

Letters

Compact and Free-Positioning Omnidirectional Wireless Power Transfer System for Unmanned Aerial Vehicle Charging Applications

Shuai Wu ¹, Student Member, IEEE, Chunwei Cai ², Member, IEEE, Xichen Liu, Wenping Chai ³, Member, IEEE, and Shiyang Yang ⁴

Abstract—Compact design in receiver and misalignment tolerance are two basic considerations for practical applications of wireless power transfer (WPT) in unmanned aerial vehicles (UAVs). To balance these two requirements, a novel magnetic design with the composite interval-acted parallel- & vertical-flux throw, orthogonal two-dimensional flux pick-up, and power-flow summed output is proposed in this letter. The resulting magnetic structure includes a target-shaped transmitter and two quadrature receivers, and the transmitter consists of four annular-type coils which are magnetized in a bipolar mode, making it possible to form a magnetic field with a parallel- and vertical-flux complementary distribution. Moreover, by integrating two orthogonal receiving coils into one receiver, a stable summed output current can supply the UAV onboard load with only a small size receiver. A UAV WPT prototype is established based on the proposal. The results show that the prototype can deliver 325 W with a system efficiency of 86%, and especially the variation of the output current is within ± 0.76 A for different landing positions and directions. The overall system efficiency is from 87.3% down to 83.1%.

Index Terms—Complementary flux, multidimensional pick up, unmanned vehicles vehicle (UAV), wireless power transfer (WPT).

I. INTRODUCTION

UNMANNED aerial vehicles (UAVs) are one of the most flexible and adaptable platforms for undertaking inspection, delivery, and search tasks [1]. However, limited by battery capacity, the endurance time and cruising range are still too short for many applications, which has become the bottleneck in the further development of the UAV field. The traditional of

wired recharging or battery swapping is low operating efficiency, resulting in the inflexibility of UAVs.

Wireless power transfer (WPT) technology not only realizes the flexibility of relay recharging for the UAVs but also promotes the autonomous and intelligent level of UAV applications. Compared with WPT systems for electric vehicles and other applications [2], [3], the special structure and the limited payload of UAVs will bring more challenges to the adoption of the WPT system. To meet the special requirements of UAV WPT applications, some efforts have been made. In [4], a three-phase tightly coupled UAV WPT system is developed, which can deliver 150 W with a 72% dc-battery efficiency. This system characterizes by strong coupling and low electromagnetic interference, but it needs to modify the landing gear structure and is sensitive to the receiver position. To adapt the receiver to the original special shape of UAV, the face-to-face circle or rectangle coil structure is a promising solution and is studied by some research teams [5]–[7]. In [5], a magnetic structure with a nonpolarized transmitting coil and an air-cored receiving coil wrapped around the UAV's shield is proposed to transfer 13 W at a dc-battery efficiency of 60%. This proposal makes good use of the UAV structure and has the advantage of a simple structure. Unfortunately, it is challenging to develop high-power WPT systems under electromagnetic safety constraints. In [6] and [7], the air-cored receiving coil is placed under the body of UAV. In this way, the number of turns of the receiving coil will not be limited, and the transmission power capacity of the system can be adjusted arbitrarily. However, the UAV's onboard equipment will suffer from strong leakage magnetic flux interference [8]. In addition, once the belly of UAV fuselage is occupied by the receiver, the carrying of functional equipment (such as cameras) will be hindered.

To overcome those drawbacks, the authors develop a novel orthogonal magnetic structure for UAV wireless charging [9] and have carried out practical application research [10]. Although the designed system can adapt to the special shape of UAV well and the power transmission capacity is large enough, in long-term research, the authors realize that the occupied volume of the receiver is still large. And more importantly, the antimisalignments performance needs improvement.

The inevitable misalignments between the transmitter and receiver, including the lateral, longitudinal, and angle deviations,

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Shuai Wu is with the School of New Energy, Harbin Institute of Technology, Weihai 264209, China, and also with the School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China (e-mail: wushuai013@163.com).

Chunwei Cai, Xichen Liu, and Wenping Chai are with the School of New Energy, Harbin Institute of Technology, Weihai 264209, China (e-mail: caichunwei@hit.edu.cn; 1270346720@qq.com; wpchai@163.com).

Shiyang Yang is with the School of Electrical Engineering and Automation, Harbin Institute of Technology, Harbin 150001, China (e-mail: syyang@hit.edu.cn).

