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A Review on UAV Wireless Charging: Fundamentals, Applications, Charging Techniques and Standards

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ABSTRACT Unmanned Aerial Vehicles (UAVs) are becoming increasingly popular for applications such as inspections, delivery, agriculture, surveillance, and many more. It is estimated that, by 2040, UAVs/drones will become a mainstream delivery channel to satisfy the growing demand for parcel delivery. Though the UAVs are gaining interest in civil applications, the future of UAV charging is facing a set of vital concerns and open research challenges. Considering the case of parcel delivery, handling countless drones and their charging will become complex and laborious. The need for non-contact based multi-device charging techniques will be crucial in saving time and human resources. To efficiently address this issue, Wireless Power Transmission (WPT) for UAVs is a promising technology for multi-drone charging and autonomous handling of multiple devices. In the literature of the past five years, limited surveys were conducted for wireless UAV charging. Moreover, vital problems such as coil weight constraints, comparison between existing charging techniques, shielding methods and many other key issues are not addressed. This motivates the author in conducting this review for addressing the crucial aspects of wireless UAV charging. Furthermore, this review provides a comprehensive comparative study on wireless charging's technical aspects conducted by prominent research laboratories, universities, and industries. The paper also discusses UAVs' history, UAVs structure, categories of UAVs, mathematical formulation of coil and WPT standards for safer operation.

INDEX TERMS Wireless power transfer, drone, UAV, inductive power transfer, capacitive power transfer, magnetic resonance charging, coil design, compensation networks.

ABBREVIATION

BLDC	Brushless DC Motor
BoL	Beginning of Life
CAGR	Compound Annual Growth Rate
CoC	Coefficient of Coupling
CPT	Capacitive Power Transfer
DAN	Drone Acknowledgement Number
DLC	Distributed Laser Charging
DoD	Depth of Discharge
EM	Electro Magnetic
EMF	Electro Magnetic Field
EoL	End of Life
ESC	Electronic Speed Controller
EV	Electric Vehicle
FC	Flight Controller
FPV	First Person View
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle
HF	High Frequency
HTS	High-Temperature Superconducting
IPT	Inductive Power Transfer
Li-Ion	Lithium-Ion
LiPo	Lithium Polymer
MPT	Microwave Power Transmission
MRC	Magnetic Resonant Coupling
NPNT	No-Permission No-Take-off
OAN	Owner Acknowledgement Number
PDB	Power Distribution Board

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PE	Power Electronic
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photo-Voltaic
RPV	Remotely Piloted Vehicle
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-Off and Landing
WPT	Wireless Power Transfer

I. INTRODUCTION
A drone is a colloquial term for Unmanned Aerial Vehicle (UAV), commonly referred to a commercial quadcopter. Initially, drones were developed as camera operated remotely piloted bomb carriers in 1944 US military missions. In the past decade, drone technology caught up to civilian applications; Owing to its high maneuverability, compact design and lightweight, the technology has boundless potential for several applications such as Inspections [1], [2], Agriculture [3], [4], 3D Mapping-Modelling [5], Surveillance-Monitoring [6], [7], Damage Assessment [8], [9], Parcel delivery, Photography, Leisure/Hobby flying and numerous other applications. Fig. 1 shows wide areas of drone applications. It is estimated that by 2025 the drone market would reach $43 billion in total sales with a Compound Annual Growth Rate (CARG) of 13.8%, as illustrated in Fig. 2 [10]. Drones have been designed to be piloted remotely, either by using a radio controller or by using preprogrammed flight paths. Nowadays, semi-autonomous drones [11]–[14] are becoming popular in photography and leisure flying. However, drones are power-hungry machines, working against gravity, depleting the battery within minutes of their operation. Most of the photography drones have a battery life of less than 30 minutes [15], [16], thus severely affecting the performance over an area of interest. A common way of recharging a depleted drone is through battery swapping, where a depleted battery is plugged out of the drone and replaced with a fully charged one. The physical battery swapping method requires the aid of human personnel, severely affecting autonomous drone operations in remote areas or hard to reach places. In recent years, few drone charging methods were proposed, which used Non-Electro Magnetic Field (EMF) based techniques for prolonging UAVs flight time. The Non-EMF based charging strategies are Gust soaring [17], [18], Integration of PV arrays [19], Laser beaming and Battery dumping [20]. The EMF-based charging techniques are categorized based on the transmission range: Near Field Transmission and Far-Field Transmission. Near field transmission techniques includes Capacitive Power Transfer (CPT) [21], [22], Inductive Power Transfer (IPT) [23] and Magnetic Resonant Coupling (MRC) [24]. Far-field transmission techniques are Laser-based transmission [25] and Microwave Power Transmission (MPT) [26]. The charging type for UAVs is illustrated in Table 1.

A. MOTIVATION
The usage of drones for applications such as delivery, surveillance and monitoring will soon be handling countless drone units. Managing such a large number of units and charging them through the wired medium will become a tedious task. A centralized charging mechanism such as wireless charging would aid in multi-device charging and autonomous monitoring of individual units. Wireless power technology being developed for EVs are not limited to weight constraints. Drone, being an airborne vehicle, is obligated to reduce weight for longer flight times. Researchers are focusing majorly on developing drones for various applications, and limited work is being proposed for autonomous drone charging. Moreover, wireless power technology comes with its shortcomings, such as efficiency, misalignment tolerance, the weight of transmission-receiver coil, control strategies, and EM waves' effect on the human body. To the best of the author's knowledge, in the literature of the past five years, the implementation of wireless charging for drones is moving at a very slow pace, which will be a challenge for charging the exponentially growing drone units. This motivates the author in presenting a review article on wireless UAV charging techniques. This review aims to address the wireless charging concept for drones with real-time case studies by prominent research institutes and industries. Furthermore, this article also delivers future research directions and challenges in the field of wireless charging technology for drones.

B. BACKGROUND ON EMF-BASED CHARGING METHODS
The EMF-based charging methods have gained popularity in recent decades for small electric appliances and Electric Vehicle (EV). Similar technology can be adopted for autonomous drone charging. In comparison to IPT, CPT works for short distances in the range of a few mm. Jiejian *et al.* demonstrated an experiment using a high capacitive coupling of 10 nF to transmit greater than 1 kW at an operating frequency of 540 kHz. However, CPT has a stronger magnetic field emission compared to IPT [27], [28]. IPT has gained the interest of researchers for charging home appliances such as smart watches, smartphones, tablets, autonomous robotic vacuum cleaners and inspection robots [29]–[36]. In terms of kW transmissions, IPT is being implemented for EVs [37]–[40], as IPT has high misalignment tolerance, more extended transmission range, high power density, and more efficiency than other techniques. Studies have been conducted to efficiently merge WPT technology into drone charging [41]–[49]. Multiple scientific studies determine Inductive charging for effective power transmission to a few cm intended for drone charging. IPT is resilient towards environmental factors such as accumulating dust and water droplets on the charging pad while simultaneously maintaining efficiency levels [41]–[44]. WPT for drones can overcome the drawbacks of battery swapping and eliminate the need for human intervention in autonomous missions. Attempts to develop WPT drone charging pads have been made by companies [50]–[54] with an average power transmission rate of 200-300 W, especially Global Energy Transmission (GET) Corporation [54] is working on inflight charging at a transfer rate of 12 kW.

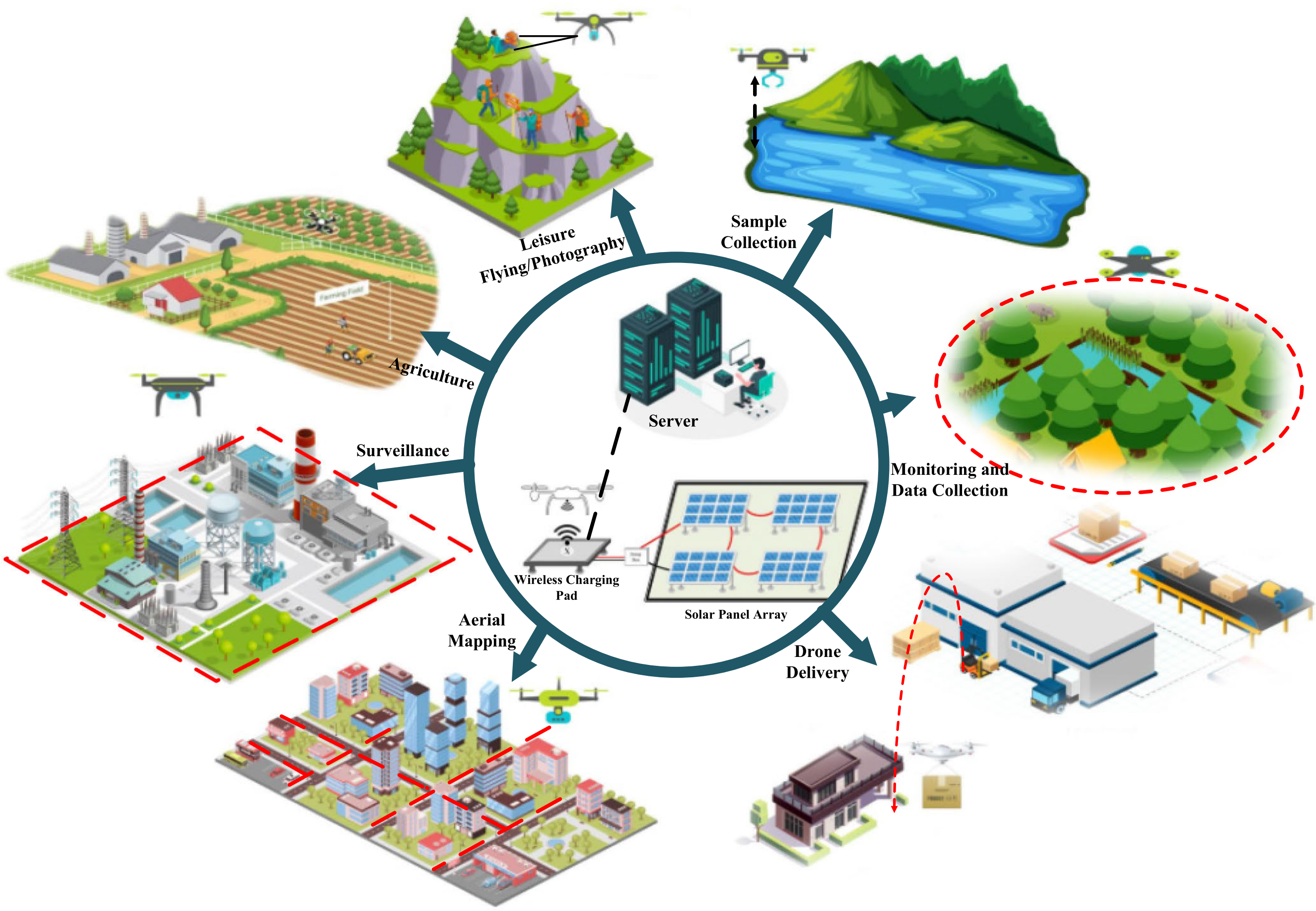


FIGURE 1. Applications of commercial drones in diverse sectors.

