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TOPICAL REVIEW

Critical Review of Recent Development of Wireless Power Transfer Technology for Unmanned Aerial Vehicles

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ABSTRACT Recently, unmanned aerial vehicles (UAVs) have shown immense potential in military and civilian applications. However, the limited endurance of UAVs poses a crucial challenge to their widespread adoption and development. Fortunately, wireless power transfer (WPT) technology has emerged as a promising solution to address this issue. In contrast to the previous papers on the topic, this review aims to provide a holistic top-down view of WPT technology for UAVs. More specifically, it introduces the fundamental principles of WPT technology firstly. Then, the design and optimization methods of coupling mechanisms, especially for UAVs, are introduced and compared. Numerous different and significant designs are reviewed and discussed. Furthermore, the compensation topology and control strategies are elaborated in detail subsequently. Finally, the key technical challenges faced by WPT for UAVs are put forward and future directions for development is proposed. Therefore, this review can be considered as an expedient reference for researchers conducting studies in the field of WPT technology for UAVs. Keeping this in mind, we present meaningful perspective for each of the analyzed key aspects, providing inspiration for what follows.

INDEX TERMS UAV, wireless power transfer, wireless charging, coupling mechanism, compensation topology, control strategy.

ABBREVIATION

UAVs	Unmanned aerial vehicles.
WPT	Wireless power transfer.
LWPT	Laser WPT.
MWPT	Microwave WPT.
ECPT	Electric field coupled WPT.
MCR	Magnetic coupling resonant.
MCM	Magnetic coupling mechanism.
S-S	Series- Series type.
S-P	Series- Parallel type.
P-S	Parallel- Series type.
P-P	Parallel- Parallel type.
CC	constant current.
CV	constant-voltage.
PT	Principle of parity-time.
3D	Three-dimensional.

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I. INTRODUCTION

UAVs today have gained its popularity and become an ideal approach to execute all kinds of complex tasks, including military purposes and civilian uses [1], [2]. The deployment of UAVs not only saves time and resources but also safeguards human lives. Over the past few decades, the market of UAVs has been increasing rapidly and the UAVs have been employed in more extensive applications. According to

Drone Ind. Insights UG, the global UAV market will exceed \$48 billion by 2025 [3], [4]. Currently, UAVs are mainly powered by batteries. Due to limited energy storage capacity, a UAV can only operate within the limited time and range. To extend working lifetime, several effective methods have been flourished in the last decade, such as disassembly charging and solar-powered supply [5], [6]. Despite these intensive efforts, the duration of UAV flight remains an unsolved bottleneck and probably become a crucial factor that hinders the widespread application of UAVs.

As an epoch-making technique of energization, WPT technology offers a band-new pattern to charge batteries in electric devices [7]. Thanks to its numerous conspicuous characteristics (position-free, flexibility, convenience, and movability), WPT technology has been adopted to energize electric-driven equipment [8]. It also has opened up a revolutionary paradigm for prolonging the flight time of UAVs [9]. Nowadays, researches on WPT technology for UAVs have become the front-burner issue and draw a great many attentions for plenty of journal and conference publications, panel discussions at flagship workshops, as well as keynote talks [10]. For the vast majority of these studies, WPT technology for UAVs has been developed quickly and comprehensively in recent year, especially in several key techniques.

However, in order to address future treads and research directions, we first provide research status of UAV charging, which will naturally drive the requirements of WPT technology for UAVs. Then, we briefly describe the development history of WPT, especially for UAVs. To this end, we discuss the literature summarizing the UAVs wireless charging technology and present the contributions of this review paper. Finally, we present the organization of the remaining sections of this review paper.

A. DRIVERS FOR UAVs WIRELESS CHARGING

Over the last few years, UAVs have been used in many different applications in industry and military domains, such as artificial intelligence [11], mapping-modelling [12] and agriculture [13]. The main commercial business applications of UAVs are depicted in Fig. 1.

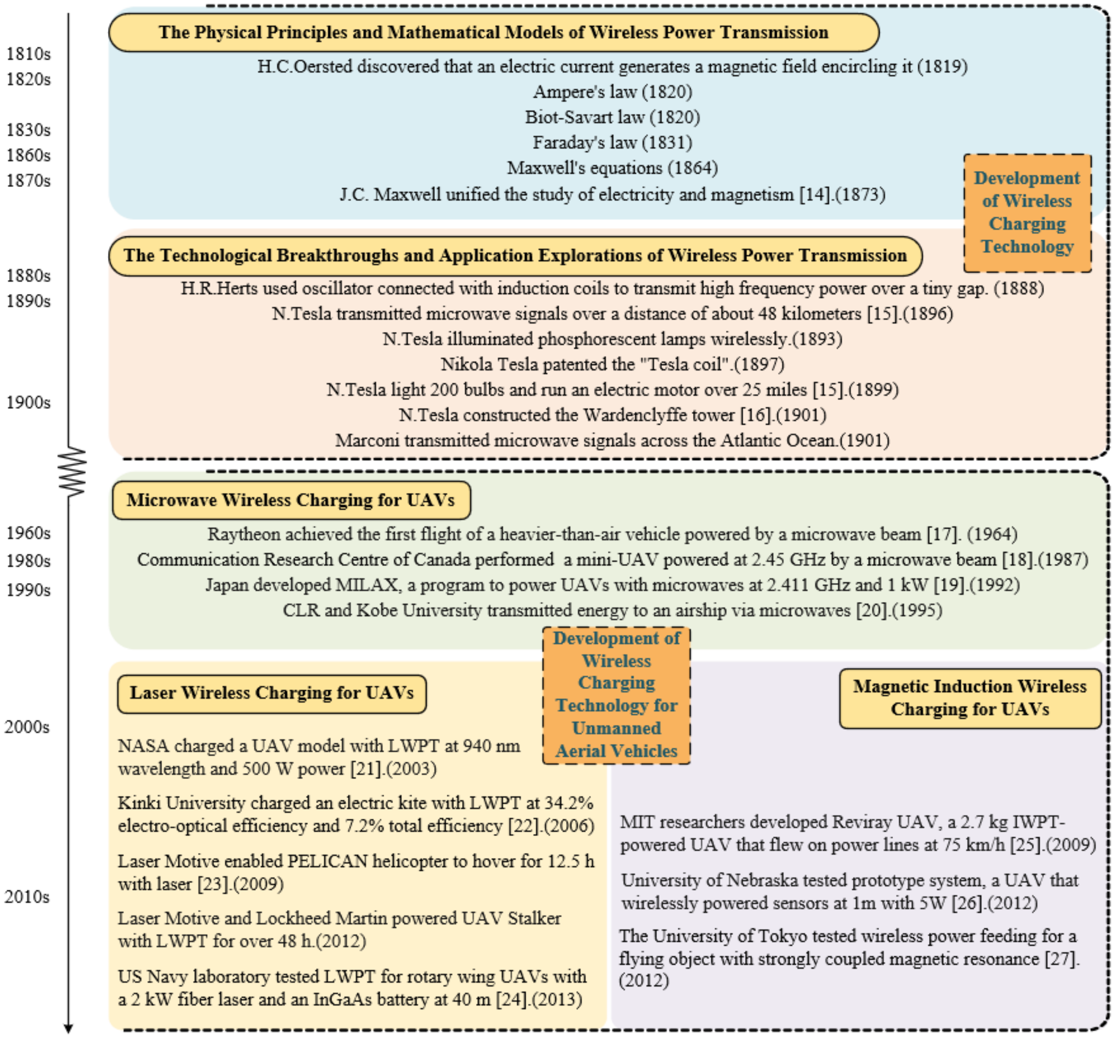
To prolong the flight time of UAVs, various approaches have been adopted for powering the batteries of UAVs. Currently, three commonly-used methods of charging UAVs are wired charging method, power change mode and solar-powered energization, respectively. Among these, conventional contact-based charging system is the most common method. It has many advantages, such as simplicity, fast charging, and low cost. However, this method is dependent heavily on compatible chargers or data cables. In addition, it is limited by power outlets, wire lengths, and potential inconveniences caused by electrical wiring aging. Fortunately, power change mode has become an effective way gradually and batteries of UAVs can be disassembled in a short time by using specialized chargers. Obviously, this method is suitable for large-scale UAV applications due to its high charging efficiency. Nevertheless, it needs frequent battery disassembly, which can cause damage to the UAV and necessitate additional charging equipment. Due to the rise of new energy, solar-powered energization has exploded in popularity recently. It can charge batteries through photovoltaic arrays on the UAV's wings. This approach presents numerous advantages such as energy efficiency, environment friendly, and the ability to achieve autonomous charging during flight. Nevertheless, this method has slow charging speeds and low conversion efficiency. In addition, this technique is heavily dependent on environment. Compared with these three types of charging methods of UAVs, WPT technology provides a more intelligent, flexible and reliable method to charge UAVs.

FIGURE 1. Main commercial business applications of UAVs.

B. HISTORY OF WPT TECHNOLOGY FOR UAVs

Fig. 2 displays the brief development history of WPT technology, especially for UAVs. In the early 19th century, theoretical basis of electromagnetics was built integrally, which resulted in the emergence of WPT technology [14]. Towards the end of the 19th century, several creative pioneers attempted to transfer energy through electromagnetic induction or electric fields [15], [16]. However, these efforts unfortunately were in vain due to low efficiency and safety concerns.