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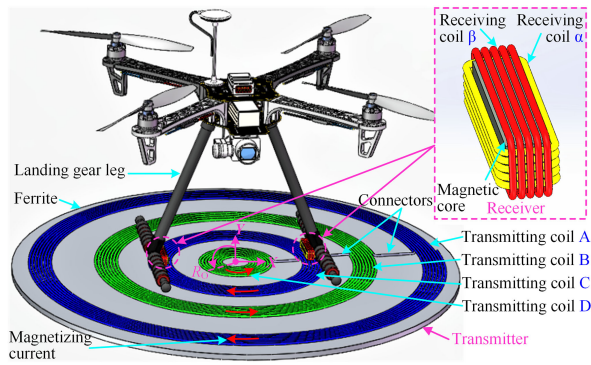


Fig. 1. General overview of the proposed magnetic structure.

result in varied output power and impaired efficiency, becoming another major impediment for the application of UAV WPT technology. To deal with the misalignments, a frustum shape charging platform is proposed for guiding a UAV landing into a fixed location [11]. This scheme has a simple structure but needs to adjust the UAV structure. Another possible solution is using a movable transmitter for aligning the transmitter to the receiver [12]. There will be a receiver position detection system and a movable mechanical part, becoming more complex and less reliable. Using a coil array transmitter is also an effective approach to realize reliable charging for a misaligned load [13], [14]. When misalignment happens, the alternative coils closest to the load can be activated to transfer power. However, accurate load position detection and multiple coils control will undoubtedly increase the complexity and cost of the system. As an alternative, the idea of multiphase magnetic-flux pickup, used in the other applications [15]–[17], cannot only simplify the structure and modulation complexity of the transmitter but also improve the flux utilization and the output stability under misalignment. This idea may also have a positive effect on promoting the advancement of UAV WPT systems.

The size and weight of the receiver, power transmission capability, and antimisalignment performance are the key factors to determine the applicable scope of UAV WPT system. Therefore, compact receiver design and two-dimensional (2D) reliable wide-area powering are the key design objectives for UAV WPT applications. As an alternative magnetic structure to satisfy all the two objectives, a novel magnetic coupler is proposed in this letter. The next section will introduce the proposed magnetic structure and its operation principle.

II. MAGNETIC STRUCTURE PROPOSAL AND ANALYSIS

A. Magnetic Structure

The physical structure of the proposed magnetic coupler is depicted in Fig. 1. On the transmitting side, four annular-type coils (transmitting coils A–D) are included, which are placed on the upper surface of a backing ferrite. The radius of the four transmitting coils decreases in turn, resulting in the transmitter being shaped like a “target.” The winding directions of transmitting coils are different, that is, transmitting coils A and C are wound clockwise, and transmitting coils B and D are wound counterclockwise. The four coils are successively connected in

series from the outside to the inside and driven by a single ac. Therefore, the magnetizing current flows of any two adjacent transmitting coils are opposite, which creates conditions for the simultaneous generation of parallel and vertical magnetic flux over the transmitter, and further ensures the free-positioning omnidirectional power transfer. It should be mentioned that this design takes four-transmitting-coil as a basic case to illustrate the operation principle of the proposal. The number of coils can also be expanded according to the demand for the antimisalignment range in practical application.

In the receiving-side, two identical receivers are mounted on the cross bars at bottom of the two landing gears. The two receivers are used to improve the system power level. If the required transmission power is small, one receiver can also operate. Each receiver consists of a rectangular magnetic core and two orthogonal receiving coils (receiving coils α and β). Since the fragile ferrite is easy to be damaged during the UAV landing, the magnetic core on the receiving side needs to use a flexible magnetic material, such as Fe-based nanocrystalline ribbons [10]. The cross section of receiving coil α is parallel to the transmitting plane, whereas the cross section of receiving coil β is perpendicular to the transmitting plane so that the two receiving coils can be effective for vertical and parallel magnetic flux component pickup, respectively. In addition, the two receiving coils can be decoupled from each other. As shown in Fig. 1, the proposed magnetic structure breaks through the traditional face-to-face magnetic mechanism applied in UAV WPT applications. Such a design would enjoy the following merits.