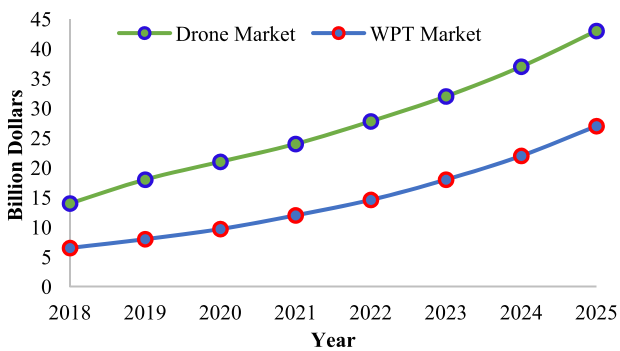


FIGURE 2. Statistics of Drones and WPT market growth (Data Source: MarketsandMarkets Report 2020-2025, Drone Industry Insight Report [10]).

TABLE 1. Charging methods to charging types.

Non-EMF Based Charging	Charging Type	EMF Based Charging	Charging Type
Gust Soaring	In-flight Charging	Capacitive Charging	Stationary charging up to a few mm
PV Integrated	In-flight Charging	Inductive Charging	Stationary charging up to a few cm
Laser Beaming	In-flight Charging	Magnetic Resonant Charging	Stationary charging up to a few cm
Battery Dumping	In-flight Charging		

C. STRUCTURE AND CONTRIBUTION

Fig. 3. Illustrates the organization of the proposed review article. The article aims to develop a wireless power transfer circuit for drone charging while identifying the key aspects of wireless power and drone technologies. The significant contributions of the paper are as follows:

- This paper aims to deliver a comprehensive study on wireless charging technology for drones.
- A brief history of UAVs and their categories are presented in details with illustrative figures.
- The fundamental theory behind wireless charging technology and its types are illustrated with real-time case studies.

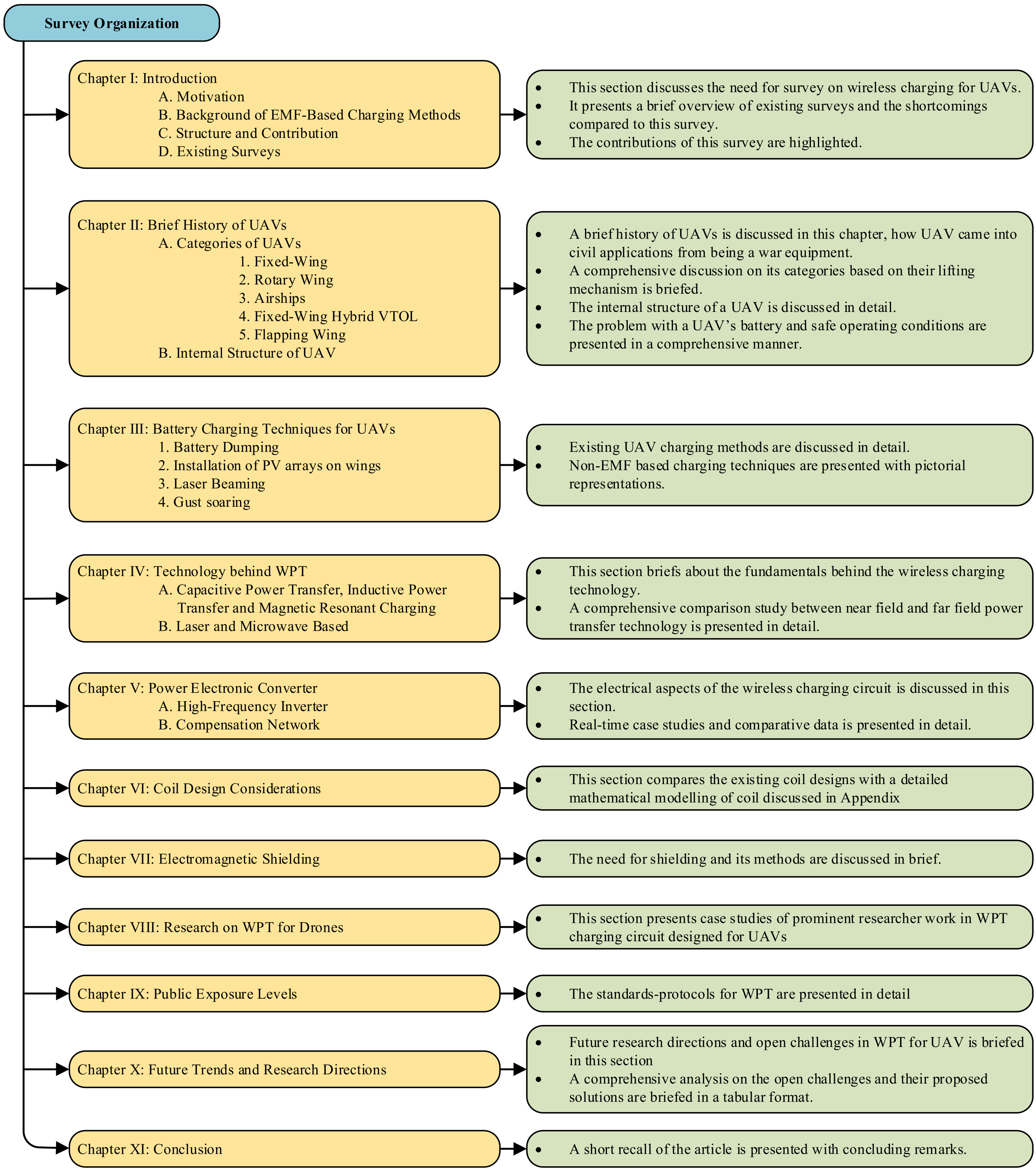


FIGURE 3. Organization of the review article.

- The design of wireless charging coils is presented with mathematical modelling and simulations.
- A detailed outlook of electrostatic shielding techniques is presented in this work.
- A detailed analysis by prominent institutes and industries is presented for developing wireless charging pads for drones in this work.
- Future research directions and open challenges in the field of wireless charging for UAVs are briefed.

D. EXISTING SURVEYS

The existing review articles on UAVs predominantly focus on their applications, majorly related to the IoT sector [61]–[65]. Limited literature is available on UAV's internal structure,

TABLE 2. Comparison of surveys on UAV wireless charging (✓) is indicated for topic covered (✗) is indicated for topic not covered.

Topics	Ref. [55]	Ref. [56]	Ref. [57]	Ref. [58]	Ref. [20]	Ref. [59]	Ref. [60]	This Survey
Applications of UAVs	✓	✓	✓	✓	✗	✗	✗	✓
Market Opportunities	✗	✓	✗	✗	✗	✗	✗	✓
Classification of UAVs	✓	✓	✓	✓	✗	✗	✗	✓
Structure of UAVs	✓	✗	✗	✗	✗	✗	✗	✓
Charging Techniques	✓	✗	✗	✗	✓	✗	✓	✓
Wireless Charging Techniques	✗	✗	✗	✗	✓	✓	✓	✓
WPT Mathematical Modelling	✗	✗	✗	✗	✗	✗	✓	✓
Wireless Charging Standards	✗	✗	✗	✗	✗	✗	✗	✓
Future Trends and Research Directions	✗	✓	✗	✗	✗	✓	✗	✓

wireless circuit modelling, challenges and future trends. Table 2 portrays a summary of surveys conducted in the last five years in UAV charging on different aspects of unmanned aerial vehicles such as classifications, charging techniques, market opportunities and applications. Townsend *et al.* [66] compared various types of unmanned aerial vehicles, their power sources and recommended few solutions for improving their flight time. The authors concluded that drones powered by combustion engines provide better efficiency; however, pollution being their biggest downfall. Similarly, solar charging offers an eco-friendly charging circuit which requires a high investment and maintenance cost. Tahir *et al.* [57] analyzed on classification, structure, characteristics and applications of UAV. In this study, the authors aimed to examine the public awareness levels in terms of UAV and their applications. They conducted a subjective analysis in two countries (Finland and Pakistan) and circulated among 187 different discipline people. The questionnaire includes knowledge, applications, surveillance, concerns and usage of the UAVs. The authors identified that 95% of the people are aware of UAV technology, 23% utilized UAV for various purposes, and 60% agreed that UAV serves as better surveillance devices. Albeaino *et al.* [58] presented a systematic literature review on UAVs with their classification and applications in the discipline of construction, engineering and architecture. The authors discussed the various sensors and transducers embedded or mounted on UAV for a stable flight and serving their applications. Also investigated on additional technologies of UAV to enhance the performance and suppress other technical and environmental challenges. Boris Galkin *et al.* [20] studied UAVs characteristics and charging techniques in terms of implementing flying cellular networks. The authors addressed the benefits and drawbacks of available charging techniques; however, they concluded that in-detail studies have to be conducted to increase flight time. Le *et al.* [59] reviewed near field charging techniques for UAV in the aspect of transfer power, transfer efficiency and charging distance. The authors also provided an overview of challenges and opportunities in near field transmission, which summarized that mid-range charging techniques such as IPT could increase the range of UAVs. Lu *et al.* [60] discussed the available charging techniques for UAVs such as EMF-based and Non-EMF based transmission. The authors observed WPT charging technique is robust in improving the flight time of UAV. The authors proposed that the drone can be charged from the high power transmission lines using electromagnetic radiations generated from the transmission lines and tested using the same IPT technique. In the preliminary study, the authors observed the receiver should be placed close to the source as the voltage is inversely proportional to the distance. Boukoberine *et al.* [55] reviewed on UAV market, structure, classifications, charging techniques and applications. The authors in addition detailed on UAV energy management strategies and concluded that more studies are required for proposing prediction based energy consumption of UAV for managing scheduled flight times. Shakhatreh *et al.* [56] provided a detailed literature survey on market opportunities, classification, applications, future trends and opportunities. The authors also identified the benefits and key challenges in UAV civil applications: security, network, swarming, charging, and collision-related. The author stated that the key challenges mentioned prey for the future scope of the UAVs. Many researchers reviewed various aspects of the UAVs; however, the WPT for the UAVs are not thoroughly discussed in any study. This review study presented multiple aspects of UAVs such as applications, market opportunities, classifications, structure, charging techniques. This study also detailed on WPT with different WPT techniques, mathematical modelling, charging standards with future trends and research directions in WPT for UAV, making this article one of its kind.

The article begins with a brief history of UAVs (Section 2) and then move on to UAV charging methods (Section 3). Section 4 discusses the fundamentals of Wireless Charging and its types, followed by Section 5, which discusses the electrical aspects of the wireless charging circuit (Power Electronic Converters). In Section 6, Coil design and design aspects are briefed. Section 7 discusses the need and types of Electro-Magnetic (EM) Shielding methods. Section 8 deals with Real-Time Case Studies of drone WPT. Section 9 discusses the Public Exposure Levels set by governing authorities. The paper ends with a glimpse of Future Trends and research directions (Section 10).

