A Lightweight Wireless Charging method for Unmanned Aerial Vehicles

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Abstract. Recently, more and more unmanned aerial vehicles (UAVs) have been used in industry, public services and commercial fields. However, the UAV is generally limited by the battery capacity, and the operation radius is greatly limited. In this paper, to increase the flight time of the UAV, the recharging station by using wireless power transfer (WPT) technology is proposed. A new receiver magnetic coupler is given, the receiver coil is wound around the hollow ferrite core, and the proposed structure provides many benefits: 1) first, there is a large magnetic flux captured surface, which can improve the mutual coupling between the primary side and secondary side. 2) Second, own to the hollow ferrite core, the receiver side is light, which has little effect on the weight bearing of UAV. 3) Third, it is easy to be installed on the UAV, since the receiving coil is compact. 4) Moreover, the proposed WPT system provides enough anti misalignment capability for UAV.

1. Introduction
Recently, more and more unmanned aerial vehicles (UAVs) have been used in industry, public services and commercial fields, because they have dazzling ability in improving equipment operation and maintenance level, disaster exploration, disaster relief and other aspects. UAV has higher safety and efficiency, and is easy to be popularized, so it has great application value. However, the UAV is generally limited by the battery capacity, and the operation radius is greatly limited [1]-[3].

To increase the flight time of the UAV, there are mainly two methods can be utilized. Firstly, by equipping the UAV with a higher capacity battery but this inevitably increases the weight of the UAV [4]. Secondly, by the construction of battery replacement or recharging station in the flight area. As for constructing the battery replacement station, this can realize more rapid energy supplement, however, the required high precision mechanical structure let the construction cost high. Generally, the mainstream charging system of UAV adopts contact charging [3]. Although this method allows high power transfer efficiency, there are also some problems, such as the plug wear, poor environmental adaptability, and need for human intervention, etc. Obviously, the traditional contact based power supply method for UAV hinders the intelligent level of UAV.

Recently, wireless power transfer (WPT) through magnetic coupling is gaining global popularity [5]-[7], and it has been applied in numerous applications such as biomedical implants, electric vehicles (EVs) and it will also be a revolutionary way to automate the recharging process for UAVs. WPT
technology has the characteristics of convenience and safety, which can realize UAV completely unmanned autonomous charging.

In this paper, a new receiver magnetic coupler is proposed, the receiver coil is wound around the hollow ferrite core, and the proposed structure provides many benefits: 1) first, there is a large magnetic flux captured surface, which can improve the mutual coupling between the primary side and secondary side. 2) Second, own to the hollow ferrite core, the receiver side is light, which has little effect on the weight bearing of UAV. 3) Third, it is easy to be installed on the UAV, since the receiving coil is compact. 4) Moreover, the proposed WPT system provides enough anti misalignment capability for UAV.

2. System Configuration and the coupling structure
The main goal of the proposed WPT system is to automatically recharge the UAVs. In the proposed system, the transmitter coil is placed in a ground pad station, while the receiver coil is placed on-board the UAV. Generally, UAVs are equipped with systems like cameras, proximity sensors, etc. All of these devices require an undisturbed viewing area. To meet this requirement, the constraint in the WPT design concerns the shape and the size of the on-board secondary coil that must be adequately designed.

The general overview of the proposed magnetic structure for UAVs wireless charging system is shown in Fig. 1. Unipolar coil $L_P$ is the transmitter coil, $L_S$ is the receiver coil. To enhance the magnetic coupling, a 1 mm thick hollow ferrite core is used on the receiver side, while the receiver coil is wound around the hollow ferrite core.

![Fig. 1(a) The proposed coupling structure; (b) Sizes of the coupling structure;](image)

In this paper, 300-strand Litz wire with a diameter of 3 mm is used to construct the coils $L_P$ and $L_S$. The number of turns of $L_P$ and $L_S$ are 15 and 20, respectively. The number of layers of $L_P$ and $L_S$ are 1 and 2, respectively.

Fig. 2 is plotted by using Matlab, shows the measured mutual inductance $M_{PS}$ between $L_P$ and $L_S$. It shows that the variation of $M_{PS}$ is relatively symmetrical and small corresponding to the misalignment, thus enabling power transfer a symmetrical misalignment tolerance.
3. Circuit Topology and the Analysis of Power Transfer

3.1 Circuit Topology

Fig. 3 depicts the circuit diagram of the proposed WPT system, where the inductor-capacitor-capacitor-capacitor (LCC-C) compensation topology is utilized to compensate the transfer coils. There are some merits for the LCC compensation circuit, which are: 1) the current in the transmitter is independent of the load; 2) the input impedance of LCC circuit network is purely resistive, which only supplies the active power to the load. The parasitic resistances of $L_P$ and $L_S$ are labeled as $R_{LP}$ and $R_{LS}$, respectively. The parasitic resistances of the compensation components are relatively small, therefore they can be ignored to simplify the analysis. The battery voltage and current of the UAV are sent back to the primary side through the wireless communication for controlling the inverter in a closed-loop manner.

