The State-of-the-art of Wireless Charging of Drones via Inductive Power Transfer and Capacitive Power Transfer

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Abstract. Nowadays, two kinds of WPT systems, inductive power transfer (IPT) and capacitive power transfer (CPT), are becoming increasingly popular for applications such as medical devices, aeronautical and space technologies. In the unmanned aerial vehicle (UAV), one of the most important things is the charging efficiency of the battery. This paper aims at finding optimal structures and comparing the fundamental structures between CPT and IPT. Then according to the basic features of UAV, this paper seeks for the most suitable wireless charging system based on the specific characteristics of CPT and IPT. IPT is with high flux leakage and huge heat dissipation, but it can only travel a short distance. CPT has low active power loss and there is no need for specialized personnel to maintain and manage, and also no noise, but it is poor stability against external short circuit and its characteristic is not good.

Keywords: Wireless charging; WPT; Inductive power transfer; Capacitive power transfer; UAV.

1. Introduction

Wireless power transfer (WPT) technology is a brand-new power transmission technology that transfers energy from the transmitting end to the receiving end in the form of no electrical connection using space intangible soft media (electric field or magnetic field). Its application enables the electric equipment to avoid the disadvantages of metal contact pulling, striking, abrasion and leakage, and get rid of the constraints of cables. It has unique advantages and broad prospects in many important applications such as implantable medical devices, electric vehicle charging, LED lighting, and rail transit.

In contrast to electromagnetic radiation, which can be used for long-distance transmission and is typically employed at the kilometer level, electromagnetic resonance is mostly used for medium-distance transmission, typically at the meter level. The electronic devices used during the workweek, such as mobile phones, laptop computers, and other devices, require batteries and regular recharging. It is vital to select a specific location to charge because the power cord is frequently inserted and taken out, which is unsafe and difficult to handle. Because some chargers, charging lines, and plugs don't adhere to the same standards, the environment is polluted and resources are wasted. In uncommon situations, such as mines and oil mining places, conventional control transmission strategies have gigantic potential security dangers, such as casualties caused by electric sparkles. Another point is that it is troublesome to embrace the control dissemination strategy of laying control lines for confined islands and base stations working in hilly ranges. The taken toll is tall, not to specify the yearly upkeep and care costs. Within the over circumstance, remote transmission of power gets to be increasingly imperative and critical. In this manner, it was chosen as one of the best ten scientific inquiries about bearing within the future by American Innovation survey magazine.

There are two types of charging methods, which are EMF-based charging and non-EMF based charging. The EMF-based charging has aroused great interest in recent decades, which includes capacitive charging, inductive charging and magnetic resonant charging. It is used for near-field transmission. In comparison, non-EMF based charging is used for far-field transmission including gust soaring, PV integrated, laser integrated and battery dumping.

This paper aims at discovering the application of WPT systems on UAVs especially IPT and CPT systems. At first, the design of the IPT system including the designs of compensation topologies,

magnetic couplers and optimization of misalignment of parameters are introduced in this paper. Then the advantages and disadvantages of IPT systems are also presented in Section 2. Secondly, the advantages and disadvantages of CPT systems and improvement in the power efficiency of CPT systems are displayed in Section 3. Then the specific characters on CPT and IPT systems are applied to UAVs by considering the basic demands of UAVs' charging system. The wireless charging systems must have a high transmission efficiency, longer endurance to the environment, small sizes and cost-effectiveness. In addition, Structures are optimized to be suitable for UAVs and the advantages and disadvantages of CPT and IPT systems are compared in Section 4. As UAV has the basic challenges of less battery life and flight time. The options to optimize the wireless charging system are：

1. Increase the battery capacity with limited size and cost
2. Charge the battery from an external source of energy intermittently.
3. Seize a high energy transfer efficiency.

The paper ends with a glimpse of future trends and research directions.

2. Inductive Power Transfer

2.1 Introduction and Application of IPT

The IPT system is based on the electromagnetic induction principle, that is a current is induced when a magnet passes through a coil and cuts the magnetic field as there is a change in magnetic flux linkage. When applied in wireless charging, it replaces the transmission by wires with transmitting by a magnetic field to reach the purpose of non-contact charging. Therefore, this power transmission mode keeps it independent of wire and can completely transfer on any specific occasion. Contactless power transfer increases the powering potential for applications within hazardous and continuously changing environments. It has the advantages of easy conduction and safe transmission and it will not have any adverse phenomena like the electric spark caused by friction. Given the convenient transmission mode, stable output power, and good transmission characteristics, the IPT system has carried out relevant breakthroughs in both laboratory research and commercial product design and has gained significant achievements.

The IPT system is applied in many fields including aeronautical and space technologies, transportation, marine equipment, and intelligent manufacturing as well as mobile device charging and small electronic devices.