II. A BRIEF HISTORY OF UAVs

Author J. M. Sullivan elucidated the history of UAVs in his article. The author described that the term UAV existed since the beginning of the 20th century. UAV was defined as an aircraft with no onboard crew. In 1918, the US army started mass production of Kettering Bug flying bombs (Aerial Torpedo) developed by Charles Kettering that was catapulted and flown via radio controls. The term drone was coined to refer to the automation of such navigation controlled aerial vehicles. The drone of the late 1960s and 1970s were called Remotely Piloted Vehicle (RPV) [67]. Drones were mainly war specific equipment, gathering intelligence, reconnaissance and bomb dropping. Drones were able to infiltrate deep into enemy territory and gather intelligence without endangering the pilots' lives. The power converter technology was primitive, the equipment was heavy, and the propulsion system relied majorly on jet propulsion. However, the UAV was capable of long-range missions. An example of such Weaponised UAV is the RQ-1 Predator; it is capable of delivering air to air and air to ground missiles [68]. Nowadays, a drone is referred to as any reusable air vehicle which can be piloted remotely. Since the last decade, power converter technology has matured and electrical components are miniaturized, making the system more compact and sophisticated. The cost factor of the technology has also come down, making it affordable for the general public. Commercial-Hobby drones are now used for leisure flying, photography, parcel delivery, surveillance, temporary communication towers, remote area sample collection [69]–[71], 3D mapping [72] and thermal image-based maintenance [73]. Many modern applications include seeds planting [74], airport security from birds, disaster management [75], spraying of disinfectant for contagious pandemics, and the applications are limited only by the imagination [76], [77]. Advancements in drone technology has led researcher into developing autonomous UAVs; some UAVs used biomimicry for navigation [78]. A quadcopter type drone named SAMWISE (Smoothening and Mapping with Inertial State Estimation) quadcopter was developed by MIT and DRAPER for DARPA [11]. It worked on inertial navigation systems and required no GPS signals. It has vision capability and is fully autonomous [12]. Similarly, VOLIRO is a hexacopter with tilting rotors, creating 12 degrees of freedom maneuverability. These can operate in complex environments [13]. A drone is even being developed mimicking animatronic mobility, such as the BAT BOT (B2), a micro air vehicle developed by the University of Illinois, whose base design was based on the flapping mechanism of that of a bat [14].

A. CATEGORIES OF UAVs

Advances in the field of aeronautics have led to the development of abundant categories of flying robots. The UAVs differ in size, endurance, propulsion, range, payload, travel speed, and wing types based on the applications. Several other factors such as lift, drag, the thrust generated, and gravity affect a UAV design. The UAVs can be categorized into Fixed-wings, Rotary-wings, Airships, Fixed-wing Hybrid Vertical Take-Off and Landing (VTOL), and Flapping wings as illustrated in Fig. 4.

Fixed-wings, as the name suggests, the wings of these UAVs are fixed, and the rigid structure of the UAVs body generate aerodynamic lift under the wing. When subjected to forward airspeed, the wings' tilt control creates a lift to position the UAV in the required direction.

Rotary-wing UAVs have rotating propellers that generate an upward aerodynamic lift. These are heavier than the conventional fixed-wing UAVs. However, the rapid maneuverability of these UAVs has made them useful for short-range missions.

AirShips, also called dirigible balloon or blimp, works on the principle that the balloon is filled with lifting gas, making them lighter than the dense surrounding air.

Fixed-wing Hybrid VTOL combines the advantages of both fixed-wing and rotary-wing for long endurance. These can lift vertically using the VTOL propulsion and fly using the fixed-wing propulsion system for longer durations.

Flapping wing, also known as ornithopter, mimics the biological flapping mechanism of birds and insects. The aerodynamic lift is generated by pushing the air below its wings synchronously.

B. INTERNAL STRUCTURE OF UAV

This paper concentrates majorly on the rotary-wing UAVs due to their easy maneuverability in tight spaces and their ability to lift/land vertically with precision, making them useful for short-range autonomous operations. Rotary wing UAVs are further categorized into Single rotor and Multi-rotor. Multi-rotor UAVs are named based on the number of rotors on the UAV, such as Tricopter (having three rotors), Quadcopter (having four rotors), Hexacopter (having six rotors) and Octocopter (having eight rotors). For this paper, Quadcopters and Hexacopters are studied to implement wireless charging technology into them. For ease of understanding, Quadcopters/Hexacopters will be addressed as drones. As shown in detail in Fig. 5, a generic drone consists of a Flight Controller (FC), Brushless DC (BLDC) Motors, Electronic Speed Controller (ESC), Power Distribution Board (PDB), Lithium Polymer (LiPo) battery, Radio transmitter-receiver, First Person View (FPV) camera, video transmission-receiving module and a frame.

The Flight Controller is the brain of the system and is responsible for stability, motor control, and flight log

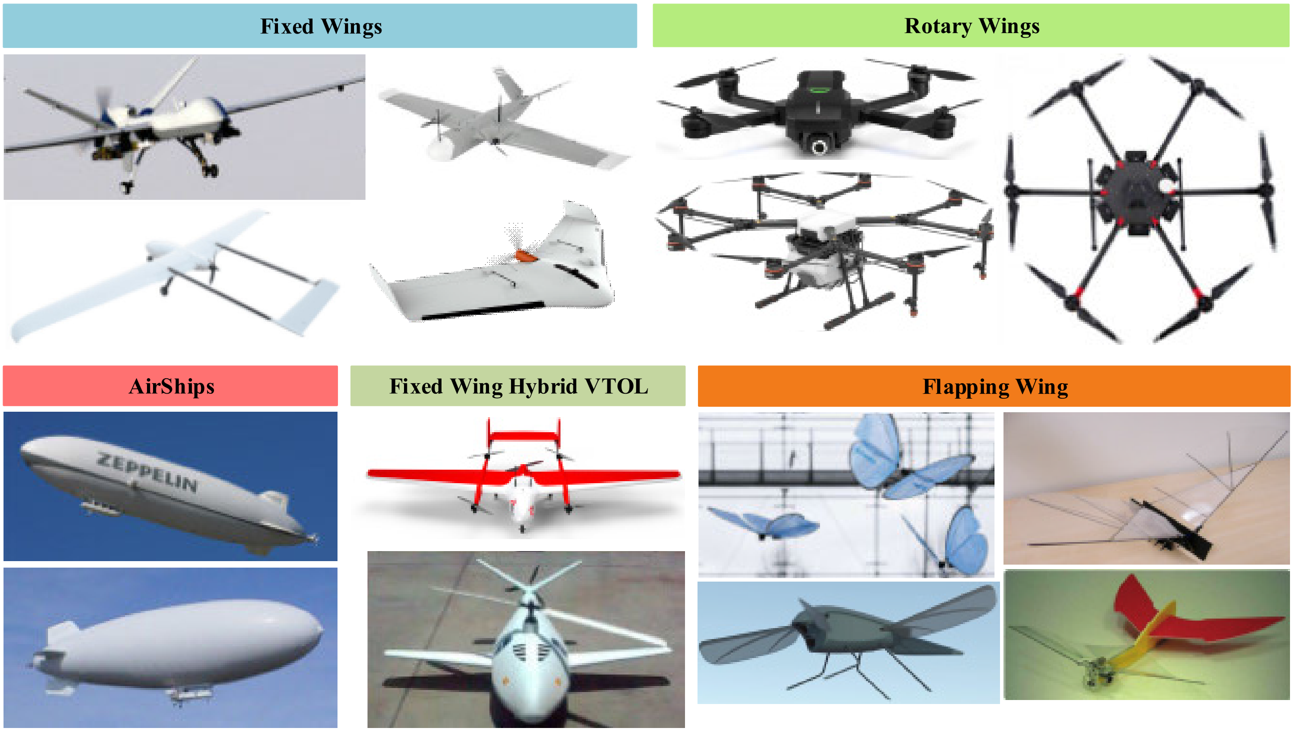


FIGURE 4. Categories of UAVs.

TABLE 3. Comparison between popular battery technologies.

Battery	Voltage per cell	Energy		Power	Efficiency %	Operating Temperature °C
		Wh/l	Wh/kg	W/kg		
Lead Acid	2.1	50-70	20-40	300	85	-30 to 60
NiMH	1.2	200	40-60	1300-500	80	-20 to 50
Li-ion	3.6	150-200	100-200	3000-800	93	-20 to 55

storage. As shown in Fig. 6, The PID loop in the FC filters and reads the signals received from the radio receiver as the change in angular velocities for the directional control of the drone. The Proportional, Integral and Differential blocks have respective scaling factors that need to be tuned for efficient flight control. The modified signal is then sent to the respective ESCs for the drone's motion control [79]. The radio receiver generally operates in the frequency of 2.45/5.8 GHz depending on the environment and obstacles between the ground system and drone. 5.8 GHz has long range but limited data transmission capabilities and vice versa.

BLDC motors are compact-powerful motors that operate at high RPM when a suitable power source is provided. These are controlled using the ESCs by delivering the required power from the source to the motor via the control signals from the flight controller. Furthermore, these motors have a linear torque/current relationship and constant torque under load conditions.

FPV camera is used for the experience of controlling the drone from the viewpoint of sitting inside the drone. These are helpful while operating a drone out of the line of sight. The FPV camera is aided by the video transmission-receiver module and powered by the drone's battery.

LiPo battery is the powerhouse of the drone. LiPo batteries have a higher discharge rate compared to NiMH and Lead-acid batteries. LiPo batteries are lighter and can be packed into the required shape and size. However, special care has to be given during charging, discharging and storage, as they are known to fire when mishandled, illustrated in detail in Fig. 7.

Based on the study presented in [80], Lithium batteries are most suited for UAVs because of their high power to weight ratio. A comparative study is presented in Table 3 on popular batteries. A research study carried out by [81] depicted that a Lithium battery's weight is directly proportional to its capacity. With the increase in UAV weight, the battery discharges more rapidly and severely limits UAVs' flight time. Li-Ion/LiPo batteries are sensitive to voltage-temperature