3.2 Analysis of the Power Transfer Characteristics

The compensation capacitors $C_T$, $C_P$, $C_S$ are with the following mathematical relation:

$$ C_T = \left( \omega^2 L_T \right)^{-1} \quad C_P = \left[ \omega^2 \left( L_T - L_G \right) \right]^{-1} \quad C_S = \left( \omega^2 L_S \right)^{-1} \quad (1) $$

where $\omega$ is the operating angular frequency, and it can be calculated by $2\pi f$ with $f$ as the operating frequency of the inverter.
Fig. 3 Circuit topology of the proposed WPT system.

Thanks to the filter characteristic of the compensation networks, only the fundamental harmonic should be considered when analyze the circuit. To control the inverter, the Phase-shifted modulation (PSM) method is used. The output voltage of the inverter in phasor form can be calculated as shown in equation (2).

$$\dot{U}_d = \frac{2\sqrt{2}U_{dc}}{\pi} \sin\frac{\delta}{2} < 0$$  \hspace{1cm} (2)

where $\delta$ is the conduction angle.

The equivalent resistance of the rectifier can be calculated as

$$R_{eq} = \frac{8}{\pi^2} R_L \hspace{1cm} (3)$$

According to the Kirchhoff’s voltage law (KVL), the equivalent circuit can be described by the following equations

$$\begin{align*}
\dot{U}_d &= (jX_{LT} + jX_{CT})\dot{I}_T - jX_{CT}\dot{I}_P \\
0 &= (jX_{LP} + jX_{CP} + jX_{CT} + R_L)\dot{I}_P - jX_{CT}\dot{I}_T - jX_{MPS}\dot{I}_S \\
0 &= -jX_{MPS}\dot{I}_P + (jX_{LS} + jX_{CS} + R_S + R_{eq})\dot{I}_S \\
\dot{U}_S &= R_{eq}\dot{I}_S \\
\dot{U}_L &= \frac{\pi^2}{4} \dot{U}_S
\end{align*}$$  \hspace{1cm} (4)

where $U_S$ is the root mean square (RMS) value of $\dot{U}_S$ and

$$\begin{align*}
X_{LT} &= \omega L_T \\
X_{CT} &= 1/\omega C_T \\
X_{MPS} &= \omega M_{ps} \\
X_{LP} &= \omega L_P \\
X_{CP} &= 1/\omega C_P \\
X_{LS} &= \omega L_S \\
X_{CS} &= 1/\omega C_S
\end{align*}$$  \hspace{1cm} (5)

By substituting (1), (2), (3) and (5) into (4), the currents crossing $L_T$, $L_P$ and $L_S$ and the output voltage $U_L$ of the rectifier can be derived as shown in (6). As can be seen from (6), the transmitting coil current is independent of the load.

$$\begin{align*}
\dot{I}_T &= \frac{\dot{U}_m}{\omega^2 L_T^2} \left( R_{LP} + \frac{\omega^2 M_{ps}^2}{R_{LS} + R_{eq}} \right) \\
\dot{I}_P &= \frac{\dot{U}_m}{j\omega L_T} \\
\dot{I}_S &= -\frac{M_{ps}\dot{U}_m}{(R_{LS} + R_{eq}) L_T} \\
\dot{U}_L &= \frac{M_{ps} U_d R_{eq} \sin\frac{\delta}{2}}{(R_{LS} + R_{eq}) L_T}
\end{align*}$$  \hspace{1cm} (6)

The input impedances of the LCC circuit network can be calculated as shown in (7), which indicates that the impedance of the inverter is purely resistive, and hence only the active power is provided to the load.

$$\begin{align*}
\text{Input Impedance} &= \frac{M_{ps} U_d R_{eq} \sin\frac{\delta}{2}}{(R_{LS} + R_{eq}) L_T}
\end{align*}$$  \hspace{1cm} (7)
\[ Z_{in} = \frac{U_m}{I_r} = \frac{\omega^2 L_s^2}{R_p + \frac{\omega^2 M_{ps}^2}{R_{ls} + R_{eq}}} \]  

(7)

4. Conclusions

This paper proposes a recharging method of UAV by using WPT technology. A new receiver magnetic coupler is proposed, the receiver coil is wound around the hollow ferrite core, and the proposed structure provides many benefits: 1) first, there is a large magnetic flux captured surface, which can improve the mutual coupling between the primary side and secondary side. 2) Second, owing to the hollow ferrite core, the receiver side is light, which has little effect on the weight bearing of UAV. 3) Third, it is easy to be installed on the UAV, since the receiving coil is compact. 4) Moreover, the proposed WPT system provides enough anti-misalignment capability for UAV.

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