In the early 20th century, the exploration of microwave-based energy transmission emerged. Nonetheless, the high-efficiency conversion of microwaves back into electricity did not succeed due to limitations in technology, which seriously hindered the progress of WPT application. It was not until 1964 that W.C. Brown successfully achieved this goal using rectifying antennas. A model helicopter was also powered experimentally, which proved the feasibility of microwave WPT (MWPT) [17]. Significantly, this achievement promoted the application of microwave-based WPT technology in UAVs. In addition, this approach was



H.C.Oersted discovered that an electric current generates a magnetic field encircling it (1819)
Ampere's law (1820)
Biot-Savart law (1820)
Faraday's law (1831)
Maxwell's equations (1864)
J.C. Maxwell unified the study of electricity and magnetism [14].(1873)

H.R.Herts used oscillator connected with induction coils to transmit high frequency power over a tiny gap. (1888)
N.Tesla transmitted microwave signals over a distance of about 48 kilometers [15].(1896)
N.Tesla illuminated phosphorescent lamps wirelessly.(1893)
Nikola Tesla patented the "Tesla coil".(1897)
N.Tesla light 200 bulbs and run an electric motor over 25 miles [15].(1899)
N.Tesla constructed the Wardenclyffe tower [16].(1901)
Marconi transmitted microwave signals across the Atlantic Ocean.(1901)

Raytheon achieved the first flight of a heavier-than-air vehicle powered by a microwave beam [17]. (1964)
Communication Research Centre of Canada performed a mini-UAV powered at 2.45 GHz by a microwave beam [18].(1987)
Japan developed MILAX, a program to power UAVs with microwaves at 2.411 GHz and 1 kW [19].(1992)
CLR and Kobe University transmitted energy to an airship via microwaves [20].(1995)

NASA charged a UAV model with LWPT at 940 nm wavelength and 500 W power [21].(2003)

Kinki University charged an electric kite with LWPT at 34.2% electro-optical efficiency and 7.2% total efficiency [22].(2006)

Laser Motive enabled PELICAN helicopter to hover for 12.5 h with laser [23].(2009)

Laser Motive and Lockheed Martin powered UAV Stalker with LWPT for over 48 h.(2012)

US Navy laboratory tested LWPT for rotary wing UAVs with a 2 kW fiber laser and an InGaAs battery at 40 m [24].(2013)

MIT researchers developed Reviray UAV, a 2.7 kg IWPT-powered UAV that flew on power lines at 75 km/h [25].(2009)

University of Nebraska tested prototype system, a UAV that wirelessly powered sensors at 1m with 5W [26].(2012)

The University of Tokyo tested wireless power feeding for a flying object with strongly coupled magnetic resonance [27]. (2012)

FIGURE 2. The developmental history of WPT technology and its application in UAVs.

innovatively adapted and optimized to apply to the unique needs and scenarios of UAVs.

Simultaneously, in the early 21st century, the introduction and development of alternative methods like laser, electric field coupling, and magnetic field coupling have been studied generally and made substantial progress in UAV wireless charging [21], [22], [23], [24], [25], [26], [27], [28], [29]. These advancements offered new solutions for extended flight durations and autonomous recharging of UAVs. Up to now, WPT via magnetic coupling resonant WPT (MCR-WPT) has developed into the preferred method due to many excellent performances. Therefore, WPT via magnetic coupling resonant will be highlighted as the main research approach in the subsequent analysis in this review paper.

C. LITERATURE REVIEW: WPT TECHNOLOGY FOR UAVs

By now, a considerable number of papers have explored for UAVs wireless charging. These articles provide insights, possible applications and solutions from all aspects. Among them, Prithvi Krishna Chittoor et al. present in-depth review about WPT technology for UAVs. This paper offers various key technologies, including fundamental knowledge, application scenarios, charging methods, and standard specifications of the technology [30]. A comparative analysis of existing techniques is proposed, associated with key future research discussions of WPT for UAVs in [31]. Moreover, the main issues and challenges faced by the technology are also summarized.

In addition, there are articles focusing on more specific research areas. For instance, in [32], the feasibility and challenges of wirelessly charging UAVs for real-time inspection of power line is analyzed emphatically. In [33], power and communication aspects of UAV wireless charging are deeply studied. Additionally, many operational aspects are optimized, including energy management, data collection, operational utility, location, scheduling, and safety. In [34] and [35], in-depth analyses and evaluations of UAV wireless charging technology from theoretical and practical

TABLE 1. Comparison of surveys on UAV wireless charging (✓) is indicated for topic covered (✗) is indicated for topic not covered.

Topics	Application of UAVs	Classification of Charging Methods for UAV	Comparison of WPT Technologies	The MCM Structures	Comparison of Compensation Topologies	Control strategies of WPT System for UAVs	Major Challenges and Prospects
Ref.[30]	√	×	×	×	√	×	√
Ref.[32]	√	×	√	×	×	×	×
Ref.[33]	√	×	√	×	×	×	×
Ref.[34]	√	√	×	×	×	×	√
Ref.[35]	√	×	√	×	√	×	×
Ref.[36]	√	√	×	×	×	×	×
This Survey	√	√	√	√	√	√	√

perspectives are provided. Besides, [36] is dedicated to rotary-wing UAV wireless charging stations, offering specialized knowledge and technical support for such applications.

In summary, research on UAV wireless charging technology has attracted plenty of attention in recent years, and its applications in various fields are expected to keep growing.

D. CONTRIBUTIONS OF THIS ARTICLE

While the aforementioned and other papers cover crucial aspects of WPT technology for UAVs, the current review paper aims to provide a holistic top-down view of UAVs wireless charging. Table 1 compares the main structural composition of wireless charging systems for UAVs reported in recent years. The academic contributions of this paper are as follows:

- The paper provides a comprehensive introduction to the principles, characteristics, and application scenarios of UAV wireless charging technology. It categorizes and compares different types of wireless charging methods, including electric field coupling, magnetic resonance coupling, laser, and microwave methods.
- The paper analyzes the design of coupling mechanisms, compensation topologies, and control strategies for UAVs based on magnetic resonance wireless charging technology.
- The paper takes a comprehensive look at the main challenges and issues faced by UAV wireless charging technology in practical applications. The paper also outlines potential directions and prospects for future development, involving novel devices, materials, theories, and applications

E. ORGANIZATION OF THIS ARTICLE

The remainder of this article is organized as follows. In Section II, the paper presents an overview of four main wireless charging technologies and summarizes their applications and research progress in the field of UAVs. It highlights the versatile characteristics of MCR-WPT as an ideal choice for small UAV charging. Then, compensation topology design is introduced and discussed in detail in Section III. In Section IV, compensation topology of WPT for UAVs is expounded, especially for complex topology structure. In Section V, control strategy design was compared. It takes prevalent control strategy types into account and analyzes factors to consider in control strategy design.

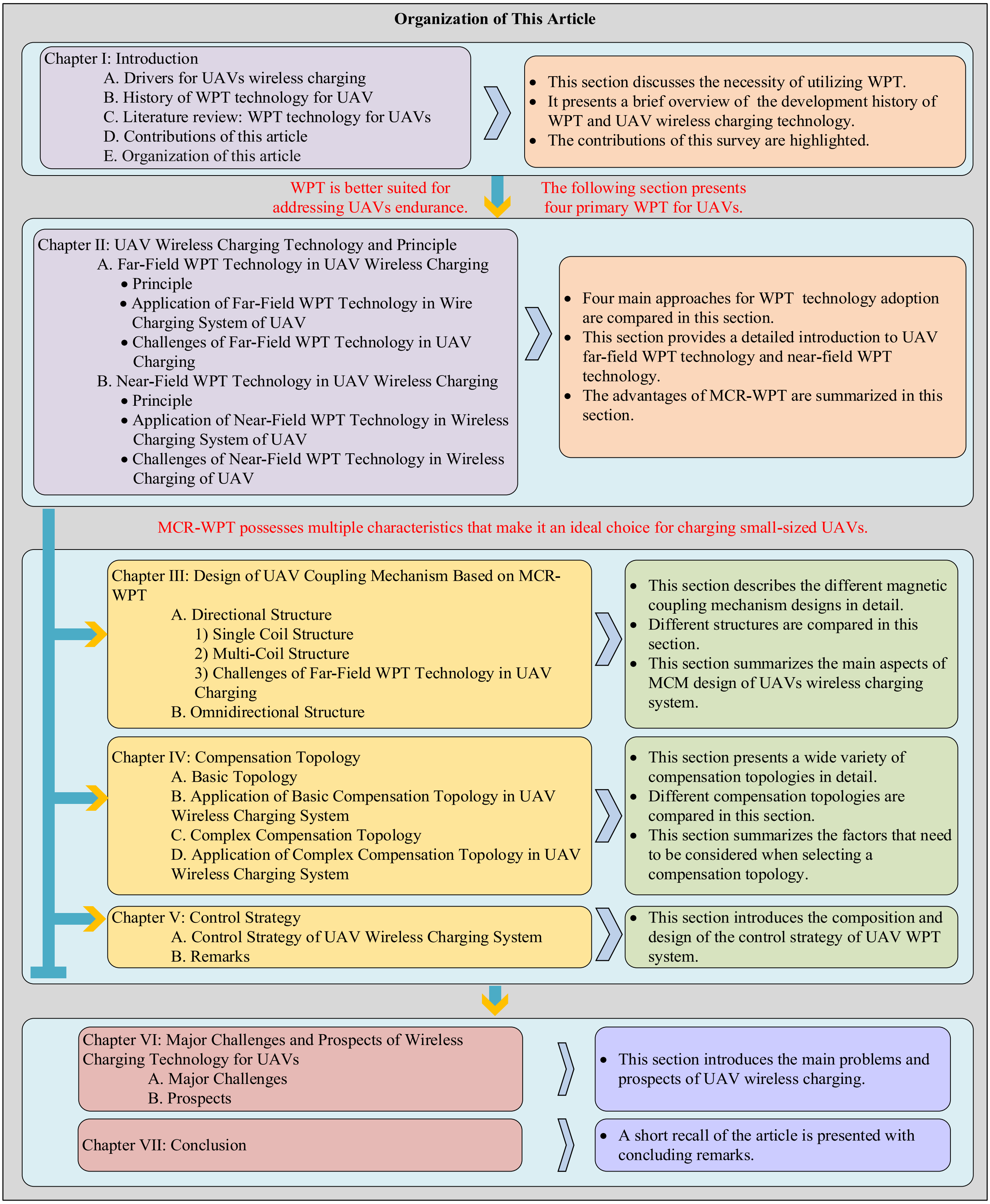
In the conclusion and outlook section, the paper summarizes the main content and conclusions. In addition, some ideas and suggestions for the future development directions and challenges of UAV wireless charging technology are proposed. Fig. 3 presents the structural composition of this paper.

II. UAV WIRELESS CHARGING TECHNOLOGY AND PRINCIPLE

Based on different fundamental principles, WPT technology can be categorized into various types, as depicted in Fig. 4 [37]. In the field of UAVs, there are primarily four main approaches, namely, laser WPT (LWPT), and MWPT, electric field coupled WPT (ECPT), and MCR-WPT. In the following sections, we will elaborate these methods from principle, application and challenges for UAVs in detail.

A. FAR-FIELD WPT TECHNOLOGY IN UAV WIRELESS CHARGING

LWPT is one of the most promising technologies in the long-range WPT field. Fig. 5 show the basic principle of LWPT. As seen, the input power (AC power supply, batteries or generator) is converted into a monochromatic beam of light through a laser, which is then directed and emitted via an optical system to the remote PV receiver. In the receiving terminal, dedicated PV array that match the wavelength and



Organization of This Article

Chapter I: Introduction
- A. Drivers for UAVs wireless charging
- B. History of WPT technology for UAV
- C. Literature review: WPT technology for UAVs
- D. Contributions of this article
- E. Organization of this article

- This section discusses the necessity of utilizing WPT.
- It presents a brief overview of the development history of WPT and UAV wireless charging technology.
- The contributions of this survey are highlighted.

