Letters

A 500-W Wireless Charging System With Lightweight Pick-Up for Unmanned Aerial Vehicles

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***Abstract*—This letter develops a wireless charging system based on a novel orthogonal magnetic structure and primary-side power control to simplify the structure and reduce the weight of on-board pick-up for recharging the unmanned aerial vehicles (UAVs). The novel magnetic structure has a polarized transmitter with a flat U-type core and a perpendicular air-cored receiving coil, guaranteeing the magnetic flux operation space away from a UAV body by coil structure itself and also reducing the weight of a magnetic receiver. The power flow to the battery is controlled by the primary side based on charging current and voltage feedback by pick-up. Simulations based on ANSYS Maxwell and experiments are carried out to validate the proposal. The weight of a magnetic receiver is 130 g. And the system can deliver 500 W with a dc-to-battery efficiency of 90.8%, meanwhile 10 A constant current/50 V constant voltage charging for 12S lithium-ion battery is achieved by the closed-loop system.**

***Index Terms*—Magnetic structure, primary-side control, unmanned aerial vehicles (UAVs), wireless charging.**

I. Introduction

Wireless charging technology has been successfully applied in numerous situations [1]–[3], and it will also be a revolutionary way to automate the recharging process for unmanned aerial vehicles (UAVs). The operation efficiency and utilization rate of the UAVs can be effectively improved by using unattended-operation recharging base stations. Due to the special structure and the limited payload of UAVs, the adaptability to UAV's structure and weight of pick-up (which includes a receiver of a magnetic coupler and a pick-up circuit) are two vital indexes in the design of a UAV wireless charging system. In order to reduce the weight and improve structure rigidity of the receiver, avoiding the use of ferrite cores at the receiver for UAV wireless charging has been a consensus [4]–[10], since the ferrites are heavy and fragile. Therefore, the magnetic design for wireless charging of UAVs focuses more on the design of flux pattern, structure, and installation position of the receiving coil. In [4], the nonpolarized transmitter and a circular receiving coil installed on one side of the UAV body were adopted to deliver 51 W to UAV with 63.4% dc–dc efficiency. Similarly, Kumar *et al.* [5] wound the circular receiving coil around the UAV body, and the system can transfer 35 W with a 71% dc–dc efficiency. Campi *et al.* [6] placed a circular receiving coil under the body of UAV, and the transmission power of the system was 70 W with 89% link efficiency. If the receiving coil is mounted on the UAV body, there will inevitably be a large air gap between the transmitter and receiver, which will lead to very weak coupling between them. More importantly, magnetic flux will enter the UAV body. As the EMI study in [6], even if the receiving coil is installed under the body of UAV, the leakage flux does interfere with the equipment in the UAV body. In order to strengthen coupling ability of magnetic coupler, Ke *at al.* [7] wound the receiving coil at the bottom of the landing gear leg. However, the adverse effect of leakage flux to gimbal and camera or other sensors, which are usually installed under the UAV bodies, is also inevitable. Although leakage flux can be effectively screened by an aluminum sheet, it will seriously increase the weight of pick-up. A suitable solution, proposed in [8], installed a small receiving coil on the bottom of one of the landing gears leg. There was very small magnetic field operation space to cause less influence with UAVs. However, the magnetic coupler has better adaptability only for low-power UAVs, since the receiving coil must be very small, depending on the location of the installation, which leads to poor capability to capture the flux. Therefore, better magnetic structure needs to be proposed for the UAV wireless charging system.

In the wireless charging system, the power controller acts as a battery charger to regulate the output current and voltage to the battery. Usually, the power controller can be integrated at the pick-up to achieve power regulation for UAVs powered by a 3S or 4S lithium-polymer battery [8], [9]. In this letter, the development of a 500-W wireless charging system is considered to recharge the UAVs with a 12S (the nominal voltage is 44.4 V) and 12 000 mA·h lithium-polymer battery, which is often used in medium-sized UAVs, such as DJI MG-1. If the methods to control power flow at the pick-up are applied to this design, the size and weight of the power controller will be larger, and the heat dissipation is also difficult to be solved for highly integrated UAVs. To minimize the size of the pick-up circuit, the methods

