efficiency and tolerance to misalignment. A prototype of the Wireless Power Transfer (WPT) system of 200 W strength was designed and tested to validate the design. In such configurations, even under significant misalignment conditions, considerable enhancements in the transfer power efficiency are found, which satisfies all the requirements of weight and aerodynamic for UAV operation. A new design of coil for the receiver not only makes possible friction-free energy transfer for both the landing and taking-off events but also provides reduced dimensions of the whole system so that it is applicable in critical weight, efficiency, and flexibility in terms of UAV application. This work may bring a promising solution in improving the endurance and flexibility of UAVs by efficiently utilizing wireless charging technology.

**Keywords:** Wireless Power Transfer, Coil Design, Misalignment, Compensation Circuit

1. Introduction

Recently more Unmanned Aerial Vehicles (UAVs), known as drones, are being used in many applications such as surveillance, agriculture and commercial delivery [1]. UAV can perform different tasks without human intervention in transportation, surveillance, military operations, observation, object detection and tracking [2]- [3]. However, the flight time of the drone is usually limited due to low battery capacity [4]. This results in the return of the drone to the base charging station where it needs human intervention to replace the battery in the charging connector [5]. In various applications, the primary objective of UAV is to develop a fully autonomous vehicle by making an automatic charging system. Different techniques are proposed in the literature using the actuator-based contact charging process and contactless charging system [6]. Among all the wireless charging enhances flexibility in drone functionality. Even though various wireless charging techniques are available in the literature, Inductive Wireless Power Technology (WPT) is an efficient and reliable power transmission between ground base and the UAV [7]- [8]. The drone uses electromagnetic coils to charge its battery using WPT approach. The system consists of a transmitting and receiving side, each equipped with coils to transfer power from the source to the load. The receiving coil is installed on-board, while the transmitting side is a ground station with a transmitting coil. However, poor landing effects can cause misalignment, causing power loss and affecting the charging system's efficiency. To address this issue, a charging system is proposed to mitigate poor landing effects and increase power transmission efficiency [9]. This applicant takes into various aspects into consideration majorly the additional weight of the on-board WPT systems should be minimized as much as possible. Another important aspect is the misalignment of the WPT coils due to inaccurate landing of the drone which could reduce the coupling coefficient between the coils. These two aspects have been investigated by several past works and required solutions have been presented [10]- [11]. The primary and secondary circuits of a WPT system were powered by two circular planar spiral coils [12]. The key drawbacks of this arrangement are the size and weight of the on-board components, which significantly lowers the drone's payload. To decrease the possibility of a misalignment condition between the transmitting and receiving coils, an automated landing technique is provided in [13]. In [14], a WPT charging system with a movable primary coil was introduced. To align the primary coil with the on-board secondary coil after landing, this method is based on a mechanical mechanism. The positioning system's complexity, which may cause reliability problems, is its primary drawback. Finally, a charging system based on radio frequency (RF) transmission was presented in [15]. This solution allows to improve the distance between transmitter and receiver but with a reduction of the efficiency and transferred power.

Coil design is one of the most important aspects in wireless charging. It acts in stationery charging mode in the form of a pad. Circular and rectangular coils are mostly used in EVs due to their simplicity [16]. The shape of the coil should be chosen according to its requirements such as large air gap, lightweight, aerodynamic, misalignment tolerance, high efficiency and coupling [17]. High coupling will reduce the leakage flux between transmitter and receiver. The rectangular spring coil is a crucial component in WPT systems due to its spring-like structure, ensuring reliable performance even with misalignment and movement [18]. Its rectangular shape allows for more uniform magnetic field distribution, improving power transfer efficiency. This design is ideal for applications like electric vehicles and drone charging [19]- [20]. Compact, multi-layered windings enhance inductive properties, boosting system efficiency [21]. Proper windings ensure flexibility and high efficiency, while minimizing parasitic losses and ensuring proper inductance [22]- [24]. Here, a novel rectangular helical coil design is proposed on the receiver side with the goal of making the drone landing platform of lighter weight and ergonomic design [25]. It also consists of a circular transmitter coil for charging the ground pad. Hence, a new WPT charging system was designed to achieve the objective of minimization of weight, size and misalignment for high performance in power transfer. In this paper, a new receiver coil made up of copper is proposed. This structure provides many benefits:

* The large magnetic flux captured surface enhances mutual coupling between the primary and secondary sides.
* The receiver coil is made of copper which makes it lightweight and has little effect on the weight of the UAV pad.
* Compact coil structure will be easier to install in the UAV without blocking the viewing area of the sensor.