2.2 System Overall Structure

2.2.1 Typical IPT system structure

The voltage source, power pads, and controller are the three primary parts of the IPT system. A typical IPT system block diagram is shown in Fig. 1. The high-frequency alternating magnetic field is produced by the transmitter pad, and a DC power source generates the high-frequency sinusoidal current that passes through the inverter. The receiver pad on the secondary side then receives the electrical energy generated by the AC from the primary side via wireless transmission. High-frequency AC is converted to DC by the rectifier circuit, which then uses the converter to adjust the voltage and current before charging the battery.

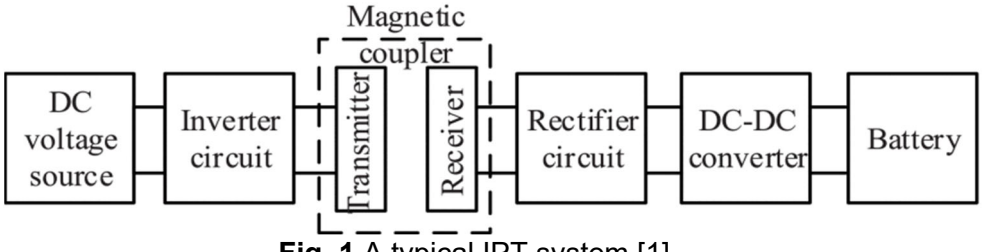


Fig. 1 A typical IPT system [1]

2.2.2 Design of compensation topology

The compensation topology is very important as it is related to the resonant frequency, the coupling and power transfer capability, and high efficiency.

There are four basic compensation structures SS, SP, PS, PP and other hybrid compensation structures including the inductance-capacitance-inductance (LCL) compensation, integrated inductance-capacitance-capacitance (LCC) compensation, S/SP, SP/S and so on. There are many types of research to optimize the compensation topology and nearly 52 compensation configurations are further explored. The method to select compensation topology is due to the economy, system safety, simplifying the control strategy of the primary side, and facilitating bidirectional power flow operation.

The requirements of the design on compensation topology are in the following 4 aspects.

1. ZPA detection between exciting voltage and current.
2. To ensure that the current and voltage are not relevant to the load.
3. Current and voltage of the system are not limited by the mode controller.
4. A Small number of compensation components, high system power density, and high efficiency.

The four fundamental compensation structures each have unique qualities. However, it is challenging to put all four of the fundamental compensation topologies into actual practice. Regarding PP and PS, when the input voltage changes sign, the voltage of the parallel capacitor in the primary coil will raise the e.m.f. The capacitor will then stop receiving current, losing its ability to serve as a compensating mechanism. The parallel compensated receiver in the PP compensation topology has the current source property that makes it better suited for battery charging. However, if the coupling coefficient and load conditions change, the resonant condition will as well. According to various parameter adjustments, SS and SP will have entirely distinct properties. SS and SP are better suited for high-power transmission. The amount of copper needed is lower for SS compensation topology. and can operate at a frequency that is unaffected by the load and coupling coefficient. The SS and SP are combined to form the complex compensation topology known as S/SP. It resolves the issue of the input ZPA's refusal to be realized in SP and the excessive sensitivity of the coupling coefficient in SS.

In [2], a type of integrated LCC system is introduced. Its property of continuous output current that is independent of load exists. Additionally, the resonant frequency is unaffected by the load circumstances or the coupling coefficient k. In [3], a series-parallel hybrid (SPPS) model is put together. Compared to the model SS, it has a higher transmission power and a longer transmission distance. An LCL parallel resonant circuit with a current feature is used for WPT in [4]. It has numerous receivers, which is crucial. CLCL is a different compensation topology proposed in [5]. Because of the symmetry of this arrangement, the IPT system could transfer power in both directions. However, in these topologies, the inductances of the supplementary inductors are either greater than or equal to the inductances of the primary coils. As a result, more room is needed to accommodate these inductors.

2.2.3 Design of magnetic coupler

Two popular designs are the DD structure and the circular pad structure [6].

Since the structure of circular pad structures inherently provides low loss and low leakage, they have received much research. Several optimizations are done in [7] to be less expensive, more durable, and lighter than frequently used inductive couplers. It is not advisable to make the charger heavy because it cannot deliver enough magnetic flux to a receiver when the length of the air gap is greater than a quarter of the pad and is not cost-effective. However, much bigger diameters are necessary to have a larger air gap.

For DD structures, two pads are polarized to provide a powerful magnetic field, enhance coupling, and increase misalignment tolerance. A preliminary prototype was built to assess the effects of including aluminum shielding [8]. The DD coupler structure has a better coupling than the circular pad structure because it offers a charging zone that is more than five times larger and more economical

than a circular pad of comparable size and price. The path height of a single-sided flux is also twice as large in the DD coupler structure as it is in the circular pad.