- 1) The receiver has compact size and is easy to be installed on an UAV under the premise of ensuring medium- and high-power transmission capacity.
- 2) The drive and control of transmitter is simple because it only needs one excitation source and does not need complex modulation methods.
- 3) The landing platform can be flat without any auxiliary mechanical mechanism, and because the magnetic coupler shows misalignment tolerance (described later), the UAV can land easily and freely.
- 4) It has safe magnetic field performance. The main magnetic flux is away from UAV’s fuselage, since the receiver is close to landing platform, and the bipolar magnetizing approach shapes the magnetic field.

B. Magnetic Field Distribution and the Free-Positioning Omnidirectional Power Transferring Ability

The magnetic field distribution on a cross section generated by the transmitter is simulated by ANSYS Maxwell and is demonstrated in Fig. 2. As illustrated in Fig. 2(a), the parallel- and vertical-flux are distributed at intervals along the horizontal direction, and complementary to each other. Meanwhile, as shown in Fig. 2(c), the receiver can pick up both parallel and vertical magnetic flux. With the complementary characteristics of parallel- and vertical-flux thrown by the transmitter, the summed collected powers from the two orthogonal receiving coils in each receiver can be stable when it is offset horizontally. Moreover, the transmitter owns a ring shape, so the impacts of angle misalignment can also be avoided.

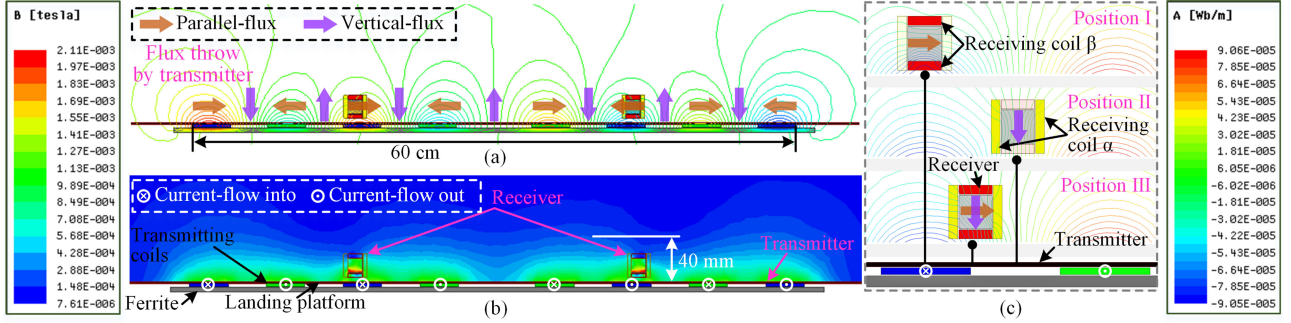


Fig. 2. Magnetic field distribution of the proposed magnetic coupler on a cross section. (a) Magnetic flux thrown by transmitter. (b) Magnetic flux density. (c) Magnetic flux picked up by receiver at different positions.

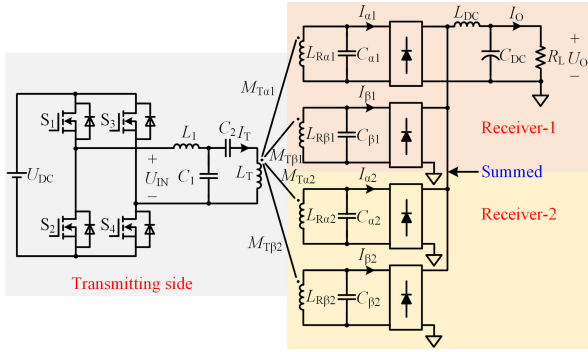


Fig. 3. Circuit topology of the UAV WPT system.

The magnetic flux density distribution is shown in Fig. 2(b). It can be concluded that magnetic field distribution is reasonably uniform, and the thrown magnetic flux of the transmitter is close to the landing platform. Therefore, the proposed magnetic structure presents great advantages to improve misalignment tolerance and avoids electromagnetic interference on UAV compared with the traditional face-to-face structures.

III. CIRCUIT DESIGN AND ANALYSIS FOR THE PROPOSED MAGNETIC STRUCTURE

A. Power Circuit Topology

The circuit topology of the free-positioning omnidirectional WPT system is shown in Fig. 3. The transmitting resonant tank is driven by an H-bridge inverter powering by a dc voltage source U_{dc} . The inductance-capacitance-capacitance (LCC) compensation circuit composed of L_1 , C_1 , C_2 is employed in transmitting side to supply a constant current I_T for the transmitter. A capacitor C_{ij} ($i = \alpha, \beta$ and $j = 1, 2$) is connected in parallel to each receiving coil, to form a constant current I_{ij} . The collected powers from the four receiving channels have flowed to their corresponding rectifiers, which are connected in parallel to provide a summed output. L_T and L_{Rij} are the self-inductance of the transmitting coil and the receiving coils, respectively, and M_{Tij} is the mutual inductance between the transmitting coil and receiving coil.