The remaining section of this paper is organized as follows: The proposed charging system is presented in Section II. Design of Coil structure is discussed in Section III. The design of the inductive power transfer system is discussed and analyzed along with the suitable compensation and its derivation in Section IV. In Section V, the methodology is discussed, and the simulation results are shown. Finally, conclusion is summarized in Section VI.

2. Wireless Charging System for Drone

The proposed charging system is based on inductive wireless power transfer, involving the coupling of the transmitter and receiver coils. The secondary coil is mounted onboard the drone, while the primary coil is installed at the base station. To avoid reducing flight time, the onboard components must be lightweight. The drone is powered by lithium-ion batteries, which provide high power for fast charging. The battery consists of three Li-ion cells connected in series, with a nominal voltage of 11.1V and a rated capacity of 4.2 Ah. Achieving optimal efficiency and power transfer is of great importance. Another critical factor to consider is the potential misalignment of the coils, which can occur due to imperfect drone landings.

A sketch is shown below which depicts the configuration of the transmitter and receiver on the drone. The design of the charging system starts with the landing gear by satisfying the mechanical specifications, which can be achieved by offering a sufficient suspension system to enable drone flying. The landing gear's mechanical design therefore places limitations on the electrical design of the receiving coil in terms of shape, height above the ground, payload view, etc. Therefore, for the landing gear to function as a secondary coil in the electrical design, only minor modifications need to be made to its mechanical construction. The primary coil is meant to ensure the electrical standards in terms of transmitting power, efficiency, and tolerance to misalignment situations after the secondary coil configuration has been established. Different dimensions such as the air gap, number of the turns, diameter is modified to get optimal efficiency and to avoid misalignment. A rectangular helical coil is selected as the receiver. The secondary coil's design complements the gear perfectly and doesn't interfere with the cameras' viewing area or aerodynamics. The secondary coil's location, which is far from the drone frame where the electronic components are housed, is another benefit. Because of the time-varying magnetic field produced by the coil currents, this significantly lowers the risk of electromagnetic interference on the drone's electronic equipment.

A diagram of a drone

Description automatically generated

Figure 1. Configuration of the proposed wireless charging system

Figure 1 illustrates the transmitter side and receiver side, which are the two components of wireless power transfer. The power supply, power electronics, compensation topology, and Tx coil make up the primary side. Conversely, the Rx coil, compensation topology, and power electronics make up the secondary side. There is an inverter on the primary side and a rectifier on the secondary side. It is the power that excites the primary side and is fed to the secondary side from the source. The resonance frequency is used to operate the system for maximum power transmission between the primary and secondary sides. The design of the compensation network is one the most important aspects of wireless power transmission. It is done by adding capacitors in series or parallel with the primary and secondary coils and then operating at the resonant frequency of the circuit. The four compensation types commonly used are series-series(SS), series- parallel(SP), parallel-series(PS) and parallel-parallel(PP). The compensation scheme impacts circuit behavior, features like capacitor and inductors' maximum voltage and current values, primary circuit requirements, secondary circuit output behavior, and coupling and load effects. In the proposed charging system SS compensation is used, which is an established and analyzed in detail, and the expression for the input current, output current, efficiency are obtained. A SS Compensation network is chosen as it precisely aligns coils and is intended to transfer a nominal power at the maximum mutual inductance. The input voltage, efficiency, and current of the SS topology will all be higher when the mutual inductance is at its maximum.

3. Design of IPT system

The IPT system for drone WPT includes an AC power source, PFC converter, secondary compensation circuit, rectifier, and battery. Designing the power electronics and magnetic coupler depends on battery specifications. With the use of two coils operating as a loosely coupled transformer and magnetic resonant coupling, WPT technology facilitates the transfer of electrical energy. Figure 2 gives the whole electrical circuit of a WPT system. The self-inductances L1 and L2 are present in the two connected coils. The losses in the coils are modeled by the mutual inductance M and the self-resistances R1 and R2. To reduce the AC losses due to proximity and skin effects a copper wire is used to create the coils

A diagram of a circuit

Description automatically generated

**Figure 2.** Electrical circuit of a WPT charging system with SS compensation network

Compensation networks are usually added to obtain resonance condition between the transmitter and the receiver and to maintain proper electrical performance of the system. Some basic requirements for proper functioning of the compensation network are the primary and secondary inductances which resonate with the compensating capacitor to produce reactive power, hence is necessary for the inductances to produce a sufficient magnetic field. Therefore, reducing the power supply's volt-ampere (VA) rating is the fundamental purpose of a primary coil's compensation. To optimize the secondary coil's capacity for power transfer, compensating eliminates the inductance. At the transmitter end, the inverter is used to produce a high frequency square wave input voltage(V) from the DC source. At the receiver side this high frequency voltage is first rectified by the rectifier. This DC output voltage is then filtered by the low pass filter composed of capacitor ands series inductance. The primary side is simplified with a sinusoidal voltage source,Vs and a small internal resistance,Rg The load is simplified to an equivalent resistance,RL. For calculating the system parameters, such as L1, L2, M equivalent circuit is compressed to simplified circuit. The values of C1, C2 calculated at resonant frequency for the selected compensation network.