WPT is better suited for addressing UAVs endurance.

The following section presents four primary WPT for UAVs.

Chapter II: UAV Wireless Charging Technology and Principle
- A. Far-Field WPT Technology in UAV Wireless Charging
  - Principle
  - Application of Far-Field WPT Technology in Wire Charging System of UAV
  - Challenges of Far-Field WPT Technology in UAV Charging
- B. Near-Field WPT Technology in UAV Wireless Charging
  - Principle
  - Application of Near-Field WPT Technology in Wireless Charging System of UAV
  - Challenges of Near-Field WPT Technology in Wireless Charging of UAV

- Four main approaches for WPT technology adoption are compared in this section.
- This section provides a detailed introduction to UAV far-field WPT technology and near-field WPT technology.
- The advantages of MCR-WPT are summarized in this section.

MCR-WPT possesses multiple characteristics that make it an ideal choice for charging small-sized UAVs.

Chapter III: Design of UAV Coupling Mechanism Based on MCR-WPT
- A. Directional Structure
  - 1) Single Coil Structure
  - 2) Multi-Coil Structure
  - 3) Challenges of Far-Field WPT Technology in UAV Charging
- B. Omnidirectional Structure

- This section describes the different magnetic coupling mechanism designs in detail.
- Different structures are compared in this section.
- This section summarizes the main aspects of MCM design of UAVs wireless charging system.

Chapter IV: Compensation Topology
- A. Basic Topology
- B. Application of Basic Compensation Topology in UAV Wireless Charging System
- C. Complex Compensation Topology
- D. Application of Complex Compensation Topology in UAV Wireless Charging System

- This section presents a wide variety of compensation topologies in detail.
- Different compensation topologies are compared in this section.
- This section summarizes the factors that need to be considered when selecting a compensation topology.

Chapter V: Control Strategy
- A. Control Strategy of UAV Wireless Charging System
- B. Remarks

- This section introduces the composition and design of the control strategy of UAV WPT system.

Chapter VI: Major Challenges and Prospects of Wireless Charging Technology for UAVs
- A. Major Challenges
- B. Prospects

- This section introduces the main problems and prospects of UAV wireless charging.

Chapter VII: Conclusion

- A short recall of the article is presented with concluding remarks.

FIGURE 3. Organization of the review article.

beam intensity of the laser converts the laser back into electricity, which is then input through the power management system for various loads. LWPT offers several advantages, including extended transmission distances and high power density [38]. However, its cost is notably elevated, primarily attributed to the demanding nature of lasers generator,

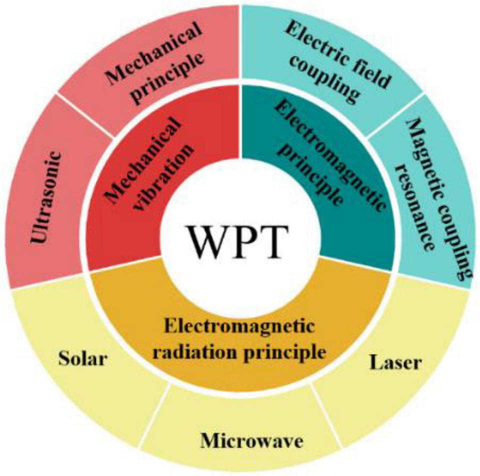


FIGURE 4. Classification of WPT technologies.

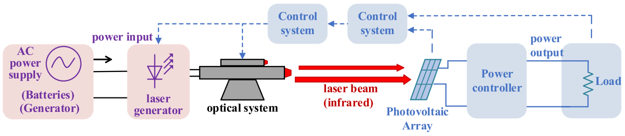


FIGURE 5. The principle of LWPT technologies.

optical components, and tracking systems, both in terms of their intricate materials and technology requirements. These factors pose considerable challenges during both manufacturing and maintenance phases. Despite the higher cost, LWPT remains well-suited for delivering adaptable, convenient, and dependable power to mobile electronic devices like UAVs, satellites, and deep space probes.

MWPT technology provides a new energy supply pattern for UAVs with its characteristics of low space transmission loss and large transmission power [39], [40]. As shown in Fig. 6., electric energy is converted to a microwave beam of a specific frequency via microwave generated. Then it is transmitted directionally through the microwave transmitting antenna. And the rectenna at the receiving end converts the microwave beam into direct current energy. It should be noted that matching network is also essential for high efficiency in MWPT systems. Simultaneously, high-frequency rectifier needs to be well-designed for high-efficiency energy conversion in the receiving terminal. In terms of cost, MWPT technology occupies a middle ground, with microwave transmitters, receivers, and antennas incurring moderate expenses. While these components require a certain level of materials and technology, they are relatively cost-effective. MWPT technology offers a convenient, secure, and dependable power source for mobile devices like aircraft, satellites, and deep space probes.

As mentioned above, both LWPT and MWPT technologies offer long-distance and high-power transmission in the field of UAVs wireless charging. However, the poor security is the main issue that limits the implement of these two WPT systems. High-frequency large-power energy is inevitably harmful to surroundings or the creatures along the transmission path. Worse, it may cause harm to human beings. Therefore, these two methods are not applicable to implantable medical devices charging. Currently, both technologies are still under exploration and experimentation, and there is still long way to go before achieving commercialization and widespread adoption.

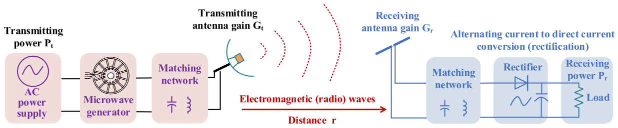


FIGURE 6. The principle of MWPT technology.

In 2017, a 2.45 GHz MWPT system for UAVs was developed by the Defense Science and Technology Agency of Singapore [42]. The receiver of this system comprises a receiving antenna array, rectifier, and power management circuit. UAV battery can be charged at a distance of 4 m with conversion power of 12 W. The system demonstrates advantages in antenna, rectification, and power management. However, it also had many unsolved issues, such as low efficiency, short range, and poor stability. Takabayashi et al. proposed an MPT system for C-band wireless charging of micro-UAVs. A lightweight and compact rectenna array with an output power of 20 W was employed [43]. The array consisted of 16 units, which composed of a cellular substrate and GaAs Schottky barrier diode. Operating at 5.8 GHz frequency, it can deliver 27.0 W DC power at 19.0 V, weighing 37.5 g. Therefore, the power-to-weight ratio is 0.72 W/g, and the conversion efficiency reaches 61.9%. The system employs phased-array as the transmitting antenna structure, offering strong directionality and adjustability but bearing drawbacks of complexity and susceptibility to damage.

Research group from Carleton University dynamically adjusted the power and angle of the laser charging source of UAVs to enhance operational efficiency and safety [24]. This method accounted for low-power laser charging and assumed UAVs rest and charge on a single structure. However, it may limit UAV flexibility and efficiency in complex environments. Future investigations need take multiple structures or other available platforms into account. Reference [45] investigated LWPT system for UAVs and GaAs photovoltaic panels was adopted as the receiving end's solar cell material. To enhance efficiency and lifespan of the solar panels, a two-phase heat pipe cooling system was designed to reduce their temperature. These papers have explored possible applications and solutions for UAV wireless charging. As shown in the Table 2, this typical reported application of far-field WPT technology for UAVs are listed and compared. As seen, these two methods can achieve W-level energy conversion over considerable distances. However, a complex and precise tracking system is required for high efficiency.

Although far-field WPT technology for UAVs has a long transmission distance in theory, far-field WPT technology still faces several challenges in UAV charging:

TABLE 2. Comparison of far-field WPT technologies for UAV.

Type	Output Power	Working Frequency	Wavelength	Efficiency	Reference
MWPT	134W	5.8 GHz	-	47%	[41]
MWPT	2.28W	2.45 GHz	-	0.7%	[42]
MWPT	20W	5.8 GHz	-	9.6%	[43]
LWPT	190W	-	1070 nm	9.5%	[24]
LWPT	5W	-	1550 nm	15%	[44]
LWPT	62.5W	-	810 nm	12.5%	[45]

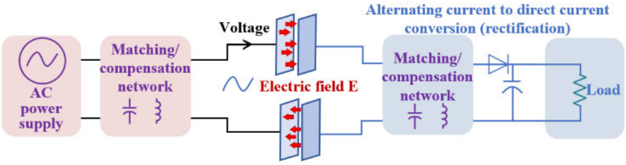


FIGURE 7. The principle of ECPT.

(1) The transmission efficiency of LWPT and MWPT technologies is affected by various factors, such as PV conversion elements and laser generators, as well as the losses of laser or microwave during transmission. In addition, the alignment and matching issues of transmitting and receiving antennas should be considered. Currently, the transmission efficiency of LWPT and MWPT generally does not exceed 15% and 10%, respectively.

(2) The flight of UAV is random and dynamic. In order to obtain a higher transmission power and efficiency, it is necessary to irradiate laser or microwave accurately on the receiving terminal. To ensure normal incidence and achieve efficient energy conversion, a laser beam or microwave control tracking system is required.

(3) In order to achieve high power and long distance energy transmission, laser beam or microwave will carry a large amount of energy during transmission. It will cause energy loss or safety risks if obstacles or charged objects are encountered in the use process.

B. NEAR-FIELD WPT TECHNOLOGY IN UAV WIRELESS CHARGING

ECPT technology for UAVs uses alternating electric field to generate displacement current. In fact, its energy conversion is similar to the charging and discharging process of parallel plate capacitor. As shown in Fig. 7 [46], [47]. To form a strong electric field between the transmitting end plates, the DC power supply is converted into high frequency AC voltage, and the voltage is boosted through the compensation network. Then the current is induced between the receiving end plates, and the load is supplied after rectification and filtering. This technology uses mental plate to transmit energy, which has the characteristics of no eddy current, low cost and low loss. However, there are also some defects such as short transmission distance and high requirements of alignment and positioning.

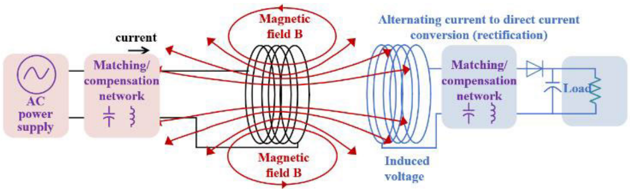


FIGURE 8. The principle of MCR-WPT.