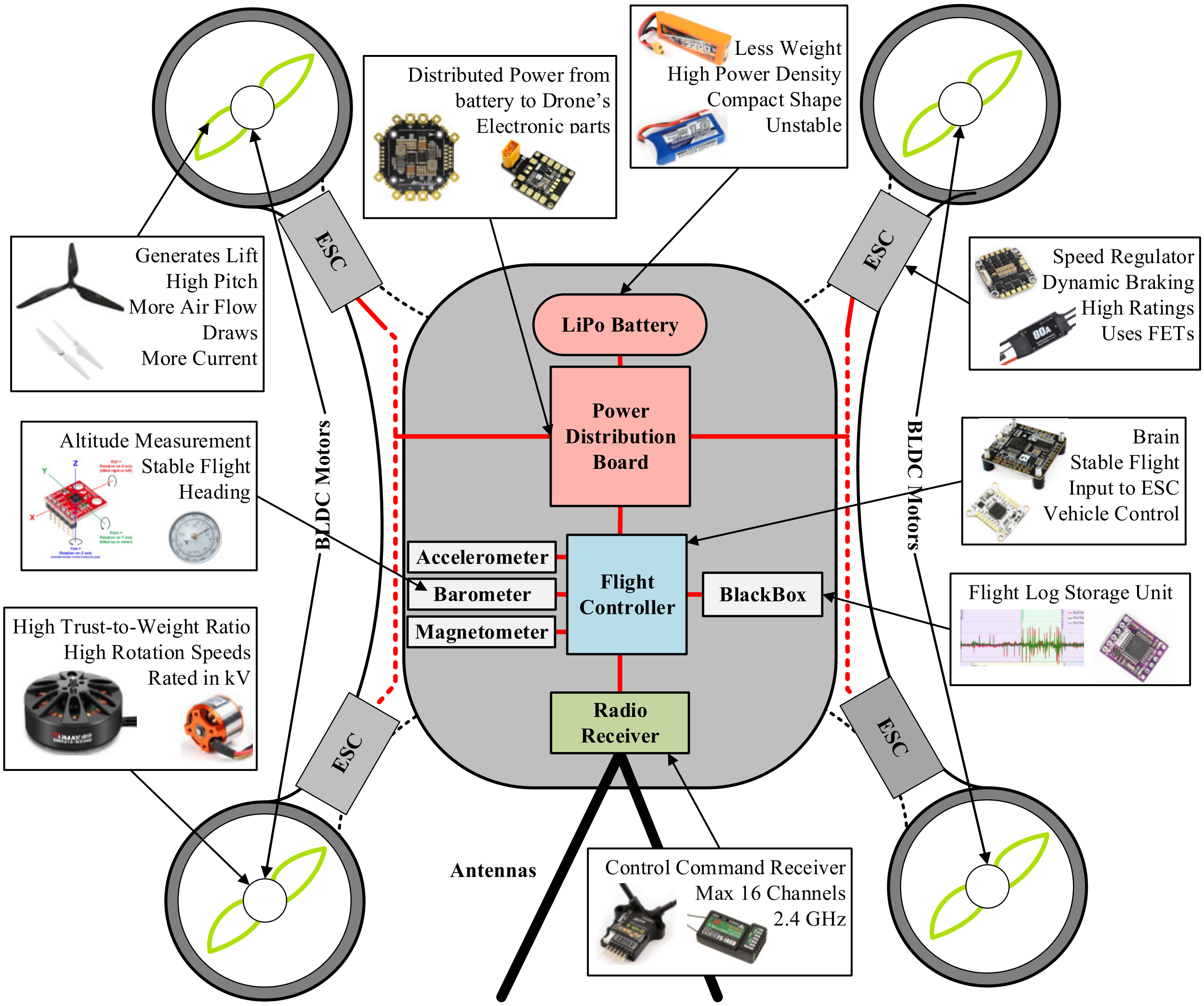


FIGURE 5. UAV internal hardware.

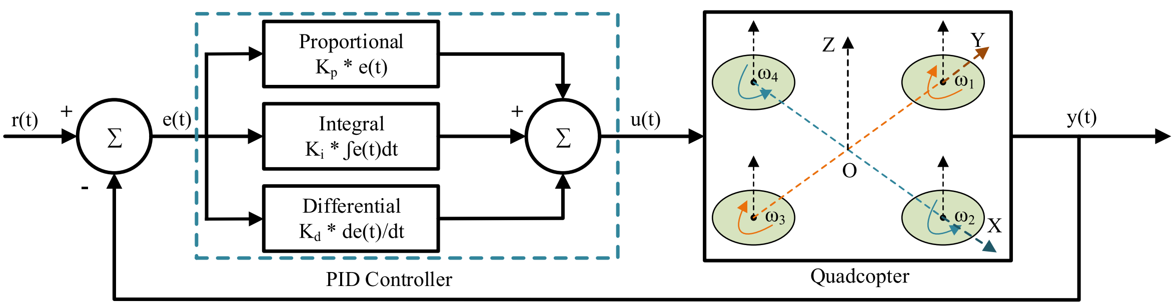


FIGURE 6. Functional Block Diagram of PID Loop of FC: Proportional, Integral and Differential scaling factors to be adjusted for an Ideal performance.

variations and operate under defined conditions, as shown in Fig. 7 (Cell voltage Vs Temperature graph) [82]. Li-Ion/LiPo batteries are ideally used between 20-80% of their capacity. As a thumb rule, End of Life (EoL) is equal to 80% of the battery's Beginning of Life (BoL), which represents that Depth of Discharge (DoD) should not exceed 80% of the battery's capacity for the battery's safe operation. Ideal battery usage characteristics are shown in Fig. 8-9.

Fig. 10 shows a comparative study between EV battery manufacturers who have to compromise between power delivery and energy storage. Unlike EVs, a drone's depleted battery must be manually detached and swapped with

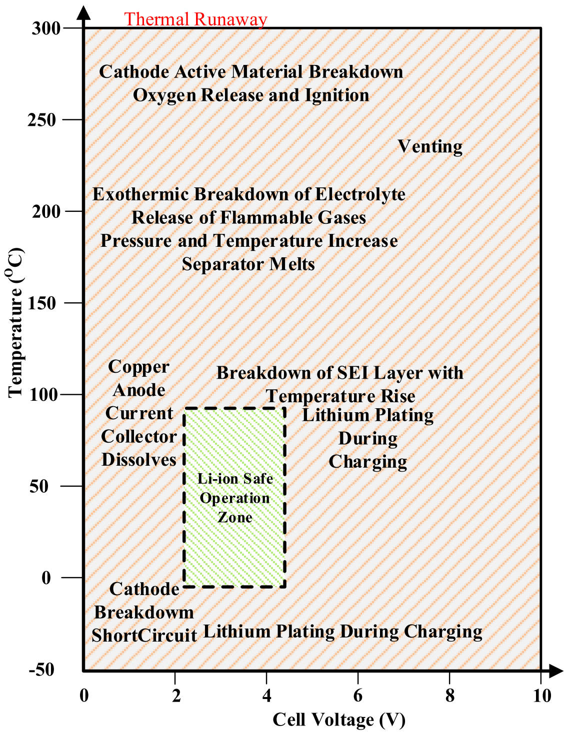


FIGURE 7. Lithium Batteries Safe Operation Zone: The green section in the graph indicates the conditions necessary for the safe operation of Lithium-Ion batteries (Data Source: mpoweruk: Battery and Energy Technologies).

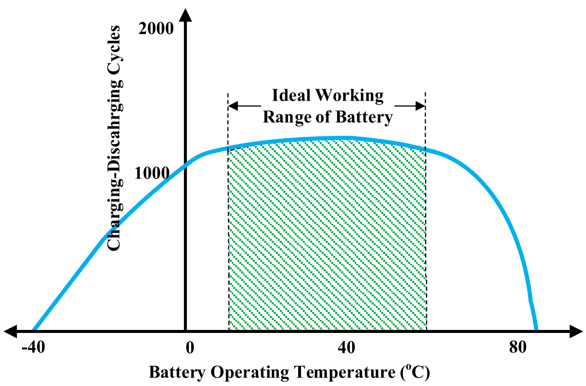


FIGURE 8. Ideal Battery Working Range: For optimal battery characteristics, the temperature of operation should be maintained between 10-60 °C.

a charged one; this action limits the implementation of autonomous applications'. The next section elaborates on the types of charging methods available for a drone.

GIST OF CHAPTER

The chapter can be summarized as follow:

- UAVs were developed as war equipment, now they are being used for many civil applications
- UAVs are categorized based on thrust generation mechanism

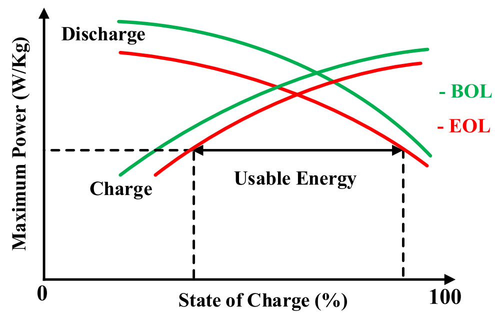


FIGURE 9. Lithium Battery Charge-Discharge Characteristics: Ideally, Lithium batteries are used between 20 – 80% of their capacity. If the limits exceed, the battery is prone to permanent damage.

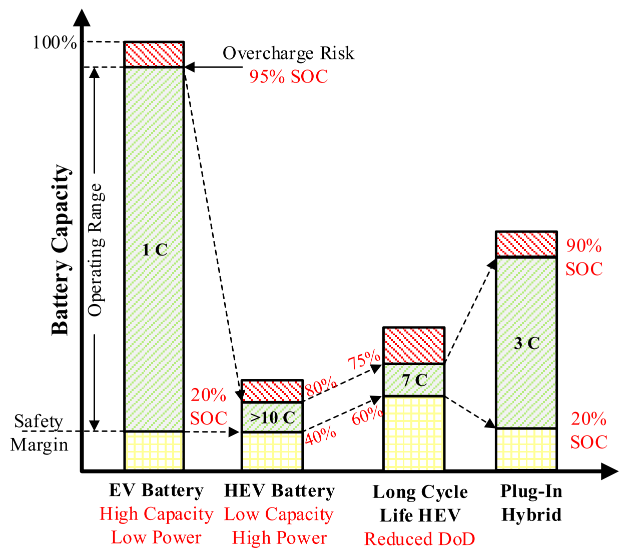


FIGURE 10. Selection of batteries for EVs: The figure shows a comparison graph between discharge rate (C) and battery capacity for different types of vehicles, in which, vehicle having low discharge rate (1 C) has a higher operating range of battery compared to HEV having a higher discharge rate (10 C) with less operating range of battery.

- The internal components of a Quadcopter consists of complex and power-hungry devices, powered by a rechargeable Li-Ion/LiPo battery
- Increasing the battery capacity, increases the system weight, thus, limiting flight time.

III. BATTERY CHARGING TECHNIQUES FOR UAVs

The widely used UAV charging technique is battery swapping; however, many new innovative approaches have been proposed. The battery charging methods are predominantly categorized into Non-EMF based charging and EMF-based charging. In non-EMF based charging techniques (shown in Fig. 11-12), the first method is called Battery Dumping, in which a UAV is equipped with multiple batteries to be dumped when the specific battery is discharged, reducing the weight and increasing the flight time simultaneously [20]. In another method, Malaver *et al.* proposed installing high-efficiency PV arrays on the UAV, which are embedded as the

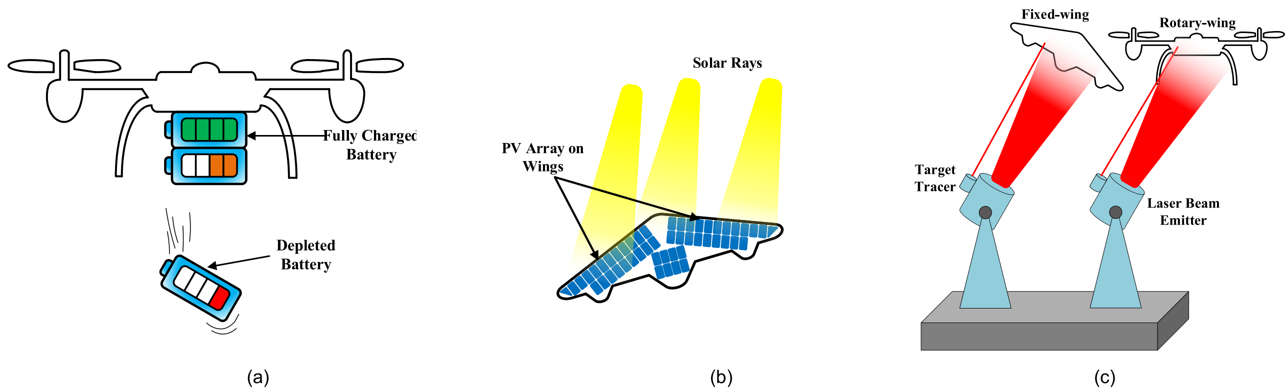


FIGURE 11. UAV Battery Charging Techniques: (a) Battery Dumping (b) Installation of PV arrays on the wings of the UAV (c) Laser Beaming.

drone's skin. During the day time, the PV array will supply power to the drone for flight, and during the night, the charged battery from the PV array will support flight time. However, the PV cells are dependent on solar radiations. The absence of sunlight will lead to the drone system's substandard performance [19]. Deittert *et al.* and Richardson *et al.* introduced an innovative method of charging called Gust Soaring. The drone gains energy from wind and airflow, from the principles of dynamic soaring. In this method, the trajectory of the drone is adjusted such that it catches the uplifting airflows and soars against the wind similar to that of albatross bird, which travels vast distances without the need for flapping their wings, conserving energy for needed maneuvers. This method is mostly dependent on wind and is applicable for fixed-wing type UAVs [17], [18]. Lastly, Laser beaming is a charging technique where a laser beam emitting unit beams a ray of infrared laser light on to the modified solar cell attached beneath the UAV's belly, charging the battery. The experiment was conducted on a quadcopter that flew for 12 hours uninterruptedly [60], [83]. Though these battery charging methods are innovative, most are not suitable for a quadcopter or hexacopter. Furthermore, these charging methods are not suitable for autonomous missions in a limited area of interest. Thus, WPT is preferred as an optimal solution for drone charging.