A diagram of a circuit

Description automatically generated

**Figure 3.** Simplified Equivalent circuit with SS Compensation

To derive the equations of efficiency, an equivalent circuit of SS topology model is shown in Figure 3. This research considers the fundamental component of voltage and current for simplicity. Using Kirchhoff’s Voltage Law (KVL), following equations can be derived using Figure 4.

(1)

(2)

where and . The SS topology model is shown in Figure 3, where Z1 and Z2 represent the impedances of the transmitter and receiver sides, respectively, and Vs is the source voltage put to the transmitter resonator at resonance frequency (ω). It is possible to express the mutual inductance (M) between the transmitter and the receiver in terms of coil inductances and coupling coefficient k , which is provided by,

(3)

Note that a smaller distance between the transmitter and reception coils, and vice versa, is represented by a higher coupling coefficient. By simplifying (1) and (2), the currents flowing through the load and the source side are computed.

and (4)

Output power at given load and the efficiency can be expressed by (5),

(5)

Additionally, in SS topology, the resonance occurs when the reactive impedance of the coil becomes zero and the reactance of the coil approaches to zero, then resonance frequencies of the transmitter and receiver become,

(6)

Large loads on general-medium-sized UAVs are common in industrial production and other sectors. Typically, a mid-sized UAV's landing gear consists of two T-shaped frameworks. Make sure the magnetic structure can adjust to the unique form of the UAV and meets the standards of lightweight and misalignment-tolerant performance, a rectangular helix coil is suggested to be incorporated to reduce weight on the drone design illustrated in Fig. W. The most basic design includes a receiver coil at the landing gear of the drone, which is wired in series. This guarantees that the flow and trajectory in side, the receiver coils are placed directly in the axis of the primary transmitting coil. This configuration strengthens the magnetic field in the middle portion and addresses the issue of poor coupling magnetic field strength when a receiving coil descends into the center area. The problem is solved by the circular transmitting coil design. tolerance for rotational misalignment during UAV landing. The configuration of this design enables an efficient and lightweight design and enables ease of landing.

The proposed WPT system and system parameters are simulated under different operating conditions. A high-frequency inverter of 85Khz of voltage output 120 V is fed into the primary transmitter coil of Inductance 430uH to induce the modified receiver coil of inductance 4.3uH. A diode H-Bridge rectifier converts the secondary current and voltage to a DC signal that charges the battery. Individual inductances (Ls, L2p, and M) are obtained from the following calculations to determine the parameters for system design. It can be calculated as follows: Vo=12 V, P=200 W

The output resistance is calculated using the formula

(6)

The load resistance is expressed in terms of

(7)

The secondary RMS voltage and current can be evaluated using

(8)

(9)

The secondary inductance can be calculated using the quality factor, load resistance and resonant frequency. Therefore, the secondary inductance is evaluated using the formula

(10)

The primary voltage is expressed as:

(11)

The primary current can be illustrated as;

(12)

The mutual inductance is

(13)

Where , , and are the secondary, primary, and mutual inductance respectively.

System Parameters

Table I provides a summary of the system parameters for an LC compensated IPT system, including primary and secondary currents and voltages. Table II gives the summary of the dimensions and design characteristics of the proposed system

**Table I**. System parameters

|  |  |
| --- | --- |
| **Parameters** | **Values** |
| Output Voltage (Vo) | 12V |
| Power of the drone(P) | 200W |
| Output Resistance (Ro) | 0.72Ω |
| Load Resistance (Rl) | 0.58Ω |
| Primary RMS Voltage (Vprms) | 120V |
| Secondary RMS Voltage (Iprms) | 10.77V |
| Primary RMS current (Iprms) | 1.66A |
| Secondary RMS current(Isrms) | 18.5A |
| Primary Inductance (Lp) | 430µH |
| Secondary Inductance (Ls) | 4.344µH |
| Mutual Inductance(M) | 12.10µH |
| Coupling Coefficient (K) | 0.28 |