B. Equivalent Circuit Model

The compensation network is designed to be resonant at angular frequency ω , the parameters of compensators should meet the following equation:

$$\omega = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{(L_T - \frac{1}{\omega^2 C_2} - \frac{X_{rec}}{\omega}) C_1}} = \frac{1}{\sqrt{L_{Rij} C_{ij}}} \quad (1)$$

where the X_{rec} is a reflected reactance of the receiving side circuit back to the transmitter, the magnitude of which is determined by the coupling of each channel, as shown in (2).

$$X_{rec} = \omega^2 \left(\frac{M_{T\alpha 1}^2}{L_{R\alpha 1}} + \frac{M_{T\beta 1}^2}{L_{R\beta 1}} \right) + \omega^2 \left(\frac{M_{T\alpha 2}^2}{L_{R\alpha 2}} + \frac{M_{T\beta 2}^2}{L_{R\beta 2}} \right) \quad (2)$$

The resonant compensation network is a band-pass filter, so the fundamental analysis method can be adopted to model the circuit. Then the magnetizing current is derived as follows:

$$I_T = \frac{2\sqrt{2} U_{DC}}{\pi \omega L_1} \quad (3)$$

It can be seen that the magnetizing current is load independent. And the output current of the each fully tuned parallel resonant tank can be expressed as follows:

$$I_{ij} = \frac{M_{Tij} I_T}{L_{Rij}} \quad (4)$$

The power flow of each pickup channel is summed behind rectifiers, so the output current of the whole system can be obtained as follows:

$$I_O = \frac{8 U_{DC}}{\pi^2 \omega L_1} \left(\frac{|M_{T\alpha 1}|}{L_{R\alpha 1}} + \frac{|M_{T\beta 1}|}{L_{R\beta 1}} + \frac{|M_{T\alpha 2}|}{L_{R\alpha 2}} + \frac{|M_{T\beta 2}|}{L_{R\beta 2}} \right) \quad (5)$$

C. System Characteristics

For the proposed magnetic structure, a core principle of parameter design is to ensure that the self-inductances of the two receiving coils in each receiver are approximately equal, and the amplitudes of mutual-inductances between the two receiving coils in each receiver and the transmitter are approximate. This can be achieved by using the parameter scanning method of any finite element simulation tool, and the mutual inductances

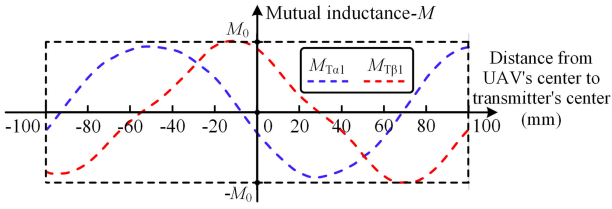


Fig. 4. Variations of the $M_{T\alpha 1}$ and $M_{T\beta 1}$ with various receiver positions when rolling 0° .

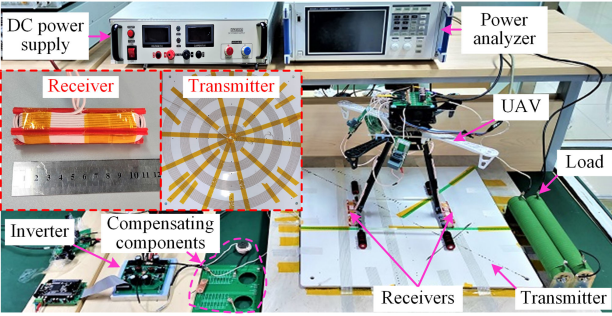


Fig. 5. Prototype of a UAV WPT system with the proposed magnetic structure.

$M_{T\alpha 1}$ and $M_{T\beta 1}$ to the horizontal misalignment in this design are shown in Fig. 4, whereas the M_0 is the amplitude of $M_{T\alpha 1}$ and $M_{T\beta 1}$. It is shown that the distributions of $M_{T\alpha 1}$ and $M_{T\beta 1}$ vary by cosine and sine, respectively. The $M_{T\alpha 2}$ and $M_{T\beta 2}$ are similar as described above, and will not be repeated here.