MCR-WPT technology is a way to realize power transmission by using the resonant coupling between two coils. As shown in Fig. 8 [48], [49]. At the transmitting end, alternating current from the power grid is converted into high-frequency AC power through power conversion. It then drives the transmitting coil to generate a high-frequency magnetic field through compensation topology. While in the receiver, the receiving coil resonates at the same frequency, inducing a high-frequency voltage in the magnetic field, which is then delivered to the load through compensation topology or matching network. Compared to traditional induction WPT, this technology offers advantages such as longer transmission distance, higher efficiency, and lower environmental interference. Notably, MCR-WPT incurs lower costs due to the economical magnetic materials and coils employed. These components do not require advanced materials or technology, resulting in cost-effective manufacturing and maintenance processes. Therefore, it is very suitable for wireless charging applications in mobile devices like UAVs. Moreover, MCR-WPT can transmit power over medium distances to multiple loads simultaneously.

ECPT and MCR-WPT technology are the mainstream technologies in the field of wireless charging, but they are rarely used in UAV charging, especially for large UAVs. The main reason is the short transmission distance. Recently, reported studies have focused on these two technologies for small UAVs.

Reference [52] proposed a novel WPT system for UAVs, which utilized a reconfigurable capacitive coupler capable of adapting to different UAVs structures, landing positions, and orientations. This system achieved an output power of 212.1 W and a DC-DC efficiency of 82.5%. Even under three-dimensional (3D) misalignment, the output current and efficiency remained stable. Reference [51] introduced a separated circular capacitive coupler design that reduced cross-coupling capacitance by increasing the distance between same-side plates. This approach improved mutual capacitance and system efficiency. It can achieve a board-to-board power transfer efficiency of 89.4% at 100 W output power. In recent years, researchers have conducted in-depth theoretical analysis and experimental verification of MCR-WPT technology for UAVs. Reference [55] presented a bidirectional WPT system that employed high-frequency MCR-WPT technology, enabling UAVs to switch between receiving mode and sending mode. This approach allowed UAVs to receive energy from the ground transmitter while

TABLE 3. Comparison of near-field WPT technologies used to power UAV.

Type	Time	Output Power	Working Frequency	Efficiency	Reference
ECPT	2020	45W	6.78MHz	78.2%	[50]
ECPT	2020	100W	1000kHz	89.4%	[51]
ECPT	2022	212.1W	500kHz	82.5%	[52]
MCR	2019	64.9W	364kHz	57.9%	[53]
MCR	2021	400W	85kHz	94%	[54]
MCR	2022	35W	5MHz	89%	[55]

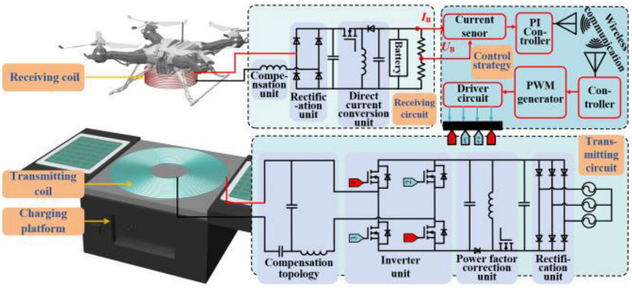


FIGURE 9. Schematic diagram of MCR-WPT for UAV.

simultaneously supplying energy to sensors. It offers advantages such as long transmission distance, lightweight design, and adaptability to complex environments. Such systems can provide reliable power support for wireless sensor networks, extending their lifetime. Table 3 provides a comparison of research results on near-field WPT technology for UAVs from both domestic and international sources.

ECPT and MCR-WPT are two extensively researched WPT technologies, which can transfer power from several kilowatts to tens of kilowatts. These technologies are primarily suitable for charging scenarios where UAVs hover or land at fixed points. However, they face several key challenges, including:

(1) Limited transmission distance: ECPT technology typically achieves a transmission distance of only a few millimeters, while MCR-WPT technology typically achieves a transmission distance of only a few tens of centimeters. This limitation hinders the application of these two WPT for UAVs.

(2) Poor anti-misalignment performance: The flight of UAV is a dynamic process and the landing position is random. For ECPT and MCR-WPT technology, the system efficiency decreases rapidly with the increase of the offset distance. It is important to improve the misalignment tolerance of coupling mechanism.

(3) Electromagnetic leakage and shielding problems: In order to ensure the flight safety of the UAV, the electromagnetic compatibility should also be considered. In general, some shielding materials, such as ferrite and metamaterials, should be added to reduce the electromagnetic leakage.

Compared with the other three WPT technologies (LWPT, MWPT and ECPT), MCR-WPT technology has many unique advantages, such as high transmission efficiency, large transmission power and low cost. Therefore, MCR-WPT has been a hot topic in the research of UAV wireless charging technology. Fig. 9 show schematically shows a block diagram of the MCR-WPT for UAVs. The remainder of this article mainly focuses on the MCR-WPT for UAVs and related studies are discussed in detail.

III. DESIGN OF UAV COUPLING MECHANISM BASED ON MCR-WPT

The magnetic coupling mechanism (MCM) is the core component in MRC-WPT for UAVs. In general, two main structural types, namely directional and omnidirectional, are predominantly used in the systems [56]. This section primarily highlights the latest research progress in these two structural types. Moreover, the advantages and disadvantages of different structural designs are introduced and compared.

A. DIRECTIONAL STRUCTURE

Directional structure is a common form of MCM, which is characterized by the directional transmission of power from the transmitter to the receiver [57], [58]. The structure has high transmission efficiency because the radiation loss in the transmission process is small [59]. Directional structure can be divided into various forms according to the number of coils and structure.

1) SINGLE COIL STRUCTURE

The single-coil structures include planar circular coil, planar rectangular coil and solenoid coil. Compared to three-dimensional coils or composite coils, flat circular and flat rectangular coils offer the advantage of simple structure and easy manufacturing. However, they exhibit lower transmission efficiency [60] and are susceptible to displacement effects. Moreover, change of the diameter will directly affect the magnetic flux distribution [61], [62]. It is easy to produce a large number of leakage fluxes, which can result in the overall transmission efficiency decline. In [63], S-S compensation can enable power transmission up to 5 kW through changing AC resistance and mutual inductance. However, the coupling coefficient decreases shapely when the coil is not aligned. Solenoid coil is a kind of tubular 3D structure with high orientation. But the structure is complex and heavy. It is mainly used in low-power and long-distance oriented WPT technology, such as fluorescent lamps and sensors [64], [65], [66], [67], [68].

In order to address the challenges of low transmission efficiency and susceptibility to misalignment associated with planar circular coils and planar rectangular coils, several studies have focused on enhancing and optimizing these coupling structures. Reference [81] proposed an asymmetric planar circular coil with different primary and secondary side turns, as shown in Fig. 10(a). The experimental results show that the system can transmit 20.46 W power under the alignment state, and the system efficiency reaches 85.25%. When the bilateral

TABLE 4. Comparison of the characteristics of four WPT technologies.

Type	Principle	Features	Applicable
Electric Field Coupled	The transmitter and receiver plates are separated, and an alternating voltage between the transmitter plates generates a varying electric field. It can induce a displacement current between the receiver plates, thus achieving WPT.	Hundreds of watts; cm-level; high transmission efficiency, up to 80%; poor safety.	Electric vehicles; Medical devices
Magnetic Coupling Resonant	The transmitting coil is connected to a high-frequency AC power source, and the receiving coil resonates at the same frequency as the transmitting coil. It can result in strong magnetic coupling and wireless energy transmission to a load connected to the receiving coil.	From tens of watts to several kilowatts; from a few centimeters to several meters; high efficiency; capable of powering multiple devices simultaneously; safe and convenient.	Electric vehicles; Consumer electronics; Implantable electronic devices
Microwave	At the transmitting end, electrical energy is converted into microwaves through a magnetron and transmitted by the transmitting antenna. At the receiving end, microwave energy is converted into electrical energy through rectification devices.	Long transmission distance (up to hundreds of kilometers), low efficiency (Typically not exceeding 10%), little affected by weather conditions, mature technology, fast attenuation with increasing distance, requiring large antenna arrays and receivers, poor directivity, high interference, low safety.	Consumer electronics; Aerospace aircraft
Laser	The transmitter converts power from a common source into a monochromatic beam of light through a laser, which is then directed and emitted via an optical system to the remote PV receiver. In the receiving terminal, dedicated PV array that match the wavelength and beam intensity of the laser converts the laser back into electricity, which is then input through the power management system for various loads.	Transmission distance (up to tens of kilometers), low efficiency (Typically not exceeding 15%), strong directivity, low interference, low safety, high frequency, low propagation loss in the atmosphere, large scattering loss, easy to interfere with communication devices, requiring accurate tracking and alignment system.	Consumer electronics; Aerospace aircraft

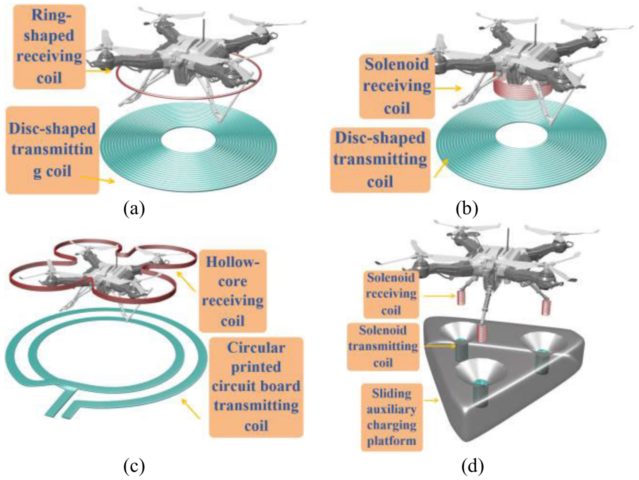


FIGURE 10. One-to-one transfer structure. (a). disc-shaped vs Ring-shaped; (b). disc-shaped vs solenoid; (c). circular printed circuit board coil vs hollow-core coil; (d). solenoid vs Solenoid.

air gap is 1 cm, its power is 17.1 W and the efficiency is 71%. In addition, it also has high misalignment tolerance.

As a kind of dynamic charging technology, MCR-WPT technology of UAV can realize energy transmission during flight. In [78], a wireless charging platform suitable for UAV in flight was designed by using nonlinear parity and time symmetry model. As shown in Fig. 10(b), the platform was composed of disk coil and solenoid coil. Furthermore, this platform can stably supply power when the UAV hovers above the charging platform in 3D space. The transmission efficiency is up to 93.6% and the output power is about 10 W. However, the electromagnetic compatibility or interference of the platform needs to be further improved.