GIST OF CHAPTER

The chapter can be summarized as follow:

- Apart from the conventional battery swapping technique, battery dumping, laser beaming, skin embedded PV array, and gust soaring are other methods for battery charging for a UAV
- Wireless charging is an optimal solution for autonomous drone charging with higher power transfer efficiency and compact design
- WPT makes the system waterproof and resilient to dust, shocks and breakage of contacts.

IV. TECHNOLOGY BEHIND WPT

Nowadays, the concept of WPT has gained a lot of interest in the transportation sector. WPT began with its implementation

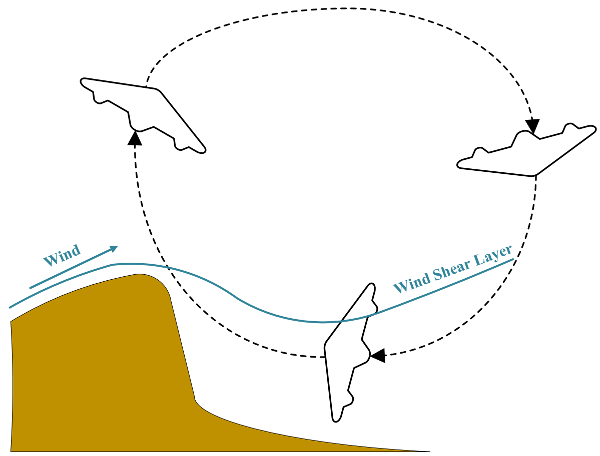


FIGURE 12. UAV battery charging technique: Gust soaring.

into portable electronics and is primarily used in smartphones, military devices and medical appliances, as shown in Fig. 13. Yet, the art of transmitting power wirelessly through the air is not new to humanity; the idea of transmitting power wirelessly has been intriguing scientists around the globe since the beginning of the 20th century. In 1905, Nikola Tesla patented a device capable of transmitting intelligible signals or power through the natural medium [84]. The idea has led to a century-long run towards the development of wireless power transfer technology. In 2007, André Kurs *et al.* from the Massachusetts Institute of Technology (MIT) attempted and succeeded in transferring 60 W of power wirelessly to power a light bulb, which sparked the beginning of WiTricity [85].

A. CAPACITIVE, INDUCTIVE AND MAGNETIC RESONANT CHARGING

The study of Wireless Power Transfer is divided into two categories based on the range of power transfer. For efficient power transfer of less than one meter, near field transmission techniques such as CPT, IPT and MRC are employed. For long-range power transmission, far-field transmission techniques such as Laser-based charging and MPT are used.

FIGURE 13. Wireless power transmission applications in diverse sectors.

In CPT, two parallel plates are separated by a small dielectric medium for the electric field to flow. CPT has the advantage of transferring power across metal barriers and causes low power losses in the metal surrounding, and it is generally applicable for lower power applications [22], [86]–[89].

The IPT technology is based on the loosely coupled transformer principle, where magnetic field induction delivers power between the coils. The system consists of a transmitting and receiving coil, with PE converters on either side of the coils. IPT has the advantage of convenient operation, safety and ease of implementation. IPT generally operates at the frequency of kHz [23], [90]–[93]. MRC is the improved form of IPT, where the losses are reduced by operating the power transfer in MHz's order. In this technology, both the transmitter and receiver coils are resonated at the same frequency. For more efficiency, an intermediate coil is placed between the two coils. The significant advantage of this technology is that it can transfer power to multiple loads simultaneously, operating at multiple frequencies [94]–[99]. Thus, MRC is ideal for multi drone charging where multiple drones are working simultaneously to achieve a collective goal. Table 4 presents case studies of wireless power transfer techniques. Table 5 and 6 draws a comparative study [24], [97], [100]–[107].

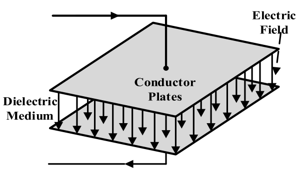
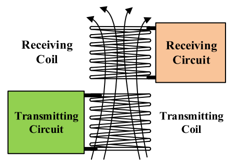
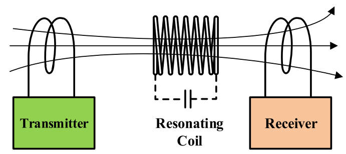
B. LASER AND MICROWAVE BASED CHARGING

A Laser-based power transmission system can transfer 2 W over a range of 5 m. This technology is called Distributed Laser Charging (DLC). These are used to power small sensors with low power ratings. DLC generally works in Line of Sight; any disruption between the transmitter and receiver causes the loss of power transmission [108]. MPT system is theoretically employed for very long-range power transmission and operates at a frequency of 1-6 GHz with an efficiency of up to 80% [109]–[112]. PE converters play an essential role in optimizing power transfer efficiency. Thus, it is necessary to understand the design of PE converters. The next section deals with the development of a High-Frequency (HF) Inverter for WPT and the need for Compensation Topologies in detail.

TABLE 4. Case studies of wireless power transfer techniques.

Charging Type	Frequency	Power Transferred	Distance	Reference
Capacitive Charging	4.2 MHz	3.7 W	0.13 mm	[22], [88]-[91]
Inductive Charging	22 kHz	100 kW	127 mm	[23], [92]-[95]
Magnetic Resonant Charging	60 kHz	818 kW	50 mm	[24], [99], [102]-[109]
Laser Beaming	2.4 GHz	1 W	3.66 m	[25], [110]
Microwave Transmission	5.8 GHz 2.45 GHz	50 W 4.39 kW	-	[111]-[114]

TABLE 5. Comparison between near field transmission techniques.

Capacitive Power Transfer	Inductive Power Transfer	Magnetic Resonant Charging
		
Proposed idea in 1891.	Proposed idea in 1830s	Proposed idea in 2007
Power Transfer Method: varying Electric Field	Power Transfer Method: varying Magnetic Field	Power Transfer Method: Resonance between circuits
Narrow Frequency range: 100's kHz – 10's MHz	Broad frequency range: 10's kHz – 10's MHz	Frequency Range: Moderate 6.78 MHz
Gap between coils: < 1 mm	Gap between coil: >10 cm	Gap between coil: 2 m
Gap Power Density: Low	Gap Power Density: High	Gap Power Density: High
$\mathbf{2 \le \frac{V_{Coupler}}{V_{Gap}} < 4}$	$100 < \frac{V_{Coupler}}{V_{Gap}} \le 500$	Generate magneto-inductive waves
Power Levels: Low Power application	Power Levels: Medium to High applications.	Power levels: High Power applications
Power Density: Air gap electric field strength $\left(\frac{\text{Constant current}}{Frequency}\right)$	Power Density: Core saturation flux $\left(\frac{\text{Constant Voltage}}{Frequency}\right)$	-
Energy density: $\pi \varepsilon_o \varepsilon_r E^2_{c\_max}$	Energy Density: $\pi \frac{B^2_{L\_max}}{\mu_o \mu_r}$	-
Medium: Capable of passing through metals	Medium: Only through air	Medium: Objects, materials, body tissues.
For high power transfer: Low cost	For high power transfer: High cost	For high power transfer: High cost
Coupler area: Less	Coupler area: High	Coupler area: High
Eddy current losses: NA	Eddy current losses: Large	Eddy current losses: Large
Power Losses: High	Power Losses: Low	Power Losses: Low
Reference: [22], [88]-[91]	Reference: [23], [92]-[95]	Reference: [24], [99], [102]-[107]

GIST OF CHAPTER

The chapter can be summarized as follow:

- WPT technology can be categorized based on transmission range: (a) Near Field Transmission- Capacitive Power Transfer, Inductive Power Transfer and Magnetic Resonant Power Transfer. (b) Laser and Microwave based charging
- The ideal choice for drone charging is IPT because of its high misalignment tolerance, compact design and power transfer capability to the satisfactory range.

V. POWER ELECTRONIC CONVERTERS

UAV charging requires a compact coil arrangement to be incorporated into the structure with a few cm of efficient

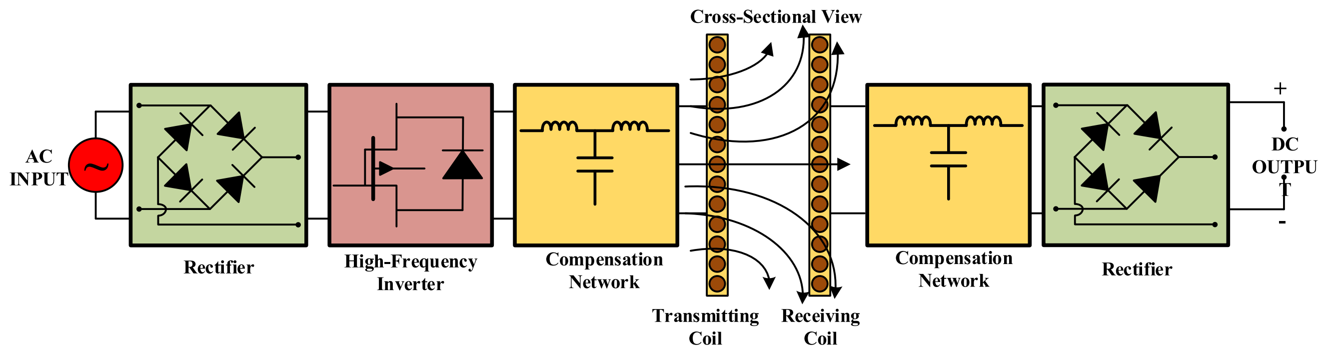
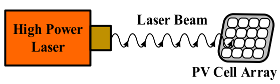
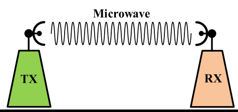


FIGURE 14. Structure of an IPT system.

TABLE 6. Laser-Based charging vs microwave-based charging.