**Table II.** Coil design Parameters

|  |  |  |
| --- | --- | --- |
| Parameters | Transmitter | Receiver |
| Air Gap between windings(mm) | 1.2 | 1.5 |
| Pitch(mm) | 0 | 0 |
| No of turns | 33 | 6 |
| Start helix radius(mm) | 100 | 100 |
| Radius change(mm) | 6.1 | 6.1 |
| Core thickness(mm) | 3 | 2 |
| Core diameter(mm) | 6 | 4 |

A diagram of a plane

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1. Plane view

A blue square with a rainbow colored circle

Description automatically generated with medium confidence

1. Top view

A computer screen shot of a computer

Description automatically generated

1. Side view

A blue square with a rainbow colored circle

Description automatically generated

1. Top view Receiver coil center position

A computer generated image of a rainbow colored circle

Description automatically generated with medium confidence

(e)Receiver coil displaced towards negative Y-axis

A colorful diagram of a solar system

Description automatically generated with medium confidence

(f)Receiver displaced towards X-axis

A blue square with a rainbow circle and a swing

Description automatically generated with medium confidence

(g) Receiver coil displaced towards positive Y axis

**Figure 4**. Simulated rectangular helical receiver with Circular Transmitter at different views

The WPT system is required to charge a battery with a capacity of 4200mAh, a nominal voltage of 11.2V and a maximum charging voltage of 12.6V. Compensation in primary coils minimizes volt-ampere rating, while in secondary coils, it cancels inductance to maximize power transfer capability. The maximum efficiency of a WPT system can be determined by the coupling coefficient and quality factor. In this section, the performance of WPT is evaluated according to the different internal and external factors related to the receiver and transmitter position. A system for wireless power transmission was designed in order to measure the effect of inductive coupling from a transmitter coil to two receiver coils formed as rectilinear helices. The model was made in Finite Element Software to analyze magnetic flux interactions and test whether the system can be used for effective wireless charging and for obtaining the magnetic field value. The base unit of the set up was a transmitter coil with diameter 3 mm, consisting of 33 turns. On the other hand, each receiver coil had a diameter of 2 mm and 6 turns but was placed at different positions above the transmitter in order to observe the change in flux due to the geometric arrangement. The system took into consideration an eddy current solution type to reflect the back and forth electromagnetic activity between the coils. Terminal ends of transmitter and receiver coils were applied with uniform current excitations to provide an identical excitation throughout the entire system. A rectangular sheet was included in the model geometrically between the transmitter coil and the receiver coil for the purpose of magnetic field visualization and flux analysis in the system. In the configuration where receiver coils were placed at various spatial angles relative to the transmitter coil, the induced inductance was measured to be 430 µH which implies that the coils present configuration has a considerable magnetic coupling. This apparent inductance value suggests that there could be good prospects of wireless charging as there is reasonable magnetic coupling. The rectangular sheet was able to show detailed flux regions explaining the magnetic field and also showing how different positions of the receiver coil affect the inductive coupling in the system. The two-coil receiver system is shown. Using Maxwell software, the magnetic field evolution is studied and this is shown at different positions of the receiver coil. The built-model has one coil transmitter which has the same dimensions, cited in Table II. Similarly, the receiver coil has been designed with the same dimensions. As shown at all positions, the quantity of magnetic field in receiver coil is very high as the red color is very concentrated in the centers of the coil. This is more related to the superposition of the transmitter and the two receivers. The concentration of the red color in the two receiver coils is related to the internal magnetic field that appears between two receiver coils. As shown, 5296µT is the maximum magnetic field value and 10.496 µT is the minimum value. This form of magnetic field is shown in every figure.

**4. Simulation and Hardware Results and Discussion**

The simulation results of the inductive wireless power transfer using SS compensation is shown in the Figure 5(a)-(c). The voltage and current waveforms at different coupling coefficients is illustrated. At different coupling coefficients, voltage and current waveforms of the primary side coil, secondary side coil and battery are obtained.