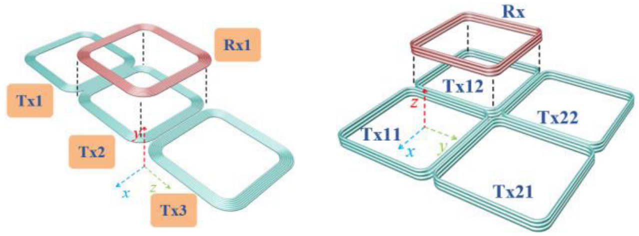
In order to reduce the aerodynamic resistance of UAV, copper plated plastic structure is used to manufacture the hollow receiving coil, which was installed on the anti-collision frame of UAV, as shown in Fig. 10(c) [83]. The transmitter consisted of two rounds of printed circuit board coils with an outside diameter of 20 cm. The UAV did not need batteries and could hover freely near the charging platform to achieve dynamic load power supply or charging. However, one problem is that other electronics on the UAV can be disturbed by electromagnetic fields generated by the coupling mechanism. Therefore, it is necessary to design appropriate electromagnetic shielding technology to ensure the normal operation of UAV.

Besides, a tight-coupled three-phase resonant magnetic field charging system was proposed for wireless charging of UAVs [84]. As shown in Fig. 10(d), the system uses small solenoid coils as transmitting and receiving ends. When the UAV lands on the wireless charging platform, the receiving coil wound on the landing gear will fall into the corresponding hole of the charging platform. And it will be nested in the transmitting coil to transmit energy by forming a closed magnetic flux path. Therefore, the system has the characteristics of closed magnetic flux path and high transmission efficiency. And the system can achieve a coil-to-coil transmission efficiency of 91% and a total system efficiency of 72% with an operating frequency of 60 kHz and a power level of 150 W.

2) MULTI-COIL STRUCTURE

Multiple coils can be combined to achieve directional shaping of the magnetic field, which can improve the electromagnetic energy transmission efficiency and stability [85]. But the manufacturing difficulty and cost will increase. The

FIGURE 11. A charging system based on DD coils.



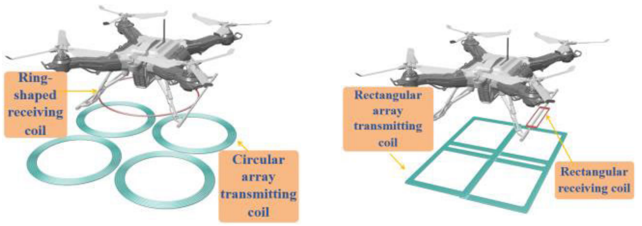
(a) (b)

FIGURE 12. Array coil. (a). 1 × 3 structure. (b). 2 × 2 structure.

multi-coil structures commonly used in UAV charging are DD coils and DDQ coils. DD coil consists of two rectangular coils with smooth curved edges, which can generate vertical flux and reduce edge leakage flux [86]. Compared with DD coil, DDQ coil is more effective in terms of magnetic field strength in both vertical and horizontal directions. Besides, DDQ coil has more flexibility and larger charging area [87].

In order to reduce the structural complexity and weight of UAV, an orthogonal MCM was designed and implemented [77]. The transmitting end of the mechanism used DD coil, while the receiving end used hollow coil wound on the landing gear of the UAV. It was placed vertically with the transmitting coil, as shown in Fig. 11. As seen, it can narrow the bilateral gap and enhance the magnetic coupling intensity. Therefore, it has a large magnetic flux capture area. The charging power can reach 500 W, and the system efficiency is as high as 90.8%. The system has good anti-misalignment performance in the x and z axis directions but weak anti-migration ability in the y axis direction, so it has certain requirements for UAV positioning accuracy.

Array coil is an electromagnetic structure composed of multiple parallel independent coils through cross connection, which can transmit energy over a long distance. This structure utilizes the interaction and coupling between the coils to generate a strong electromagnetic field and extend the induction range [88]. In UAV wireless charging, the array coils come in various forms to meet different needs. In 2012, Miwa et al. proposed one-dimensional transmitting coil array to expand the energy transmission area and increase alignment fault tolerance, as shown in Fig. 12(a) [89]. Then, a 2 × 2 array coil was proposed to improve anti-migration characteristics in the *x* and *y* axis directions. It can expand the energy receiving area and increase the spatial freedom, as shown in Fig. 12(b) [90].



(a) (b)

FIGURE 13. A charging system based on Array coil. (a) circular array transmitting. (b) rectangular array transmitting coil.

It should be noted that a multi-coil structure can be utilized at either the transmitter or the receiver to achieve WPT. For instance, in high-power WPT application scenarios, a transmitter consisting of multiple coils and a receiver with a single coil can form a one-to-many transmission structure [91], [92], [93]. This array-type transmitter coil coupling structure design has many advantages. Firstly, it enables dynamic adjustment of the transmitter's magnetic field distribution based on the receiver's position and state. Moreover, it can reduce the current and temperature rise of each coil and enhance system reliability and safety. Finally, it can increase the coil spacing and improving the quality factor and efficiency of the systems [94].

In order to realize automatic alignment and efficient charging of UAV, a 2 × 2 array structure MCR-WPT system was designed, as shown in Fig. 13(a) [95]. The system consisted of four independent array units. The transmitter coil mounted on a charging platform that can be moved in four directions. When the UAV lands on a charging platform, the transmitter can automatically adjust to the optimal position within 2 seconds with an alignment accuracy of 98.8%. The transmission power of the system is 60 W and the transmission efficiency is 85%. To mitigate the impact of coil misalignment on the coupling coefficient, multiple transmitting coils were employed to cover the charging area, which can ensure strong coupling across all possible landing positions. The coupling structure is illustrated in Fig. 13(b) [76]. The system can deliver up to 75 W of power with an efficiency of 85%.

For a one-to-many MCR-WPT structure, it consists of a transmitting coil and multiple receiving coils. Each receiving coil is connected to a battery to form a battery pack [96], [97]. By adjusting the parameters and position of the receiving coil, the selective charging of different batteries in the battery pack can be realized and the voltage balance between batteries can be ensured. This structure not only improves charging efficiency and flexibility, but also extends battery life and improves the output characteristics of the battery pack. However, there is cross-coupling between multiple receiving coils [98], [99]. It alters the self-inductance and mutual inductance of the coils. As a result, the performance and stability of WPT systems are reduced. To mitigate the impact of cross-coupling, two approaches can be implemented: firstly, the design of mutually orthogonal coil structures; secondly, the augmentation of cross-coupling compensation [100].

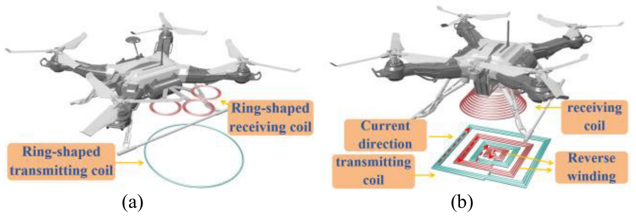


FIGURE 14. A charging system based on Array coil. (a) receiving end expandable bracket. (b) series reverse-connected coil.

In addition, 3D printing technology is also employed to create an expandable stand that can accommodate different types of UAVs. As shown in Fig. 14(a) [101], three small circular receiving coils were coupled to a circular transmitting coil. However, it is readily to cause the center of gravity shift of the UAV and bring difficulties to the flight control due to the large size and heavy weight of the UAVs.

To manipulate the magnetic field distribution flexibly, two methods are employed in wireless charging systems generally. The first method is to utilize positive superposition of magnetic fields to increase the coupling coefficient and transmission efficiency. This results in a more concentrated and intensified magnetic field. The second method is to make use of negative cancellation of magnetic fields to reduce external leakage flux and electromagnetic interference. It can create a more contained and secure magnetic field. Additionally, these methods can be employed to adjust the internal magnetic field distribution of the coupling mechanism. And it can achieve a more uniform distribution and reduce the magnitude of magnetic field variations [102].

Moreover, several design schemes have been proposed for high misalignment tolerance. Among these, a MCM with high misalignment tolerance has been designed in [103]. As shown in Fig. 14(b), square planar helical transmitting coils with unequal spacing are used to optimize coil spacing by genetic algorithm to make the magnetic field distribution more uniform. At the same time, according to the structure characteristics of UAV, the 3D spiral receiving coil with unequal radius is designed. When the maximum transmission power is 100 W, the transmission efficiency of the system can reach 92.41%, which is 56.23% higher than that of the traditional scheme. Reference [79] proposed a transmitting end, which is composed of four concentric coils. To form a uniform magnetic field above the transmitting end, two adjacent coils are connected in series and reversed. The receiving end consists of two orthogonal solenoid coils, which can receive flux in all directions. The system achieves 325 W power output and 86% system efficiency.

B. OMNIDIRECTIONAL STRUCTURE

In order to improve the flexibility and efficiency of UAV charging, the coupling mechanism of omnidirectional structure has attracted more attention. Ideally, in omnidirectional structure, the transmitter can transmit power to multiple directions and the receiver receives power at any position simultaneously. Hence, it can overcome the problem of limited position of the receiver in the directional structure [104].

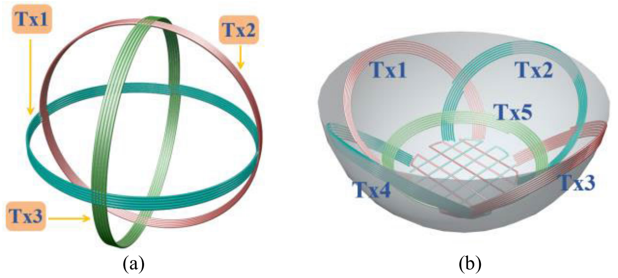
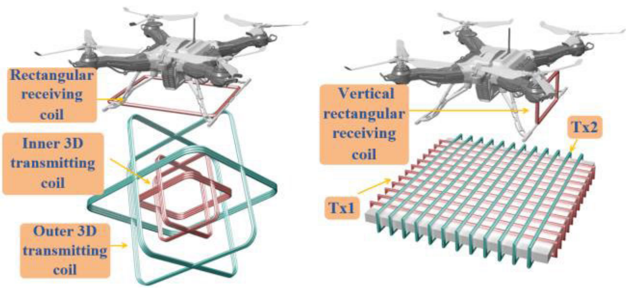


FIGURE 15. Omnidirectional coil structure. (a) spherical structure. (b) bowl-shaped structure.

Typically, a multi-coil orthogonal structure is adopted for the omnidirectional design, as shown in Fig. 15(a). The geometric normal of these three coils are located on the X, Y and Z axes respectively, and their magnetic field directions are perpendicular to the YOZ, XOZ and XOY planes [105], [106]. Since the magnetic field is passive, the magnetic circuit must be closed. Fig. 15(b) shows a special omnidirectional design with a bowl-like structure of 5 coils at the transmitting end [107]. One of the coils is located at the bottom of the bowl, and the other four coils surround the walls of the bowl. This design is to generate a uniform magnetic field in the area of the bowl. It is mainly suitable for the power supply of portable devices, so that the device can be charged wirelessly anywhere in the bowl.