Laser Charging	Microwave Charging
	
Proposed idea in 1970	Proposed idea in 1964
Beam type: Concentrated	Beam type: Non-concentrated
Very low divergence	Very high divergence
Low power transfer	High power transfer
Low power transfer	High power transfer
Long acceleration time	Short acceleration time
Frequency: 3.7 x 10^4 Hz at 810 nm	Frequency: 1 - 6 GHz
Line of Sight power transfer	Large divergence, hence Line of Sight is not needed
Reducing divergence has no effect on efficiency	Reducing divergence increases power capacity
Efficiency depends on Wavelength, electricity to laser conversion, laser transmission-attenuation, laser to electricity conversion, PV cell Temperature (major factor)	Efficiency depends on DC to RF, atmospheric attenuation, RF to DC
Transmission efficiency 80% at 810 nm wavelength	Transmission efficiency 97%
Laser to electricity and electricity to laser conversion efficiency is 60%	DC to RF and RF to DC conversion efficiency is 80%

power transfer capability. Thus, numerous researchers have selected IPT for UAV charging because of its extended range transmission capability while maintaining medium to high power levels and fewer power losses than other power transmission techniques. As depicted by Fig. 14, a wireless power transmission system has two coils, transmission coil and receiving coil, separated by an air gap. The primary coil is energized by an AC source converted to DC using a rectifying circuit. The rectified output is fed to the HF Inverter circuit, eliminating noise and converting the power signal to an HF signal. The compensation coil maintains the stability of the signal. The receiving and transmitting coils are placed around a magnetic material for proper coupling and minimizing losses. Generally, several ferrite cores are placed to provide a proper direction to the magnetic field. On the receiving side, the receiving circuit is tuned to the same resonant frequency to maximize the power transfer efficiency and reduce secondary leakage inductance. The choice of power transistors depends upon the requirement of the drone's BLDC motor. There are two choices for BLDC motor control: IGBTs and MOSFETs. In general, IGBTs have a low duty cycle for a frequency of less than 20 kHz; however, these are preferred for High-Voltage applications (greater than 1000 V, greater than 5 kW output). Whereas MOSFETs are suitable for frequencies greater than 200 kHz with a voltage rating less than 250 V and output power less than 500 W. These have long duty cycles and have good load variation characteristics. Thus, the ESCs of BLDC motor control for small to medium range UAVs use MOSFETs as their power transistors. The typical operating range of an HF inverter circuit in a WPT system is 50 kHz to 270 kHz [15], [41], [42], [45]–[47]. Mathematically, with the increase in the frequency of operation, the quality of the coil also increases, and the size of the electronics parts can be reduced, thus saving space. As drones have a restriction on weight, it is preferred to operate the charging circuit in high frequencies. Furthermore, compensation topologies aid in impedance matching between the transmitter and receiver circuit, improving the transmission efficiency drastically.

A. HIGH-FREQUENCY INVERTER

An efficient PE circuit can drastically improve the quality of the power transfer. The size of the electronic components reduces with the increase in the operating frequency. However, higher frequencies emit EMF radiations. Thus, resonant power converters are used to reduce higher switching losses. The transmitter side's PE circuit is used to convert a 50-60 Hz AC signal into an HF AC signal. The conversion process can be done in either of the two methods: AC to AC (Cycloconverter circuit) or a two-step method where AC is converted to DC, then the DC signal is converted to

TABLE 7. IPT control strategies.

Topology	Power Transfer	Distance	Efficiency	Reference
Dual Sided, Duty cycle controlled	5 kW	26.5 cm	90 %	[116]
Frequency and the Phase-shift controlled	450 V	7 cm	-	[121]
Semi-bridgeless active rectifier, Secondary Phase Shift controlled	1 kW	23 cm	94.4%	[117]
Bi-directional, optimized phase shift modulation	0.45 kW	6 cm	92%	[118]
Bi-directional, PWM controlled	6.6 kW	12 – 20 cm	88.1 - 95.3%	[120]
Bi directional, Power frequency droop controlled	1.5 kW	5.5 cm	85%	[119]
Zero-Voltage Switching Inverter	51 W	20 cm	63.4%	[44]
Class EF_2 Inverter	25 W	8 – 12 cm	75%	[113]
W Class, PWM Controlled	150 W	-	72 – 91%	[45]
Full-Bridge inverter	64 W	3.5 - 7 cm	75%	[47]
Zero-Voltage Switching	40 W	20 cm	64.16%	[15]
Class EF single switch resonant inverter, Zero-Voltage switching	13 W	7.5 cm	60%	[48]
Class EF inverter- half bridge, self-oscillating controlled,	10 W	8 cm	93.6%	[41]

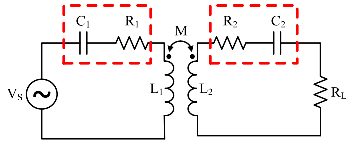
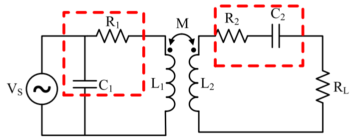
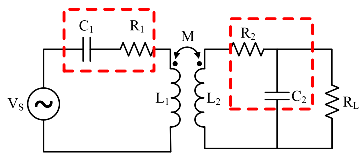
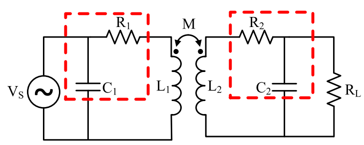
high-frequency AC using control strategies such as Pulse Width Modulation or phase-shift modulation. A full-bridge rectification circuit is used to deliver power to the battery or electronic circuit on the receiver side. A resonant frequency circuit matches the receiver side frequency with the transmitter side frequency. Generally, for drone charging circuit, researchers have been using a frequency range from 12 kHz to 13.56 MHz Control methods for the PE circuit are used for achieving desired output, high system efficiency and bidirectional power transfer. Researchers from [114] developed a 5 kW WPT system with a new dual-sided control method with an efficiency greater than 90% for the grid to battery conversion. Researchers at [115] developed a semi-bridgeless active rectifier on the receiving side for a multi-coil arrangement. Furthermore, the researchers concluded that the output voltage could be controlled by controlling the phase-shift time of the switching. The authors of [116] presented an optimized phase-shift modulation strategy to minimize the coil losses of a Series-Series WPT circuit. Authors of [117]–[120] designed and developed similar control strategy methods for IPT [15], [41], [44], [45], [47], [48], [113]. The data is further presented in Table 7. Although the PE converters do an efficient job of power conversion, the two coil arrangement of transmitter and receiver coils is a loosely coupled transformer [121]–[125], with a significant amount of leakage inductance, adding to power loss. To address these problems, compensation topologies have been employed to achieve the following:

- Improve power transfer efficiency
- Maximum Power Point Tracking
- Make the phase angle zero between transmitter and receiver
- Reduce the VA rating of the input power
- Resonate both the circuits at the same frequency
- Reduce switching losses
- Aid in soft switching
- Realize constant-current or constant-voltage charging
- High misalignment tolerance
- Bifurcation resistance and improves the overall efficiency of the circuit.

B. COMPENSATION NETWORKS

Raw electrical signals from the primary side inverter and receiver coils comprise of noise and unstable signals. A compensation network is used to regulate the noise and deliver a smoother signal. There are many topologies based on the requirement of the signal properties. Basic topologies include Series-Series Topology (SS Topology), Series-Parallel Topology (SP Topology), Parallel-Series Topology (PS Topology) and Parallel-Parallel Topology (PP Topology). Hybrid Topologies include Series-Parallel-Series Topology (SPS Topology) and LCC Topology [126]. A brief comparison study between the basic compensation topology is illustrated in Table 8. SS topology is an economical choice for high power applications. The capacitors of the circuit are independent of the load condition of the circuits, mutual inductance and Coefficient of Coupling (CoC). The resonator frequency is mostly dependent on the self-inductance, and the circuit maintains a unity power factor while delivering constant current output. Compared to SP, PS and PP, SS's efficiency and power factor at light loads is significantly high. However, when the receiver coil is absent during power transfer, the equivalent impedance of the circuit becomes zero in that case. When the secondary coil is introduced, the impulsive potential is developed in the primary coil and secondary coil, causing damage to the circuit. PS topology exhibits the same

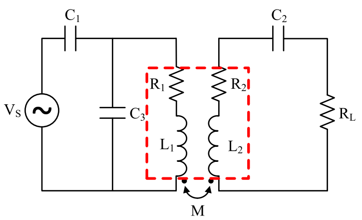
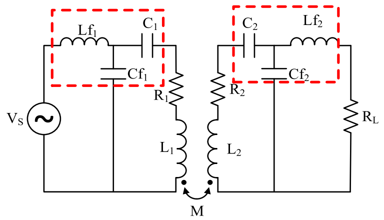
TABLE 8. Basic compensation topologies.

Compensation Topology	Features	Equations
Series-Series 	• Suitable for variable Load • Power transfer is high • Alignment tolerance is high • For constant current, efficiency is 94.6% • Suitable for High kW applications • $I_{sc} = \frac{jV_{in}}{\omega M}$ • $C_1 = \frac{C_2 L_2}{L_1}$	$Q_1 = \frac{(L_1 + M)R_L}{\omega_O M^2},$ $Q_2 = \frac{\omega_O (L_2 + M)}{R_L}$ $\eta = \frac{\omega^2 M_{12}^2 R_L}{((R_2 + R_L)^2)R_1 + (\omega^2 M_{12}^2)(R_2 + R_L))}$ Where Q_1 is Primary Quality Factor, Q_2 is Secondary Quality Factor $\eta_{max} = \frac{R_L}{R_L + R_2},$ Where ω" $\frac{\sqrt{R_1(R_2+R_L)}}{M}$
Parallel-Series 	• More sensitive to pf over long distance • Alignment tolerance is moderate • High impedance at resonant state • Suitable for less kW applications • $I_{sc} = \frac{I_{in}}{\omega^2 C_1 M}$ • $C_1 = \frac{C_2 L_2}{\frac{M^4}{L_1 C_2 L_2 R_L} + L_1}$	
Series-Parallel 	• Suitable for variable Load • Power transfer is high • Alignment tolerance is high • For constant voltage, efficiency is 94.6% • Suitable for High kW applications • $V_{oc} = \frac{L_s V_{in}}{\mathrm{M}}$ • $C_1 = \frac{C_2 \mathrm{L}_2^2}{L_1 L_2 - M^2}$	$Q_1 = \frac{\omega_O (L_a + M)(L_b + M)^2}{M^2 R_L},$ $Q_2 = \frac{R_L}{\omega_O (L_b + M)}$ Where Q_1 is Primary Quality Factor, Q_2 is Secondary Quality Factor $\eta = \frac{\omega^2 L^2 R_L}{R_L \omega^2 + R_2 \omega^2 L_2^2 + R_2 R_L^2 + \frac{R_1 R_2^2 L^2}{M^2} + \frac{R_1 L_2^4 \omega^2}{M^2}}$ $\eta_{max} = \frac{R_L}{R_L + R_2 + \frac{R_1 (L_b + M)^2}{M^2}},$ Where $\omega = \frac{\sqrt{R_2 R_L^2 M^2 + R_1 R_2^2 (L_b + M)^2}}{(L_b + M)M}$
Parallel-Parallel 	• More sensitive to pf over long distance • High impedance at resonant state • High frequency tolerance • Suitable for low power applications • $V_{oc} = \frac{L_s V_{in}}{\mathrm{j}\omega \mathrm{M} C_p}$ • $C_1 = \frac{(L_1 L_2 - M^2) C_2 L_2^2}{\frac{M^4 C_2 R_L}{L_2} + (L_1 L_2 - M^2)^2}$	

Where

Vs	Source voltage	Q_2	Secondary side Quality Factor
C_1	Capacitor connected on the primary side	I_{SC}	Short circuit current
C_2	Capacitor connected on the secondary side	V_{OC}	Open circuit Voltage
R_1	Coil resistance on the primary side	η_{max}	Maximum Efficiency
R_2	Coil resistance on the secondary side	I_{in}	Input Current
L_1	Primary side coil Inductance	V_{in}	Input Voltage
L_2	Secondary side coil Inductance	f_1	Primary side frequency
R_L	Load Resistance	f_2	Secondary side frequency
M	Mutual Coupling between coils	R_e	Equivalent effective resistance
Q_1	Primary side Quality Factor	K_c	Capacitance selection factor.