2.3 Optimization

Research on the misalignment of IPT systems has attracted a lot of interest from researchers because misalignments can affect inductances, stability, loss in power transfer, and efficiency. To enhance misalignment performance, several strategies are used, such as compensation optimization, magnetic paraders, magnetic pads, and hybrid topologies.

Ferrite structural alterations affect magnetic metrics such as IPT pad inductance, coupling factor, leakage per power, and ferrite flux densities. Improved parameters may have a wider tolerance for misalignment.

Ferromagnetic cores are impacted by misalignment between the primary and secondary subsystems, which is a coupling variation with misalignment. The efficiency of the system is improved by using ferrite cores, although this has a significant negative impact on the coils' self-inductances due to misalignment [9-10].

2.4 Limitations

There are the following limitations:

1. Short transmission distance.
2. High flux leakage and huge heat dissipation.
3. Transmission efficiency is low.

Two ways to improve efficiency:

1. To compensate the leakage inductance of the coupling coils to compensate network.
2. To improve the coupling coil by adding magnetic material (ferrite) [11].

3. Capacitive Power Transfer

3.1 Introduction of CPT

Reactive power: Many pieces of electrical machinery, including motors and distribution transformers, operate on the electromagnetic induction principle and convert and transmit energy by creating AC magnetic fields. Reactive power is the electrical energy needed to create the alternating magnetic field and the induced magnetic flux. Because the aforementioned "reactive power" has not been turned into thermal or mechanical energy, it is not "useless" energy. As a result, in addition to active power supply, the reactive power supply is also necessary, while neither is essential.

3.2 Advantages and Disadvantages of CPT

Fig. 2 displays a condensed block schematic of the descriptive CPT system. The reactive power network on the primary side and secondary side is used for impedance matching between the power source and the load like the magnetic field approach. Any WPT system uses a high-order matching network to obtain an appropriate degree of freedom in design, performance, and overall input-output connection. Such high-order networks may be difficult to analyze. Therefore, it is possible to overlook the intricate interaction between system parameters and characteristics.

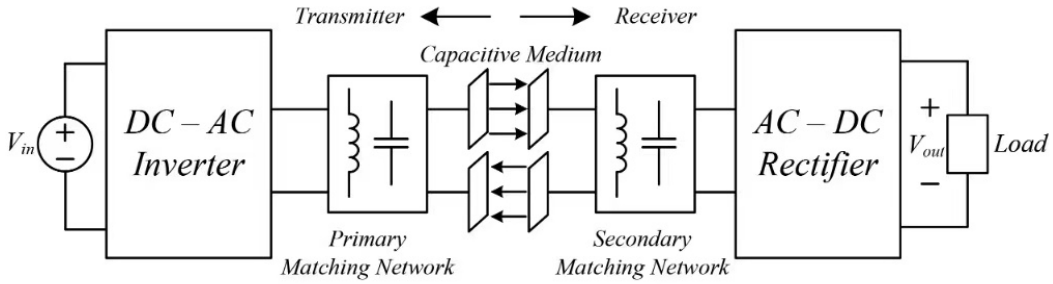


Fig. 2 A typical CPT system

The parallel capacitor was originally called a phase-shifting capacitor and later renamed a parallel capacitor. It is mainly used to make up for improving power factor, improving voltage quality and reducing line loss. The use of shunt capacitors for reactive power compensation has the following advantages and disadvantages:

3.2.1 Advantages

1. The active power loss of the power capacitor is very small, which is less than 0.5% of its reactive power capacity. And the active power loss of the dimmer is 1.5% - 5% of its output reactive power.
2. The unit capacity investment of the power capacitor is lower than that of the dimmer, and the unit capacity investment is almost independent of the total capacity.
3. The power capacitor has no rotating part, no need for specialized personnel to maintain and manage, and also no noise.
4. The power capacitor is easy to install and can be switched automatically.
5. The power capacitor can be installed dispersedly and can be installed near the reactive load. This reduces the reactive power flow in the line, thus reducing the line loss and improving the voltage quality.

3.2.2 Disadvantages

1. The voltage characteristic is not good. The inductive reactive power supplied by the capacitor decreases squarely with the voltage drop.
2. There is a residual charge after the removal of the voltage device, which needs to be fully discharged to avoid personal injury or operation accidents.
3. The capacity of the capacitor to withstand over-voltage is poor. One of the capacitors in the capacitor bank fails, which is not easy to find in time.
4. Poor stability against external short circuits. A short circuit fault of one capacitor is easy to affect other capacitors.
5. After the power capacitor is installed, it will affect the harmonic power flow in the power grid, and even amplify the harmonic current. In addition, when the power capacitor is closed, it will produce a large closing inrush current, and sometimes even excite resonance over-voltage. Therefore, protective measures to control the closing inrush current are often taken on the power capacitor circuit.