In UAV wireless charging technology, omnidirectional structure is often used to realize hovering charging or dynamic power supply. In [108], a quasi-omnidirectional dynamic WPT system designed and tested based on 3D coils, as shown in Fig. 16(a). As seen, 3D orthogonal square coils and auxiliary similar scaled-down coils as transmitting coil were adopted. To make it face the UAV's horizontal receiving coil, the position of the double-3D coil was adjusted to a specific quadrant. This optimized design enabled the receiver on the UAV to effectively capture the flux and significantly improve transmission efficiency. At the same time, a single power source is required to meet the dynamic and continuous charging requirements of the UAV during the whole flight. At the resonant frequency of 270 kHz, the maximum output power of the system was 51.7W and the transmission efficiency was 91.13%.

On the other hand, a transmitting coil with two orthogonal winding wires was designed [109]. The whole coupling mechanism is shown in Fig. 16(b). Rotating magnetic field in 3D space was achieved by adjusting the 90° phase difference of the current. The distribution of rotating magnetic field can contribute to the 6-DOF wireless charging and multi-load simultaneous wireless charging of the receiving coil. The design has simple structure and low cost. In addition, it can also expand the charging space through modular connection. The experimental results show that when the height is 70 cm and 9 receiving coils are charged at the same time, the total



(a) (b)

FIGURE 16. **A charging system based on Omnidirectional coil structure. (a) double three-dimensional transmitting coil. (b) double orthogonal winding transmitting coil.**

receiving load power is 14.2 W and the charging efficiency is 8.2%.

In conclusion, it is well known that the magnetic coupling structure should be as light as possible due to the limited shape and load of the UAVs. Therefore, lightweight and miniaturized MCM design is important for UAVs wireless charging. In addition, the anti-misalignment ability of the magnetic coupling structure plays crucial roles in WPT systems for UAVs. More important, the magnetic coupling structure should reduce magnetic leakage to avoid electromagnetic interference to the UAV and the surrounding environment. At the same time, the magnetic coupling structure should ensure sufficient flux density to realize high power wireless charging.

Certainly, it is difficult for MCM to meet all requirements at the same time. Therefore, it is necessary to develop a high-performance coupling mechanism that adapts to specific scenarios and requirements.

IV. COMPENSATION TOPOLOGY

Compensation topology is one of the key design elements of WPT technology. It makes the electromagnetic coupling system and the coil inductance resonance state by adjusting the parameters of the receiving and transmitting terminal. The utilization of compensation topologies can effectively enhance system stability, reduce errors and interferences, and maintain resonance frequency stability.

A. BASIC TOPOLOGY

There are four common compensation topologies, namely, Series-Series type (S-S), Series-Parallel type (S-P), Parallel-Parallel type (P-S), and Parallel-Parallel type (P-P), as shown in Fig. 18. Among them, S-S and S-P topologies require voltage-type inverters while P-P and P-S topologies require current-type inverters [110].

Wireless charging systems with different functional requirements need to select appropriate compensation topology. On the transmitting side, the choice of compensation topology depends on the desired transmission distance or voltage. Series compensation is suitable for long-distance transmission, while parallel compensation is suitable for situations where the transmitting coil requires a large current [111]. On the receiving side, the series compensation has voltage source characteristics and is suitable for systems with intermediate DC busbars. Parallel compensation has current source characteristics and is suitable for battery charging.

The S-S compensation topology is a low-cost compensation structure suitable for high-power applications. Its system frequency is entirely determined by the capacitance and self-inductance of the coupling mechanism, unaffected by factors such as load, coupling, and excitation. This topology can deliver a constant voltage (CV) output while maintaining a high power factor. In contrast, the S-P compensation topology features lower primary-side current and reduced switching device losses, but it requires adjusting the input frequency to match the resonant frequencies of the primary and secondary sides [112].

On the other hand, both the PS and PP compensation topologies have primary-side compensation capacitors that vary with changes in load resistance [113]. Specifically, the PS topology enables adaptive matching for wireless power transfer, automatically adjusting the value of the primary-side compensation capacitor to maintain maximum power transfer, without the need for complex feedback control or frequency tuning. This simplifies system design and implementation [114]. The PP topology, conversely, facilitates multi-frequency point selection for wireless power transfer. It allows for choosing different combinations of secondary-side compensation capacitors based on different operating frequencies, thereby enabling switching between multiple resonance frequency points. This approach enhances system flexibility and robustness, adapting to varying transmission distances and coupling coefficients [115].

B. APPLICATION OF BASIC COMPENSATION TOPOLOGY IN UAV WIRELESS CHARGING SYSTEM

In order to reduce the weight of UVA, lithium batteries are widely adopted due to their high power density and flexible packaging form. In [77], researchers achieved control over the charging of lithium batteries with a constant current (CC) by employing the S-S compensation topology. In [116], in order to further reduce the burden of the UAV wireless charging system, a simplified S-S compensation topology was adopted. To reduce the weight, only one compensation element was used at the receiving end, and smoothing capacitor was adopted instead of inductor. In addition, S-P compensation topology was adopted in [76] to realize uncontrolled circuit regulation of output voltage and reduce the weight of the receiving terminal of UAV. However, the number of turns in the receiving coil was restricted to ensure equivalent efficiency. The performance of S-S compensation topology and S-P compensation topology were compared and analyzed respectively in UAV wireless charging system. The results indicate that the selection of coil turns has an impact on the efficiency of both the S-S compensation topology and the S-P compensation topology. In general, the S-S compensation

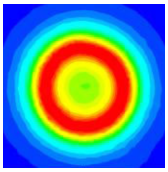
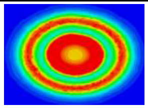
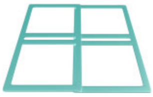
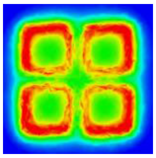
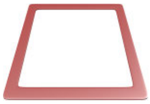
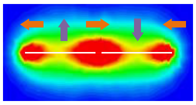
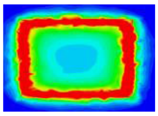
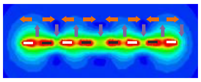
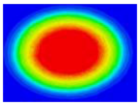
Transmitter coil type	Magnetic field simulation	Receiver coil type	Time (year)	Output power (W)	Efficiency	Working frequency	Size (Transmitter coil) (Receiver coil)	misalignment tolerance	Reference
			2022	221	83.5%	301kHz	43 mm×43 mm 43 mm×43 mm	-	[69]
			2023	135	77.5%	300kHz		-	[70]
			2022	100	80.6%	150kHz	280 mm×280 mm 75 mm×75 mm	150 mm	[71]
			2021	41.2	90.1%	6.78MHz	150 mm×150 mm 50 mm×50 mm	200 mm	[72]
			2020	26.43	91.9%	150kHz	300 mm×300 mm 100 mm×100 mm	100 mm	[73]
			2020	65.77	62.44%	162kHz	320 mm×320 mm 210 mm×210 mm	-	[74]
			2020	183.7	90.8%	302kHz	590 mm×590 mm 150 mm×150 mm	220 mm	[75]
			2018	64	79%	150kHz	400 mm×150 mm 20 mm×50 mm	70 mm	[76]
			2021	87.4	97.3%	85 kHz	200 mm×90 mm 400 mm×35 mm	400 mm	[77]
			2021	185	90%	85 kHz	188 mm×188 mm 36 mm×26 mm	40 mm	[78]
			2022	325	86%	50 kHz	600 mm×600 mm 105 mm×105 mm	100 mm	[79]
			2021	625	94%	50 kHz	400 mm×400 mm 475 mm×475 mm	100 mm	[80]

FIGURE 17. **The research progress of magnetic field coupling for UAV of the major research institutions and enterprises.**

topology is well-suited for scenarios with more coil turns and a higher coupling coefficient, as its efficiency increases with the increase of turns and coupling coefficient. On the other hand, the S-P compensation topology is more suitable for situations with fewer coil turns and a lower coupling coefficient.

C. COMPLEX COMPENSATION TOPOLOGY

In order to improve the performance of wireless charging system, some improved compensation topology structures are proposed based on the basic compensation network. Among them, the LCL compensation topology can achieve automatic switching between a charging mode with a CC and a CV by adjusting network parameters. It has advantages such as high transmission efficiency, high end-to-end peak efficiency and good light-load characteristics [117]. Especially, the LCL compensation topology can achieve high efficiency and uniform power factor under light load. It also has good harmonic filtering capability [118].

In [119] an LCC compensation topology was introduced, which is derived from the LCL compensation topology. This topology can simplify the primary side control and realize the unification of the secondary side power factor. It is characterized by constant input and output current, which can maintain high efficiency under light and heavy load conditions [120]. In addition, the topology is designed under minimum mutual

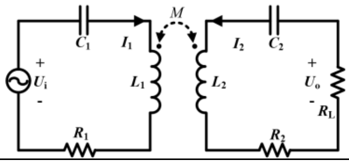
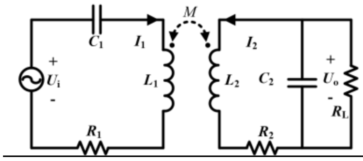
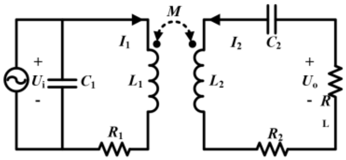
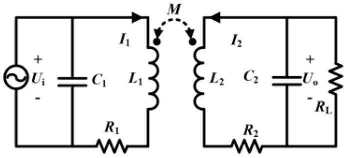
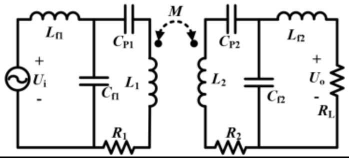
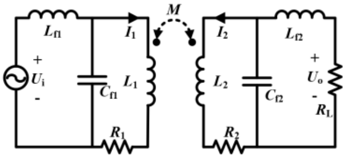
Topology type	advantages	disadvantages	applications
S-S 	Simple and easy to implement CV charging Suitable for variable load High power transfer High misalignment tolerance	Output voltage changes with load Post-stage voltage regulation circuit required Output short leads to input power increase and component damage	Electric Vehicles Industrial equipment CV charging scenarios
S-P 	CC charging Suitable for variable load High misalignment tolerance High power applications	Output current changes with load Post-stage current limiting circuit required Output open leads to input power increase and component damage	Mobile phones Implanted medical device CC charging scenarios
P-S 	Large power factor variation High impedance Moderate misalignment tolerance	Coil resistance, inductance and capacitance affect transmission efficiency Low transmission efficiency Current source needed for power supply	It can be used to achieve adaptive matching for wireless power transfer, automatically adjusting the value of the primary-side compensation capacitor based on changes in the load resistance, thereby maintaining maximum power transmission.
P-P 	Low power applications; High frequency offset tolerance High impedance at resonance state		It can be used for multi-frequency point selection in wireless power transfer, meaning different combinations of secondary-side compensation capacitors can be chosen based on various operating frequencies, thus achieving switching between multiple resonance frequency points.
LCC-LCC 	CC output at TX High reliability and stability; Reduce power device loss Reduce temperature rise; Reduce harmonic content Reduce EMI	Large capacitor required Capacitor value aligned with system frequency Frequency control or auxiliary network for load changes and optimal operation	High output current or voltage WPT: Medical implant Drones Devices dynamic wireless charging
LCL-LCL 	High efficiency High power density Suppress harmonic interference Suppress parasitic parameters High impedance	Complexity and loss from filters and damping devices Adjust LCL parameters carefully Use frequency control or additional network for load changes and optimal operation	High-output-power WPT: Vehicles Industrial equipment Household appliances

FIGURE 18. The principle and characteristics of compensation topology in WPT system.

inductance and has good anti-migration performance. Experimental results show that the topology can transmit 6.6kW power with an efficiency of 95.05% at a vertical displacement of 150 mm [121]. However, the operation of this topology is complicated due to its high order system and resonant mechanism.