TABLE 9. SPS and LCC compensation topology.

Compensation Topology	Features	Equations
SPS 	• It has the combined features of SS and PS topology • It has a good misalignment characteristics • Suitable for coil diameter less than 30 cm • Able to supply large V_L at resonance condition • Insensitive to angular misalignment up to 60°	$z_{Total} = \frac{\bar{Z}_{11}}{1+Z_{11} jC_3\omega_o}$, $Where\ \bar{Z}_{11} = \bar{Z}_1 + \bar{Z}_r$ $C_1 = \frac{1}{\omega}.\text{imag}\left(\frac{j\,\omega C_2\left(1+\frac{(\omega M)^2}{Z_2}+j\omega L_1\right)}{\frac{(\omega M)^2}{Z_2}+j\omega L_1}\right)$ $C_2 = \frac{1}{\omega^2 L_2}$ $C_3 = K_c \frac{M + L_1}{(\omega(M + L_1))^2 + \frac{M^4\omega^4}{R_e^2}}$
LCC 	• Proposed by researchers from the University of Michigan, Dearborn • Very low Z_{in} • Suitable for coil diameter greater than 30 cm • Efficiency decreases with an increase in V_L • Very sensitive to angular misalignment up to 60°	$P = \frac{8k\sqrt{L_1 L_2} V_{in} V_{out}}{\pi^2 \omega L_{f1} L_{f2}}$ $Where\ k = \frac{M}{\sqrt{L_1 L_2}}$, V_{in} = Input voltage of HF-Inverter, V_{out} = Battery Voltage. $C_1 = \frac{1}{\omega^2 (L_1 - L_{f1})}$, $C_2 = \frac{1}{\omega^2 (L_2 - L_{f2})}$ $C_{f1} = \frac{1}{\omega^2 L_{f1}}$, $C_{f2} = \frac{1}{\omega^2 L_{f2}}$

transfer impedance as Series-Series and has high efficiency, power factor at low mutual inductance. PS topology requires a current source at the primary side to compensate for any change in the instantaneous voltage, for which an inductor is placed [127]. SP topology delivers constant voltage output, but it requires a current limiting control on the primary side. SS and SP are widely suitable for high power applications such as EVs. PP topology has the same transfer impedance as SP [128]. Limited studies are conducted on PP due to low power factor, the requirement of a large current source and high load voltage [129]. SPS is a combination of SS and PS; it maintains constant output at high misalignment, suitable for dynamic charging [130]. In a recent study, double LCC topology was proposed for the resonant frequency to be independent of load condition by researchers from the University of Michigan, Dearborn. L_{f1}, C_1 and C_{f1} are the resonator elements on the transmitter side, when the source voltage V_s is fixed and constant current flows through L_1 [126]. Thus, the induced voltage is constant. On the receiver side, L_{f2}, C_2 and C_{f2} resonate with the same frequency as that of the transmitter, thus creating load-independent condition. LCC topology reduces stress on the inverter circuit and has high misalignment tolerance, illustrated in Table 9. Moreover, it requires two large identical inductors. LCC topology was tested for high power transfer of 6 kW, and it was capable of achieving 95.3% efficiency [131]. Similarly, in 2017, 6.6 kW power was transferred at 95.05% efficiency at a vertical displacement of 150 mm [132]. A WPT system is lifeless without the transmitter and receiver coils. Thus careful considerations have to be made before choosing an appropriate coil structure.

GIST OF CHAPTER

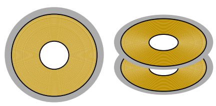
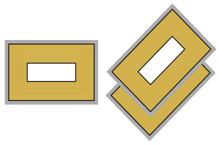
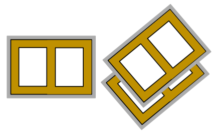
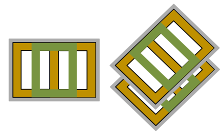
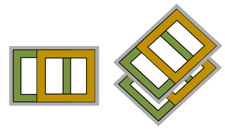
The chapter can be summarized as follow:

- The choice of an inverter depends upon the frequency of operation; MOSFETs are ideal for WPT circuit design for drone charging because of their fast switching capability and power handling up to 250V
- The literature provides a brief overview of control strategies used in WPT. From the literature, a semi-bridgeless active rectifier with phase shift controlled is the optimal choice for drone charging with a good range of power transmission at higher efficiencies
- Six compensation topologies are discussed in the literature, of which SS/SP topology is best suited for drone WPT charging owing to its high power transfer and high misalignment tolerance.

VI. COIL DESIGN CONSIDERATIONS

The transmitter and the receiver coils are the heart of the WPT system. These convert HF AC signals into magnetic waves to be transferred through an air gap. The design of these coils determine the power transfer capability and transfer distance of the system. Over the years, the WPT technology development has led to investigations on a range of planar coils. The current study has classified the planar coils into two categories based on their ability to distribute flux: Polarized Pads and Non-Polarized Pads. Non-Polarized Pads are single shaped pads that are capable of generating flux perpendicular to the plain on resting. Conventional shapes of developed Non-Polarized Pads are circular, rectangular and hexagonal. Circular pads are the widely used structure because of their simple construction, structure and minimal eddy currents.

TABLE 10. Properties of popular WPT Coil structures.

Parameters	Circular Pad	Rectangular Pad	DD Pad	DDQ Pad	Bipolar Pad
Structure					
Designed Year	2000	1990s	2011	2011	2012
Transferable Power	Medium	Medium	High	High	High
Pad design size	Medium	Medium	Small	Small	Small
Pad weight	Low	Low	Low	Medium	Medium
System material cost	Low	Low	Medium	High	Medium
Transmission distance	Low	Low	Medium	High	High
Charging zone	Small	Small	Medium	Large	Large
Misalignment tolerance	Poor	Medium	Poor	High	Medium
CoC	Low	Medium	High	High	High
EMF exposure	High	Low	Low	Low	Low
Shielding effect on CoC	Low	Medium	High	High	High
Magnetic flux	Single-sided	Single-sided	Double-sided	Double-sided	Double-sided
Polarization	Non-Polarized	Non-Polarized	Polarized	Polarized	Polarized
Common use	Transmitter	Transmitter and Receiver	Transmitter	Receiver	Receiver
Leakage flux	High	Medium	Extremely low	Extremely low	Extremely low
Number of coils	1	1	2	3	2
Interoperability	Very low	Very low	Non-interoperability with NPPs	High	High

Change in diameter has a direct influence on the magnetic flux distribution [133]–[136]. Nevertheless, this structure is prone to large leakage fluxes, resulting in decreased overall transmission efficiency. Recent developments have shown a 5 kW power transfer by modifying AC resistance and mutual inductance with only SS compensation [137]. Rectangular coils are more prone to eddy current losses due to increased inductance at corners and create hotspots. However, rectangular coils have shown a better lateral displacement than circular coils, improved effective flux distribution area [138], [139]. Polarized pads consist of two or more coils that generate flux perpendicular and parallel to the plain on resting, aiding to increase in transmission distance, CoC, shielding effect, misalignment tolerance and power transfer capability. However, these designs require more materials compared to conventional designs, increasing the system weight. Polarized pads are developed in shapes such as DD, DDQ and bipolar, where the D and Q represent the structure's shape. DD coil combines two rectangular coils with smooth curved edges that generate flux perpendicularly with minimal edge leakage fluxes. The addition of overlapped DD coils has potential applications in dynamic charging with an efficiency range of 88.3% to 90.4% at 5 km/hr. speed [140]–[143]. Recent advancements in the DD structure have improved power transfer capability to 6.6 kW at 95% efficiency with 27 μT magnetic flux density, within the International Commission's prescribed limits on Non-Ionizing Radiation Protection (ICNIRP) [144]. DDQ coils are more efficient than DD coils in generating magnetic fields perpendicular and parallel to resting planes with high system flexibility and a large charging zone. DDQ coils have shown a significant improvement in lateral misalignment tolerance [139], [145], [146]. DDQ, as a primary coil, requires different secondary topology and two synchronized inverters (two on each primary and secondary side) for optimal performance, adding to system weight. Bipolar pads are a compact version of DDQ pad technology, providing the same dual flux (parallel and perpendicular) with a reduced copper material (25-30% less copper). The flexible design reduces misalignment tolerance when acting as secondary [139]. An increase in the study of coil structures has introduced many structures such as hexagonal pads, octagonal pads, multi-thread coils, H-shaped solenoid coils and Taichi coils [147], [148]. The use of High-Temperature Superconducting (HTS) coils instead of the conventional copper coils has shown improved efficiency of 95% and power transfer capability for a four-coil system because of its little AC resistance and high-quality factor. HTS system can replace the resonator coil structure because of its large impendence in load and power coil [149]. Similar studies were conducted using HTS coils for spiral, solenoid and double pancake coil structures. It was observed that magnetization losses increased with the increase in frequency and magnetic field density. The spiral coil exhibited the lowest magnetization losses, and the solenoid coil has the highest magnetization. Moreover, HTS coils require

TABLE 11. Case study of commercial WPT charging Pads for UAVs.

Company	Output Power Specifications	Charging Type	Charging Pad Dimensions	Charging Speed	Charging Distance	Reference
WiBotic	Low Power 125 W, 10 A	Wireless	91.4 cm x 91.4 cm	Slow	< 10 cm	[50]
	High Power 300 W, 30 A	Wireless	91.4 cm x 91.4 cm	Fast	< 10 cm	
Heisha	17.5 V, 6 A max	Wireless	80 cm x 80 cm	Fast	< 10 cm	[51]
H^3 Dynamics	12 V, 17.5 A max	Wireless	2m x 2m	Fast	< 10 cm	[52]
Power Republic Corporation	200 W, 67.2 W	Wireless	-	Fast	< 10 cm	[53]
GET	12 kW, 50.3 V, 150 A	In-Flight	Circular coil < 6 m diameter	Fast	3 m	[54]
SkySense	50 V, 10 A	Contact	1.5 m x 1.5 m	Fast	-	[164]

high cooling power when the power transfer reaches the kW range due to skin effect, making them inefficient for high power rating applications [150]–[153]. The properties of prominent coil designs are briefed in Table 10. Mathematical modelling of the coils is presented in the Appendix of this paper with ANSYS Maxwell software simulated results of a 5 V DC output transmitter-receiver coil system. The studies conducted for EVs can be adopted towards low power applications such as UAVs. However, the compact space limits the usage of multiple coils into the UAV's frame. Thus, researchers have been implementing a simple circular coil structure for the transmitter and receiver circuit. EMF generated from the coils, in a way, is harmful to electronic circuits. Exposing the PE circuit to EM waves generates rogue currents damaging the internal circuitry. Thus, preventive measures have to be used when handling with high-frequency EM waves.

GIST OF CHAPTER

The chapter can be summarized as follow:

- Five popular coil structures are discussed in the literature, with DDQ structure having the least leakage flux and high transmission distance; however, the weight of coil increases the overall drone weight; thus, circular/rectangular coils structures are preferred for drone receiver circuit
- HTS coils showed performance improvement compared to copper coils, yet further research is need for their use in drone wireless charging.