3.3 Improvement in Efficiency of CPT

Under the same capacity constraints of inverters, switching devices, compensating inductors and capacitors, and port voltages, the current flowing through the switch tubes is halved by increasing the number of inverters, to improve the input power of the system and achieve the purpose of improving the transmission power of the CPT system.

4. Research on IPT and CPT for drones

With the gradual maturity of the development of science and technology, UAVs have been widely used in many fields, especially in military reconnaissance and precision attacks. UAVs has gradually become an indispensable and important force in modern warfare. All countries are actively developing new advanced UAVs, which has set off a global upsurge in advanced UAV research. One of the most crucial prospects for UAV development is long-term endurance. Currently, the performance of batteries and conventional charging techniques are the key factors limiting the endurance of UAVs. Increase the size and capacity of the batteries if you desire additional endurance. The proposed hovering wireless UAV charging technology combines the radio energy transmission technology with the UAV charging technology in the current invention. Based on the radio energy transmission technique, the UAV may be wirelessly and flexibly charged using a high-voltage cable, increasing the UAV's durability and increasing its research significance as well as its usefulness. There are two ways for UAV wireless charging, one is CPT (capability power transmission) and the other is IPT (inductive power transmission).

It is worth noting that as UAVs are applied in more and more segmented scenarios, battery power supply and charging technology are the key. When a UAV is frequently used, it can intuitively feel the increase in charging frequency. In some specific environments, when there is no time or condition for battery replacement or wired charging, operators need to take new ways to make the UAV stand by at any time and enter the working state at any time.

Because of the constraints of the special structure of UAVs, the traditional generation of wireless charging technology can not achieve space-free charging, resulting in the wireless charging of UAV not been applied. At present, the 5-8cm charging distance customized by spotting for the UAV allows the receiver to be placed in the belly of the fuselage, and even if the UAV is a certain distance from the ground, it can realize wireless charging across the air.

UAV has three advantages: first, it can be flexibly controlled; second, it has a simple structure; third, it has low cost and is widely used in monitoring, plant protection, inspection, disaster relief and other fields. The flight time of a UAV is an important indicator to measure its performance. It is the key factor to determine the flight distance, the amount of information obtained and the endurance of the UAV, as well as the number, efficiency and quality of tasks, performed. Therefore, how effectively extend the flight time of UAVs is a very important issue. At present, there are two methods to prolong the flight time of UAVs:

1. To increase the capacity of the lithium battery, but the load capacity of the drone is limited.
2. To charge the drone promptly. If the traditional wired plug-in charging method is used, it will consume a lot of manpower and reduce the flexibility of the UAV.

If the charging process does not require manual intervention, the efficiency of the UAV to perform tasks will be greatly improved.

Because of the limited volume of the UAV, the size and capacity of the battery are severely limited, which affects the endurance. Moreover, the charging steps of the UAV battery are cumbersome, and the wireless charging efficiency is low, which affects the working efficiency. Wired charging has the problem that charging equipment is easy to wear and spark. Battery technology has developed into a bottleneck period. If you want to have a larger battery capacity, it means having a larger battery volume and weight. However, increasing the battery capacity will certainly affect the mobility and lightweight of UAVs.

To design a suitable WPT system for UAVs, some specific characteristics of wireless charging of the drones must be paid attention to when applying different types of WPT systems to drones.

1. High transmission efficiency and transmission speed.
2. Longer endurance and adaptive in any conditions like high temperature, low pressure, and corrosive environment.
3. Occupy is small in size and has a small effect on the drone’s balance system.
4. Low economic cost and low repairmen fees.

5. Conclusion

As for IPT systems, DD structures are put in use as the DD structure is more suitable than circular pads as two D-pads are applied on both sides of two landing gears, which balances the drones. A DD-coupler pad also has a better coupling than a circular pad. On the other hand, the material of the coil should be lighter to reduce the repulsion when drones are driving in the air.

CPT systems can address the problem of limited operating time when minimizing compatibility and optimizing the system. It is also adaptable to environment like water and high pressure because of the specific metal plates. When optimizing the circuit, it can have a longer flight time and travel a longer distance.

In short-range power transmission, the CPT has several advantages over IPT. It has fewer power losses to the surroundings as the electromagnetic interference problem is less of a concern. So the magnetic shielding canoe was reduced, resulting in low economic cost. It uses an electric field rather than a magnetic field, which cut down the expenditure on the magnetic material.

These two models can be used to guide the design for special requirements on UAVs by altering circuit parameters, analyzing the misalignment and so on. UAVs have been developing for agriculture, mapping and monitoring weather. The new WPT systems applied to UAVs will bring about market prosperity.

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