A blue line graph with numbers

Description automatically generated with medium confidence A graph of a bar graph

Description automatically generated with medium confidence

1. (b)

A graph showing a number of waves

Description automatically generated A graph showing a number of times

Description automatically generated with medium confidence

(c) (d)

A graph showing a number of times

Description automatically generated A graph showing the time and time

Description automatically generated with medium confidence

(e) (f)

**Figure. 5** Simulation Results at k=0.2 (a) Primary side current (b) Primary side voltage (c) Secondary side Current (d) Secondary side voltage (e) Battery Current (f) Battery Voltage

A graph showing a waveform

Description automatically generated A graph of a bar chart

Description automatically generated with medium confidence

1. (b)

A graph showing a number of waves

Description automatically generated with medium confidence A graph showing time and time

Description automatically generated

(c) (d)

A graph showing time and speed

Description automatically generated A graph showing a number of seconds

Description automatically generated

(e) (f)

**Figure. 6.** Simulation Results at k=0.1 (a) Primary side current (b) Primary side voltage (c) Secondary side Current (d) Secondary side voltage (e) Battery Current (f) Battery Voltage

A graph showing a number of waves

Description automatically generatedA graph showing time and seconds

Description automatically generated

1. **(b)**

A graph showing a number of times

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Description automatically generated with medium confidence

**(c) (d)**

A graph showing the time

Description automatically generated with medium confidenceA graph showing a number of times

Description automatically generated

**(e) (f)**

**Figure. 7** Simulation Results at k=0.3 (a) Primary side current (b) Primary side voltage (c) Secondary side Current (d) Secondary side voltage (e) Battery Current (f) Battery Voltage

As illustrated in Figure 6 and Figure 7, the coupling coefficient effects the power transfer as observed in the voltage and current waveforms. Deviation from the optimal coupling coefficient introduces a noticeable ripple in the current waveform and distorts the waveform and introduces harmonics in the compensation and coupling system. Thus maintaining an optimal coupling coefficient is important to ensure maximum power transfer with lower harmonic distortion. The drone setup consists of a flight controller, 11.1V 4200 mAh battery pack with a BMS module, GPS module and quad drone frame. A high frequency inverter consisting of IRF3205 MOSFET switches and IR2110 Gate driver is built. A 200W, 20A DC-DC buck converter is also used. Along with it a BLDC motor is selected for drone flight, Pixhawk 2.4.8 drone flight controller is also installed in the setup. A KBPC 3510 bridge rectifier is also used.

A drone on a table in a room

Description automatically generated

Drone

High Frequency Inverter

Transmitter Pad

(a)

A drone on a table

Description automatically generated

Drone

Receiver Coil

(b)

Figure 8. (a) Drone Setup (b) Drone Receiver Coil

The primary side current is represented with a peak-to-peak amplitude which indicates that the current is flowing through the coil. The coil is resonating with the compensation resulting in steady oscillating current. The primary side voltage indicates a stable high-switching frequency obtained from the inverter which is given to the primary coil. The secondary current has a smaller amplitude compared to the primary side due to weak coupling coefficient. The secondary voltage has a reduced amplitude but is the induced voltage produced at the secondary side.

A screenshot of a graph

Description automatically generated

Battery Current

BatteryVoltage

Receiver Coil Current

Receiver Coil Voltage

Transmitter Coil Current

Transmitter Coil Voltage

(a)

A screenshot of a computer

Description automatically generated

Transmitter Coil Voltage

Transmitter Coil Current

Receiver Coil Voltage

Receiver Coil Current

BatteryVoltage

Battery Current

(b)

Figure 9. Hardware Results (a) Measured Waveform (b) Zoomed Portion of (a)

The battery current remains low due to low power transfer from primary to secondary whereas the battery voltage remains constant. The waveform view is illustrated in figure 9, it is observed that there is a noticeable change in receiver coil voltage due to harmonic distortion primarily due to harmonics introduced due to change in alignment and separation distance. However current THD is greatly minimized due to compensation network and inductive components in the WPT system. DC voltage and current waveform output of the full bridge rectifier is illustrated in figure 9, maintaining a constant output at 18 volts to the Buck Converter which is stepped down to the nominal charging voltage of 12 volts for the 3-cell lithium-ion battery pack.

5. Conclusions

This paper outlines a novel approach to providing UAVs with a lightweight, aerodynamic, and misalignment insensitive wireless charging system to solve the problem of extending UAV endurance and increasing its flexibility of operation. This new concept of rectangular helical coil structure in conjunction with UAV landing gear effectively realizes weight decrease, flow field optimization, and high coupling coefficient despite the misalignment of load. The comprehensive design and the verification based on a 200W prototype prove the system’s suitability of maintaining high power transfer coupled with key specifications for UAVs. The proposed design solves the problem of energy transfer without friction during both landing and taking off thus suitable for UAV’s where weight, efficiency, and operational flexibility are of great importance. This work beneficently serves the scientific development of wireless charging for UAVs as the possible ways to enhance their capacities have been studied.

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