Since the two mutual inductances in each receiver present sine and cosine distributions, respectively, the two subterms in (2) can remain constant. This ensures that the reflection impedance is not affected by the misalignments, and resonance in the transmitting side is independent of the misalignments. In addition, the values of compensation inductances are constant, and the self-inductances are not affected by misalignments. The core factor affecting the stability of output current is the mutual inductances, which is known from (5). Fortunately, the vertical- and parallel-flux components emitted by the proposed magnetic coupler are complementary on the landing platform. This makes a complementary output of the two orthogonal receiving coils, to ensure the relative stability of the summed output of each receiver.

IV. EXPERIMENTAL VERIFICATION

A. Experimental Prototype

A UAV WPT experimental prototype is established to validate the effectiveness of the proposal, as shown in Fig. 5. In this design, the outer radius of the maximum transmitting coil is chosen as 600 mm, which can be further extended for greater misalignment tolerance. The size of receiver is $105 \times 15 \times 15$ mm in size, resulting in 184 g in weight, which is size- and weight-insignificant for medium- and high-power UAVs. The inverter switches at 50 kHz, and the input dc voltage is 150 V.

B. Experimental Results

In the well-aligned case, the system working waveforms are measured as shown in Fig. 6(a). The output voltage and current of

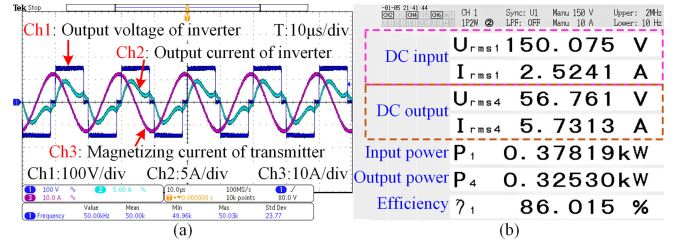
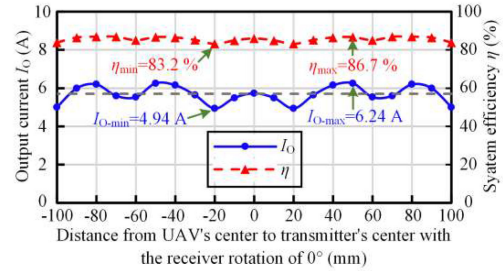
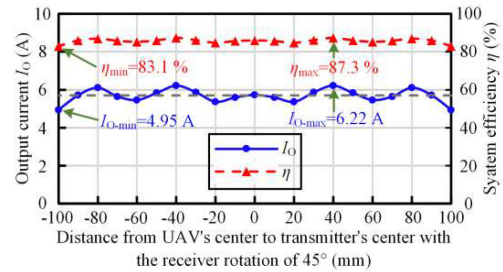


Fig. 6. Experimental results of prototype at well-aligned case. (a) Working waveforms. (b) System power.



(a)



(b)

Fig. 7. System output current and efficiency with various receiver positions. (a) Rotate 0° . (b) Rotate 45° .

circulating in the inverter. The system power and efficiency are measured by a power analyzer as shown in Fig. 6(b). The output current is 5.7 A, and output power reaches 325.3 W with a system dc-to-dc efficiency of 86%.

The output current and system efficiency are measured in the misalignment case, as shown in Fig. 7. Two angular misalignment cases, namely 0° and 45° , are considered because the proposed magnetic coupler is asymmetrical structure. It shows that the output current I_O is around 5.7 A with a variation of ± 0.76 A. Meanwhile, the system efficiency ranges from 83.1% to 87.3%. Therefore, rated current output and constant efficiency can be achieved when the UAV lands freely on the recharging platform.

V. CONCLUSION

In this letter, a novel WPT system with a target-shaped transmitter and a compact receiver is proposed to achieve free-positioning omnidirectional powering for UAV charging applications. The design idea of complementary acted and summed output of parallel- and vertical-flux is adopted in the development of magnetic structure, which not only ensures a smaller receiver size but also brings better antimisalignments performance. Besides, the proposed magnetic structure can also

reducing the leakage magnetic flux interference to the UAV. A 325 W prototype is established to validate the proposed design. The experimental results show that the proposal has high output stability with angle misalignment and horizontal misalignment.

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