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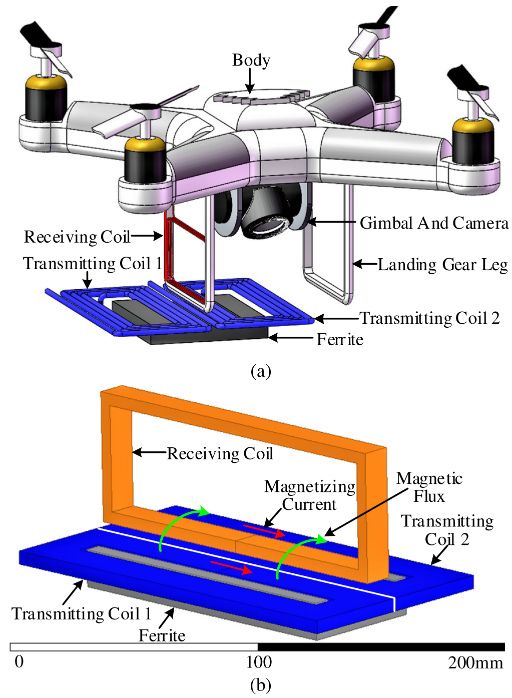

Fig. 1. (a) General overview of the UAV wireless charging system. (b) Proposed orthogonal magnetic structure for UAVs.

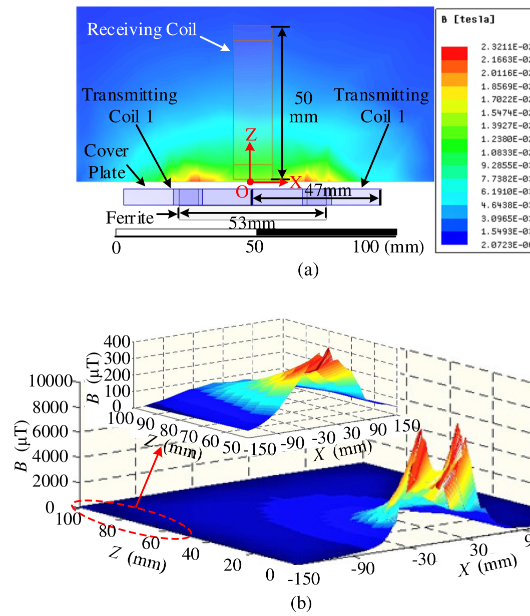

Fig. 2. (a) Magnetic flux density in on a cross section. (b) Peak leakage magnetic flux density *B* distributions in the *XZ* plane.

of primary power control have been developed for implanted medical devices [3]. Similarly, if the charging power flow can be controlled by the primary side directly, the utility of the UAVs wireless charging system will be significantly improved. Therefore, the proposal to control power flow directly from the primary is considered in this letter.

Due to the limited payload of UAVs, the on-board pick-up must be light. To achieve the purpose, this letter proposes an orthogonal magnetic structure, which can not only deliver enough power to UAVs, but also provide lightweight performance of magnetic receiver. The method of primary-side power control is used to further reduce the weight of the pick-up circuit. The proposed magnetic structure is verified via ANSYS Maxwell simulations. A 500-W wireless charging prototype for UAVs is set up to validate the proposal.

II. Proposal and Analysis of the Orthogonal Magnetic Structure

The general overview of the proposed orthogonal magnetic structure for UAVs wireless charging system is shown in Fig. 1(a). It should be noted that the graph is only used to show the magnetic structure, it is not scale practically. The air-cored receiving coil is wound around one of the landing gear legs. The receiving coil is nearly perpendicular to the transmitting pad, which breaks the traditional face-to-face magnetic structure. This structure provides many benefits: first, it can minimize the air gap between the receiving coil and the transmitting pad to strengthen the coupling ability. Second, there is a large magnetic flux captured surface, which improves the adaptability to medium- and high-power UAVs. Moreover, it is easy to be installed since the receiving coil only needs to be embedded in the leg of the traditional UAVs.