In order to select and analyze the full compensation topology scheme suitable for UAV wireless charging system, it is necessary to consider their advantages, disadvantages and applicable conditions as well as the constraints of the system.

D. APPLICATION OF COMPLEX COMPENSATION TOPOLOGY IN UAV WIRELESS CHARGING SYSTEM

In [122], a magnetic coupled resonance system suitable for dynamic wireless charging of UAV was designed. The system employed a dual LCC resonant network compensation structure to achieve control of a CC on the primary side and control of a CV on the secondary side. The problem of insufficient power transmission capacity of the dual LCL structure was solved. The system has the advantages of good transmission effect, low cost, simple implementation, safety and reliability.

In order to reduce energy loss and improve efficiency, a low voltage and high current system suitable for wireless charging of UAV was designed [123]. The system adopted LCL-S compensation topology. Compared with S-P compensation topology, the reflected impedance was pure resistance and the system stability was higher. To ensure a constant output voltage and primary-side current, the LCC-S compensation topology was employed [124], which effectively prevents primary-side overcurrent damage and satisfies the lightweight requirement of the UAV. In comparison to the

LCC-S compensation topology, the LCC-P compensation topology significantly minimizes the impact on the input impedance magnitude. Moreover, the LCC-P compensation topology can reduce switching losses. However, when the coil coupling degree is low, the input current compensated by LCC-P may increase [70]. In order to enhance the charging capacity and efficiency, a combined WPT system utilizing the LCC-P compensation topology was proposed [69]. The LCC-P compensation topology exhibits high stability and robustness. It can optimize the charging process and reduce fluctuations in output current and transmission efficiency.

The compensation topology design in the magnetically coupled resonant wireless charging system of UAV is a comprehensive problem, which needs to consider a variety of factors, including the following requirements:

(1) Stability requirements: To ensure stable wireless charging for UAVs during flight or movement, the compensation topology must exhibit excellent stability, capable of withstanding variations in factors while maintaining a constant resonance frequency and output voltage/current. Additionally, it is essential for designers to streamline the control and circuit systems.

(2) Requirements on power transmission efficiency: the design of compensation topology should optimize the power transmission efficiency to ensure that the energy loss of the charging system is minimized. This requires the selection and optimization of the type and value of the compensation components.

(3) Practical considerations: The design of the compensation topology for the MCR-WPT of UAV should take into account the specific application scenarios and characteristics of UAVs. These include environmental factors, size, weight, energy requirements, and cost.

Compensation topology design needs to make reasonable trade-offs and compromises. At the same time, further research on the theory and application of compensation topology technology is needed to explore to improve the performance and reliability of UAV wireless charging.

V. CONTROL STRATEGY

During wireless charging, the UAV may be affected by interference or abnormal effects, such as temperature changes and magnetic field fluctuations. These factors may cause the output power to be unstable or beyond the safe range. It will endanger the safety of equipment and human beings. Therefore, power control is a vital technology in the field of MCR-WPT for UAVs. Currently, the commonly used power control technologies include primary-side power control, secondary-side power control, and dual-side power control.

A. CONTROL STRATEGY OF UAV WIRELESS CHARGING SYSTEM

Secondary power control is a method to control the transmission power of wireless charging system by adjusting the output voltage or current on the receiving side. It allows for precise charging with a CC or CV, while also adds weight and complexity to the receiving side. Primary power control is a method of adjusting the output voltage or current on the receiving side through closed-loop feedback on the transmitting side. It can reduce the load and complexity of the receiving side and improve the system efficiency. Therefore, the UAV wireless charging system usually adopts primary power control. A wireless charging circuit topology and closed-loop power controller based on primary side power control was designed [77], as shown in Fig.19. The controller provides feedback on the charging voltage and current of the battery load to the charging station through wireless communication. It utilizes an incremental PID control strategy to regulate the output of the inverter bridge. It can achieve CC or CV charging. However, it is important to consider the impact of wireless communication delay on the control performance.

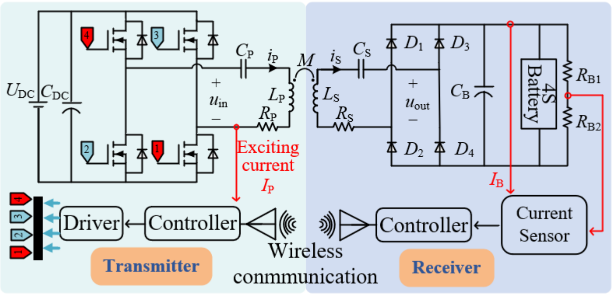


FIGURE 19. A charging system based on primary-side power control.

The traditional wireless charging control strategy is only applicable to the single-channel charging system, which limits the application scenarios of the wireless charging system. In order to improve the stability and flexibility of the wireless charging system, multi-channel transmission is a feasible method, which can realize the simultaneous charging of multiple UAVs. A multi-channel wireless charging system to provide energy for rotary-wing UAVs was designed [69]. The system used the multi-channel output current estimation control method, combined the information of the transmitter and the identification of unknown parameters. It realized the multi-channel output estimation control strategy and effectively inhibited the circulation current interference, as shown in Fig. 20. The system eliminated the need to install a complex measurement circuit and feedback communication system on the receiving side. It also can reduce the weight of the receiving side of the UAV and improve the processing speed and control accuracy. At the same time, the system has fault-tolerant capability. It can work normally even if one channel fails. This improves the performance and stability of wireless charging.

The multi-channel WPT system has the advantages of high efficiency and high flexibility. But there are also some problems, such as unbalanced power distribution, output current ripple and rectifier fault. To solve these problems, a combinable WPT system was proposed in [70], and an active current ripple mitigation scheme based on real-time current

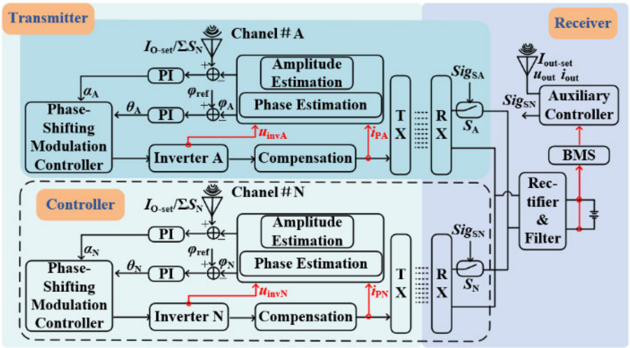


FIGURE 20. Control strategy for multi-channel wireless charging system.

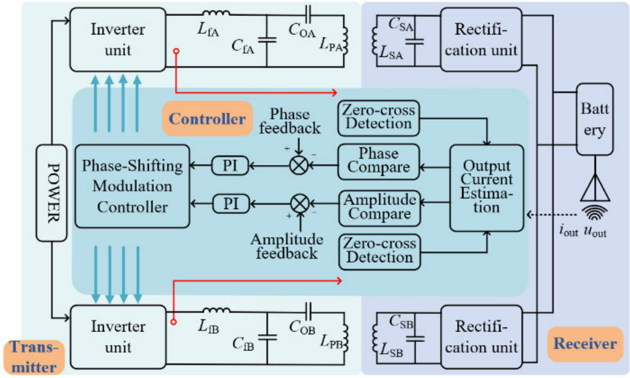


FIGURE 21. Control strategy for composable WPT system.

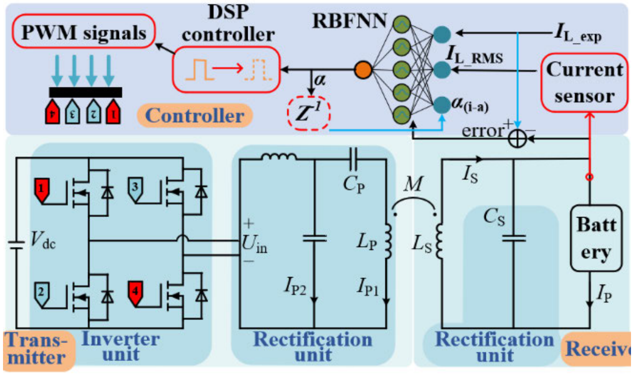


FIGURE 22. CC control based on Radial basis function neural network.

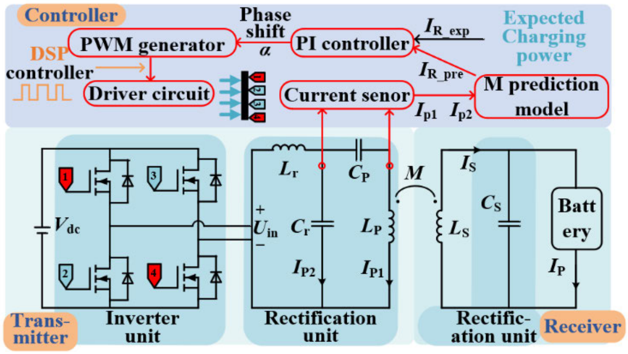


FIGURE 23. Mutual induction-dynamic prediction CC control.

estimation was designed. The scheme eliminated output current ripple using interweaving technology and mitigated resultant current ripple by adjusting the current at the receiving end. The system does not need extra communication modules, and all the control modules are arranged at the transmitter side. It can reduce the weight and cost of the UAV receiver side. The system structure is shown in Fig. 21.