As the receiving coil is placed vertically, to ensure that the thrown magnetic flux by transmitting pad goes through the receiving coil, the magnetic field of transmitting pad should be parallel to its surface. The typical flux distribution pattern used in wireless charging can include both nonpolarized field and polarized field. Among them, the polarized transmitting pad, such as double-D pad [2], can throw horizontal magnetic flux at the center of the transmitting pad. In this letter, the polarized pad is adopted for a transmitter, and the magnetic structure for UAVs wireless charging is shown in Fig. 1. A flat U-shaped ferrite core, instead of the I-shaped core, is used to guide the main flux. Two transmitting coils are wound around two side pillars of the transmitting core. The transmitting coils are connected in series, and the magnetizing current directions in the two coils are opposite, which leads that the main magnetic flux is thrown from one of the transmitting coils and returned from the other one after passing through the receiving coil. The receiving coil is located in the middle of the transmitting pad and is almost perpendicular to the transmitting pad; the physical configuration of the magnetic coupler is referred to as an orthogonal magnetic structure in this letter.

A vital consideration in the design of a wireless charging system is that it does not cause leakage magnetic flux interference to a UAV. In order to investigate the magnetic field distribution of the proposed magnetic structure, the simulations based on ANSYS Maxwell were conducted in this letter. Fig. 2(a) shows the magnetic field distribution of the proposed magnetic coupler on a cross section, where the magnetic force (ampere turns) in each transmitting coil is set to 115, which relates to 10 A peak magnetizing current at 500 W power output and 11.5 turns of each transmitting coil. It is obviously that the magnetic field is effectively converged near the surface of the transmitter pad. The thrown magnetic flux is concentrated within the magnetic structure itself, which means that most of the flux can be captured without the need for a large receiving coil, as opposed to a face-to-face structure. Meanwhile, the inductance of the transmitter L_P, inductance of the receiver L_S, and coupling coefficient k

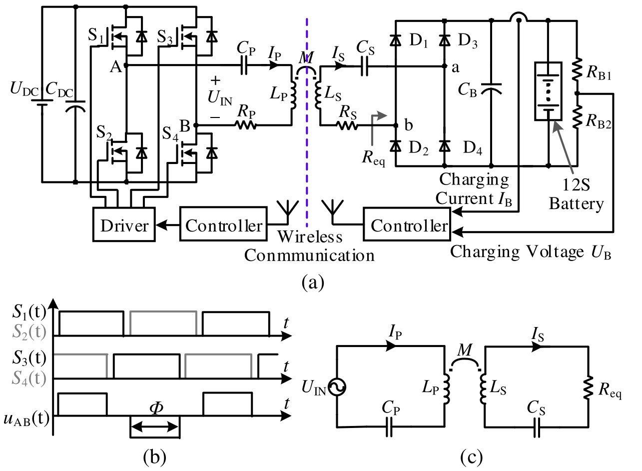

Fig. 3. (a) Wireless charging system structure. (b) Gate drive signals and output voltage of the inverter. (c) Equivalent circuit model.

can be obtained as 64.8 μH, 19.4 μH, and 0.33, respectively, via the simulation.

In Fig. 2(b), the peak magnetic flux density *B* distributions in the *XZ* plane, shown in Fig. 2(a), are plotted from simulation results. It is indicated that the magnetic flux density is stronger around the receivers and weakens continuously with farther away from the receiving coil. The maximum flux density *B* is 9299 μT, and it exists in the plane where *X* is equal to 0 mm. When $|X|$ is 150 mm and *Z* is 100 mm, the magnetic flux density reduces to 29 μT. The proposed magnetic structure presents great advantages to avoid EMI problem on the UAV compared with the face-to-face structures, which have been studied in [6] and [10]. The wireless charging system introduces little leakage interference to the nearby electronics, which means that no additional aluminum sheet is required in pick-up to shield the magnetic field and the weight of magnetic receiver is further reduced. Therefore, there will be more space to be available under the body of a UAV to install other equipment.