Most of the existing researches on UAV wireless charging are based on the UAV directly landing on the charging platform, which is not suitable for the dynamic UAV wireless flight charging system. In actual flight, the wireless flight charging system needs to provide a constant charging current for the hovering UAV under the condition that the coupling effect, parameters and charging power demand are also constantly changing. This is rarely involved in the previous research on WPT technology. To address this issue, an enhanced control approach for maintaining a CC was introduced, as depicted in Fig. 22 [125]. It used radial basis function neural network trained online to ensure consistent output of the desired current, compensating for variations. Compared with conventional control schemes such as PID control, this method had better control performance. This method could improve the charging control performance of hovering UAVs in dynamic flight, so as to effectively extend its cruising range through wireless flight charging system.

Traditional CC control schemes rely on model or quadratic parameters and require communication between transmitter and receiver. This not only increases the weight of the pickup end and the difficulty of control, but also makes the system vulnerable to delay or electromagnetic interference. To solve this problem, a unilateral estimation method which only used the primary side information to estimate mutual induction and load was proposed [126]. But the working frequency of this method was different from the resonant frequency of the circuit, which affects the output power. The method was further improved in [127], and a mutual induction-dynamic predictive CC control scheme was proposed, as shown in Fig. 23. By predicting mutual inductance of primary current and optimizing phase shifting strategy, the scheme realized mutual inductance fast tracking and output current regulation without secondary feedback. This scheme effectively improved the real-time response ability of the system to mutual inductance fluctuations, reduced the weight of the UAV and enhanced the ability of the system to resist communication failures.

At present, most researches focus on wireless charging system optimization under fixed operating parameters without feedback control. However, when the coupling conditions change, the transmission power and transmission efficiency of such a system will still fluctuate. To solve this problem, [128] drew on the principle of parity-time (PT) symmetry in quantum physics, and proposed a universal nonlinear PT-symmetric model. This model was applied to the wireless charging system of UAV in [82], and the system structure is shown in Fig. 24. It achieved stable power transmission and efficient energy utilization under dynamic coupling conditions. To simplify the circuit structure and control strategy, the system used a self-vibration control inverter to provide

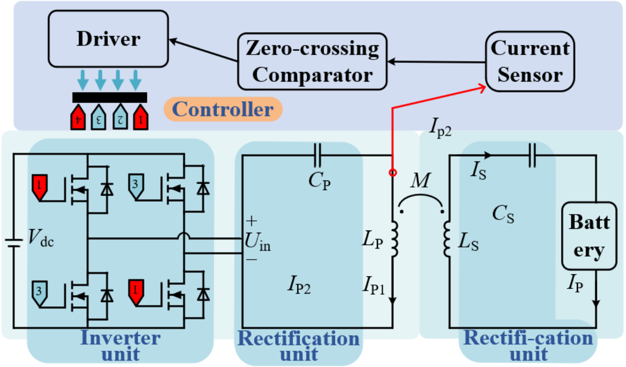


FIGURE 24. CC control based on PT symmetry principle.

nonlinear saturable gain and only need to detect the transmitting current. In addition, there was no wireless communication auxiliary circuit and no parameter adjustment. WPT system based on nonlinear PT principle has good practical application prospect.

B. REMARKS

The control strategy of a UAV wireless charging system consists of two primary components: the transmitter side and the receiver side. The transmitter side typically employs a feedback control strategy It can adjust the power output based on signals such as output power, voltage, and current. On the receiver side, the focus is on power matching between the adapter and the charger. The adapter must match the charger's output power with the battery characteristics and charging current of the UAV. This ensures appropriate charging speed and stability throughout the charging process. As UAVs exhibit dynamic characteristics, the control strategy of the UAV wireless charging system must possess fast response and adaptive capabilities. Advanced control strategies can be employed to further optimize charging efficiency and stability, such as maximum power tracking algorithms, optimal power control algorithms, and minimum power extraction algorithms. These algorithms leverage techniques such as neural networks, predictive control, and nonlinear PT symmetry to achieve rapid tracking of coupling induction and load, as well as output current regulation without requiring secondary feedback or parameter adjustment. They not only enhance real-time response and anti-interference capabilities but also reduce the weight and cost of the UAV receiver side. It can offer innovative solutions for UAV wireless charging systems.

VI. MAJOR CHALLENGES AND PROSPECTS OF WIRELESS CHARGING TECHNOLOGY FOR UAVs

A. MAJOR CHALLENGES

The WPT technology for UAVs is an innovative method. It can enhance the flight time and operational efficiency of UAVs. However, to achieve practical applications and large-scale production of this technology, numerous challenges and issues still need further research and resolution.

1) HIGH PERFORMANCE REQUIREMENTS

The efficiency of WPT for UAVs is influenced by several factors, such as distance, coil structure and environmental obstacles. To improve the efficiency, optimization of these factors is necessary in UAV wireless charging systems. In addition, the provision of ample power is required for efficient and rapid UAV wireless charging system. Because it can facilitate convenient UAVs landing and take-off with a wide range and alignment tolerance.

2) STANDARDIZATION

Currently, WPT technology for UAVs lacks a standardized protocol, which hinders interoperability and compatibility between devices and manufacturers. To address this, it is crucial for wireless charging systems to adhere to relevant guidelines or regulations. Moreover, wireless charging systems should be designed and operated in tandem with existing UAVs, taking into account factors such as size, weight, cost, and complexity of components like coils or antennas. These factors should be minimized and tailored to match the diverse batteries and chargers employed by various UAV models.

3) SCALABILITY PROBLEM

In order to realize simultaneous wireless charging of multiple UAVs, the wireless charging system needs to have intelligent management functions, which can dynamically allocate, schedule and prioritize power sources. Moreover, the flow of energy between UAV components also needs to be considered. Since different types, specifications and requirements of batteries are widely used in UAVs, wireless charging systems need to be able to identify and regulate these differences and provide the best charging parameters. Significantly, WPT systems for UAVs also need to protect batteries from overcharge, undervoltage or damage.

4) SAFETY AND COMPLIANCE ISSUES

Security is a constant topic, especially for UAV wireless charging. Potential risks should be taken into account while charging, such as overheating, electromagnetic radiation and short circuits. Among these safety issues, electromagnetic radiation is frequently considered and studied. In response, UAV wireless charging systems can selectively choose suitable operating frequencies, refine antenna designs, determine appropriate transmission distances and power levels, and augment the effectiveness of shielding layers or isolation zones. Additionally, UAV wireless charging systems should also possess the ability to withstand adverse weather conditions such as rain, dust, snow, and wind, to prevent potential damage to both the UAV and charger. Such damage could subsequently compromise the efficiency and reliability of the entire drone wireless charging system. To tackle these challenges, several measures can be adopted. For instance, the use of waterproof, dust-resistant, and snow-resistant materials or structures can protect drones and chargers. Moreover, technologies like adaptive tuning, automatic tracking, and automatic calibration can be employed to enhance signal transmission efficiency. Simultaneously, redundant design, fault tolerance, and diagnostic techniques can contribute to bolstering the overall stability of the system.

B. PROSPECTS

The wireless charging technology of UAVs plays a pivotal role in realizing the final stage of intelligent unmanned systems and represents a significant direction for future development. With the increasing utilization of UAVs across various fields, the demand for enhanced endurance and autonomy is rising. To overcome current technological limitations and elevate the operational efficiency and safety of UAVs, it is essential to explore innovations in multiple dimensions, including new devices, materials, theories, applications, and more. These endeavors have the potential to unlock new opportunities for future UAV applications and technological advancements. It can foster progress within the UAV industry.

1) NEW DEVICE

The successful implementation of UAV wireless charging technology relies on devices with high-frequency, integration, lightweight, compactness, and intelligence. It is crucial to enhance the efficiency, stability, and security of the system. Accurate control and optimization of the power transmission process should be prioritized. Key components such as the high-frequency inverter, rectifier, and power controller play a vital role in this regard. Wide-band gap materials, including gallium nitride and silicon carbide, have emerged as a research hotspot for high-frequency converters due to their advantages such as high frequency capability, strong voltage resistance, efficient heat dissipation, low on-off and switching losses. These materials exhibit high-frequency characteristics. Moreover, they enable power transmission above kW at frequencies of 6.78MHz or higher. It can reduce the weight and volume of UAVs effectively.

2) NEW MATERIALS

By utilizing specialized new materials, wireless charging technology for UAVs can achieve higher transmission efficiency, lower losses, and enhanced anti-interference capabilities. For instance, the use of superconducting materials enables the production of high-temperature superconducting magnets, which enhance the transmission efficiency and load power of wireless charging systems. Furthermore, nanocrystalline FeSiB materials in the field of nanotechnology possess high saturation magnetic induction intensity, high permeability, and low loss. They significantly improve the transmission efficiency and load power of UAV wireless charging systems. It can reduce charging time and energy loss. Additionally, these materials exhibit stable magnetic and soft magnetic properties, enabling adaptability to the charging requirements of UAVs in various environments.

3) NEW THEORY

UAV wireless charging technology encompasses multiple disciplines. It requires continuous exploration and innovation of relevant theories and methods to enhance transmission efficiency, security, stability, and other performance indicators. For instance, PT Symmetry, characterized by unidirectional transparency, ultra-sensitive phase transition, and edge states of non-Hermitian topological insulators, offers high efficiency, safety, reliability, and robust energy transmission capabilities. The real eigenstate method utilizes vibration theory to model and analyze magnetic-coupled wireless energy transmission systems. This method provides valuable insights for system design and optimization.

4) NEW APPLICATION

To meet the needs of various types, sizes, and environments of UAVs, there is a growing demand for more diversified and flexible charging platforms and devices. For instance, in the field of biomedical engineering, UAVs can be utilized for wirelessly charging implantable medical devices, including pacemakers, nerve stimulators, and drug pumps. Moreover, UAV wireless charging technology has the potential to foster integration with other cutting-edge domains like artificial intelligence, Internet of Things, cloud computing, and 5G networks. As an illustration, a UAV wireless charging station can function as a smart hub, gathering data from multiple UAV sensors and transmitting it to a centralized cloud platform for analysis and decision-making. Alternatively, by leveraging artificial intelligence algorithms, UAV wireless charging stations can optimize power management and scheduling for UAV fleets. Additionally, the seamless integration of UAV wireless charging technology with 5G networks enables high-speed data transmission and low-latency communication between UAVs and ground control stations.

VII. CONCLUSION

One of the significant challenges in the development of UAVs is their limited endurance. WPT technology holds great promise in addressing this issue. This paper presents a comprehensive review of various types and principles of WPT technology. It specifically focuses on the design and control of MCR-WPT for UAVs. The paper also highlights key considerations and challenges in the practical application of UAV wireless charging technology across various fields. Finally, it provides an outlook on the future prospects of this technology.

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