III. Design and Analysis of the Primary-Side Power Control Topology

The wireless charging system diagram for UAVs, which uses primary-side power control method to simplify the circuit structure of pick-up, is shown in Fig. 3(a). UAV wireless charging stations are often located in isolated islands and other places are away from the grid. These stations are powered by new energy generation and battery storage system, which supply power to the wireless charging system through a boost circuit. This part is equivalent to a constant dc voltage $U_{\rm DC}$ (100 V) in Fig. 3(a). Subsequently, the power flows through the inverter, compensation circuit, rectifier, and filter to charge the battery. In this letter, the series–series compensation scheme is adopted due to the following characteristics. First, its output provides constant current characteristics, which is a natural advantage for battery charging. Second, it leads to a simple pick-up structure. Since only one compensation element $(C_{\rm S})$ is needed in the pick-up compensation circuit, and a smoothing capacitor C_B, rather than an inductor, is demanded across the output, which can minimize the weight of pick-up.

The inverter is controlled by the phase shift modulation scheme, and the gate drive signals and output voltage of the inverter are shown in Fig. 3(b). The fundamental output voltage $U_{\rm IN}$ is dependent on conduction angle Φ according to the following equation:

TABLE I
Parameters of the Prototype System

Parameters	Value	Parameters	Value
f	100kHz	k	0.3
$L_{\rm P}$	59.3μH	$C_{\rm P}$	43.9nF
$L_{\rm S}$	19.8μH	$C_{\rm S}$	128.2nF

$$U_{\rm IN} = \frac{2\sqrt{2}}{\pi} U_{\rm DC} \sin\left(\frac{\phi}{2}\right). \quad (1)$$

The circuit model of the wireless charging system is shown in Fig. 3(c). In which, $U_{\rm IN}$ represents the power supply by the dc input and inverter, and $R_{\rm eq}$ is the equivalent load of the rectifier and battery. The rectifier is driven with a current source, and then, the output charging current I_B can be given by the following equation with the Fourier decomposition:

$$I_B = \frac{2\sqrt{2}}{\pi} I_S \quad (2)$$

where $I_{\rm S}$ is the effective value of the current in the receiving coil.

According to KVL, Fig. 3(b) can be described by

$$\begin{cases} (j\omega L_{\rm P} + 1/j\omega C_{\rm P}) I_{\rm P} - j\omega M I_S = U_{\rm IN} \\ (j\omega L_{\rm S} + 1/j\omega C_{\rm S} + R_{\rm eq}) I_{\rm S} - j\omega M I_P = 0 \end{cases} \quad (3)$$

where ω is the angular frequency of the inverter.

At resonance, substituting (3) into (2) results in the output charging current I_B as

$$I_B = \frac{8}{M\pi^2} \sin\left(\frac{\phi}{2}\right) U_{\rm DC}. \quad (4)$$

The output charging voltage $U_{\rm B}$ can be calculated as

$$U_B = \frac{8}{M\pi^2} \sin\left(\frac{\phi}{2}\right) U_{\rm DC} R_B \quad (5)$$

where R_B is the equivalent resistance of the battery when charged. It shows that I_B and U_B can be controlled by adjusting Φ from the primary side. In this letter, the on-board sensors sample the charging voltage U_B and charging current I_B delivered to the battery, and then these data are fed back to the primary-side controller in the charging station. Φ is controlled according to feedback information by a primary PID controller to regulate power flow to the battery.

IV. Experimental Verification

An experimental prototype based on the proposed magnetic structure and primary-side power flow control is constructed, as shown in Fig. 4. The circuit parameters are listed in Table I. The experimental results of L_P, L_S, and *k* are well-matched to the simulations. The operating frequency of the system is 100 kHz. The length and height of the receiving coil are 140 mm and 50 mm respectively, and the weight is 130 g, which is insignificant for medium- and high-power UAVs. The coupling coefficient of the proposed magnetic coupler is 0.3.

Fig. 5 shows the system operation at the maximum output power point. Fig. 5(a) indicates that the output voltage $U_{\rm AB}$ and

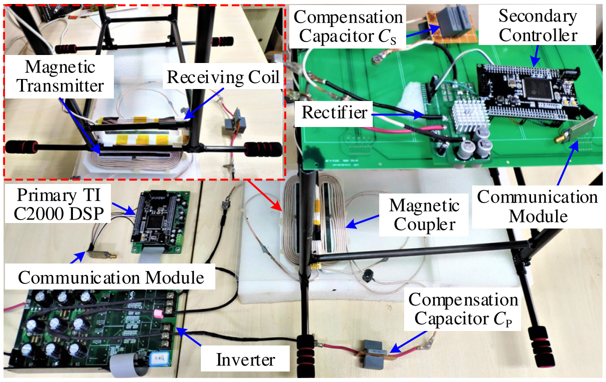

Fig. 4. Prototype of the wireless charging system.

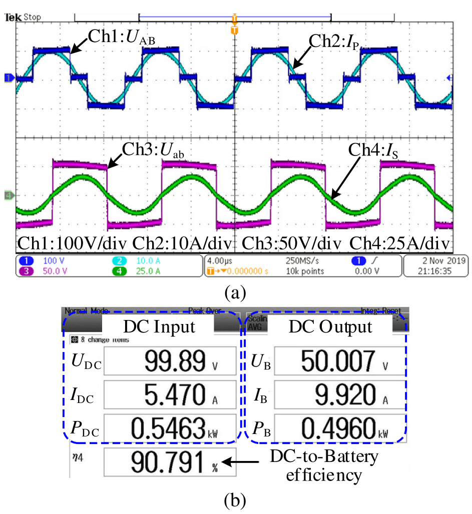

Fig. 5. Power transfer ability test. (a) Measured waveforms of system. (b) Input and output power test.

current I_P of the inverter are phase coincidences, so the inverter has only a real load resulting in a high inverting efficiency. Fig. 5(b) shows that the charging current is 9.92 A, and the charging voltage is 50.01 V, meanwhile the output power is 496 W with the whole system efficiency of 90.79%. As a result, the proposed orthogonal magnetic structure itself has the four firm merits as follows:

1) lower weight of a magnetic receiver;
2) larger power transfer capacity;
3) further reduction in the EMC generated from the power supply; and
4) better installation adaptability for UAVs special shape.

The output power of the closed-loop wireless charging system varying with change in equivalent load resistance R_B is shown in Fig. 6, which indicates that the 10 A constant charging current (CC) and 50 V constant charging voltage (CV) is achieved, respectively. Meanwhile, accurate switching from constant current to constant voltage can be accomplished. The designed system can complete the normal charging task for UAVs.

V. Conclusion

A novel orthogonal magnetic structure, which has a lightweight magnetic receiver, for UAVs, has been proposed and verified throughout this letter. The air-cored receiving coil is placed vertically in the middle of a polarized transmitter,

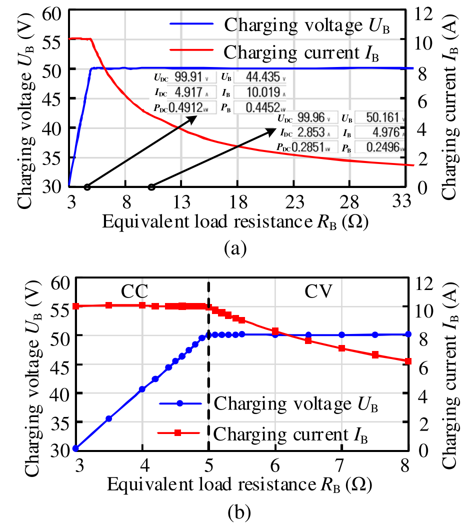

Fig. 6. Closed-loop system operation test. (a) Change the equivalent load resistance R_B from 3 to 33 Ω. (b) Change the equivalent load resistance R_B from 3 to 8 Ω.

possessing a large magnetic flux captured surface for enough power transfer and also constraining magnetic field operation space away from UAV's body by coil-structure itself. The primary-side power control method is adopted to regulate the power flow to battery, which further reduces the weight of an on-board pick-up circuit. A prototype was built for experiment. It is shown that the system can successfully deliver 500 W to a UAV with a dc-to-battery efficiency of 90.8%. The simulation and experimental results confirm the effectiveness of the proposal.

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