VII. ELECTROMAGNETIC SHIELDING

As discussed earlier, WPT is due to EM waves' presence, which can be a health risk for humans and electronic circuits [154], [155]. Simpler shielding techniques employ metallic enclosures and are essential because they:

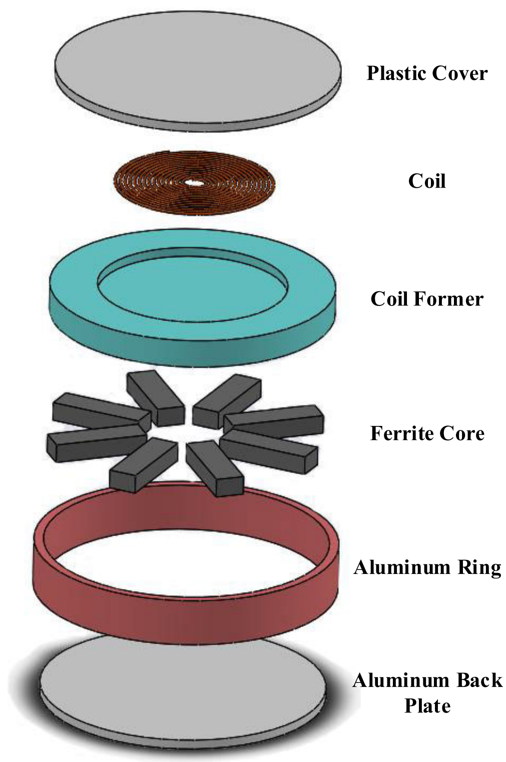


FIGURE 15. Exploded view of WPT charger.

- Isolate the main circuit from the EM source.
- Improve the immunity of the main circuit.
- Reduce the eddy currents, which could affect the working of the system.

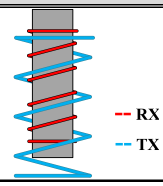
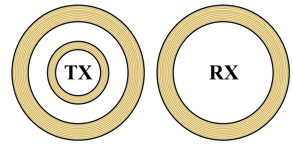
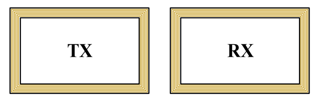
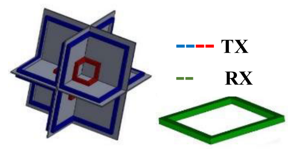
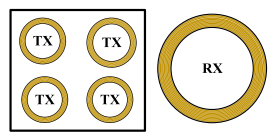
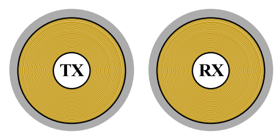
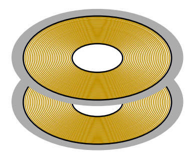
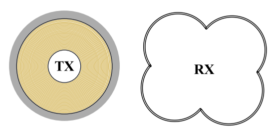
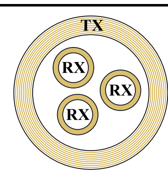
At present, the Active shielding method is widely used, as it blocks EM waves from reaching other electronic components. In the active shielding method, an addition coil is placed on the receiver coil in which current flows in the opposite direction, cancelling out the incident EM waves. In the passive shielding technique, an aluminium sheet is placed between the coil and the circuit to be protected, isolating the electronic components from the EM waves from the transmitter [156]. The addition of ferrite bars provides more stability to the system, as ferrite core-based structures have low electrical conductivity and high magnetic permeability. Thus, the ferrite materials divert the incident magnetic flux waves and flow through these magnetic materials with low reluctance path than air. Generally, the coils of a typical WPT system are operated with an air-cored coil structure or ferrite-based core, shown in Fig. 15, the latter being more efficient. Studies have shown a significant improvement in the magnetic coupling between the transmitter and receiver coils with ferrite cores [155]. The properties of ferrite cores were studied long back in 1962 by John M. Blank, patenting the Preparation of Ferromagnetic Materials concept [157]. The ferrite materials are classified into hard and soft ferromagnetic materials. Hard ferromagnetic materials are difficult to demagnetize; thus, they exhibit high coercivity (approximately 12.5 A/m to more than 250 A/m). Pure hard ferromagnetic materials ($SrFe_{12}O_{19}$, $BaFe_{12}O_{19}$, $CoFe_2O_4$) exist in hexagonal structure (varies with impurities) and are typically best-suited for applications such as magnets for loudspeakers, refrigerators and small motors. However, soft ferromagnetic materials are easy to demagnetize; thus, they exhibit low coercivity (few A/m). Typically, Manganese-zinc (Mn-Zn) and Nickel-zinc (Ni-Zn) are best suited for non-conductivity and high magnetic permeability. Soft ferrites act as conductors for generating magnetic fields with low electrical conductivity, thereby limiting eddy current losses [158], [159]. Thus, adding a ferrite core allows the circuit to operate in high frequency without losing efficiency, minimizing leakage flux, improved quality factor, self and mutual inductance and provides a more considerable tolerance for lateral misalignment [160]. Ferrite cores come in a variety of shapes (Rectangular, I shape, cylindrical). Recent studies have indicated the use of cylindrical ferrite structures to increase transfer distance, increase average transfer efficiency, and reduce the operating frequency [161].

GIST OF CHAPTER

The chapter can be summarized as follow:

- Electromagnetic Shielding is an important aspect of WPT in safeguarding the electronic and human elements of the system
- The active shield is effective, yet it increases the weight of the overall system with an addition of one more coil to the receiver circuit
- Passive shielding uses a thin aluminium layer to block EM waves
- The addition of ferrite bars provides an improved flux path on the transmitter side, thus, improving power transfer efficiency.

TABLE 12. Case studies of IPT for drone charging.

Parameters	Structure	Ref.
Output = 150 W V = 12 V, *f* = 200 kHz		[45]
Output = 65.77 W η = 62.44% (max), *f* = 162 kHz		[46]
Output = 64 W V = 16 V, I = 4 A, η = 76 - 79% , *f* = 150 kHz		[47]
Output = 51.7 W V = 12 V, I = 3 A, η = 91.13% *f* = 270 kHz		[42]
V = 40.5 V, I = 1.41 A, *f* = 270 kHz		
Output = 50 W η = 85% (max)		[43]
Output = 36 W V = 12 V, I = 3 A, Range = 0 – 10 cm η = 28 - 63%, *f* = 130 kHz		[15]
Output = 24 W V = 24 V, I = 1 A, Range = 0 – 10 cm η = at 0 cm 85.25%, at 1 cm 64.16% *f* = 12 kHz		[41]
Output= 10 W η = 93.6% (max), *f* = 1 MHz		[44]
Output = 13W V = 4.2V, η = 60%, *f* = 13.56 MHz		[48]
Output = 5W V = 5V, I = 1A, Range = 0 – 6 cm		[49]

VIII. RESEARCH ON WPT FOR DRONES

Numerous researchers have implemented UAV charging using IPT because of its compact technology and effective

TABLE 13. Public exposure levels set by ICNIRP.

Year	Standards and Guidelines	Operating Frequency	References
1967	USA Standards and Safety Levels: • Power Density limit: 10 mW/cm^2 for 0.1 hour or more • Energy Density limit: 0.1 mW-h/cm^2 for periods of 0.1 hour	10 MHz to 100 GHz	[192]
2005	IEEE C95.1 and ICNIRP 1998 Standards • Power Exposure limit: 0.08 W/kg for the human body.	3 GHz to 100 GHz	[203], [204]
	• Revised limit: 2 W/m^2	30 MHz to 100 GHz	
	• Revised limit: 10 W/m^2 • The spatial power density should not exceed 200 W/m2	400 MHz to 2 GHz	
2010-2014	IEEE C95.1 and ICNIRP Standards: • The electric field exposure criteria is that the fields cannot exceed 1.35×10^{-4} times the frequency value	30 MHz to 100 GHz	[205]
	• The magnetic field limit is 27 µT	400 MHz to 2 GHz	
2018-2019	ICNIRP Standards • An electric field of intensity 83 V/m is the maximum exposure limit set by ICNIRP • The level of the magnetic field radiation is set at 21 A/m	3 GHz to 100 GHz	[206], [207]

long-range transmission of up to a few cm. IPT is proving to be more viable for autonomous flight operations. Few research institutes have demonstrated their WPT charging pad, in which a transmitter coil is fixed to a charging station, and a receiver coil is embedded onto the drone's frame. For example, WiBotic has introduced a low-power and high-power charger purchase ready for public use. Similarly, Heisha, H^3 Dynamics, Power Republic Corporation have showcased similar types of chargers. GET has introduced an In-Flight charging technique, where the drone is charged for 6 minutes for an effective flight time of 25 minutes. Moreover, the drone never needs to land for charging; it remains in flight during the charging period. Features of the drone charging pads are mentioned in Table 11 along with a wired charging pad model developed by Sky-Sense [162]. In the next section, the technology behind wireless charging and comparative studies are discussed in detail, Table 12.

Song *et al.* [45] developed a prototype for a drone charging system that rests on an electric car. The car is charged by a battery, which charges the drone via a cylindrical WPT system, as shown in the case studies presented in Table 12. This provides the drone with a rigid structure to hold during the charging and increase the power transmission rate, achieving high efficiency and 150 W power transfer capability. Their studies concentrated on developing low EMF concentrated charger with reduced higher-order harmonics. In a much simpler approach, Yan *et al.* [46] achieved an efficiency of 62.44% at 162 kHz to transfer 65.77 W of energy using an asymmetrical coupling coil that could transfer power efficiently even with 30 mm lateral displacement. In this study, the author addressed the need for high-quality factor to tackle the misalignment problem between the loosely coupled coils. A detailed study was conducted using ANSYS Maxwell for modelling the perfect coil design. Campi *et al.* [47] conducted a similar experiment achieving 79% efficiency for 64 W peak power transfer. The experiment was conducted with a rectangular coil structure in the transmitter and receiver section. The system was able to charge optimally with a displacement of 10 mm laterally and 4 mm vertically. The use of a conventional SP compensation network is proved to be efficient than SS in terms of the reduced number of coils turns, with the output being unchanged. A much sophisticated and robust power transfer approach proposed by Han *et al.* [42] demonstrated 3D transmitting coils and a rectangular receiving coil with 91.13% power transfer efficiency at 270 kHz for 51.7 W power. The intricate 3D design ensures maximum coupling with the receiver coil and covers a much larger part of the receiving area. Rohan *et al.* [43] proposed a multi-transmitter coil with a single receiver unit approach. This ensures that the misalignment of the receiver system would still have functional mutual coupling, thus achieving 85% transmission efficiency for 50 W of power transfer. [15], [41], [44] used a much conventional power transfer approach using circular coils to achieve high efficiency for low power applications at HF. Jawad *et al.* [15] developed an independent

TABLE 14. Open Research Directions and its associated challenges with possible solutions.

Research Directions	Challenges	Proposed Solutions	References
Drone Charging	Jamming of charging pad, Jamming attacks	• Frequency Splitting charging, MRC • Periodic switching off and listening for nodes	[165]-[168]
	Spoofing attacks	• Use of Digital Signatures for data integrity and authentication	[168], [198]
	Energy Saving	• Listening for receiver nodes and switching off when not needed	[198], [199]
	Safety Attacks	• Deployment of EM and temperature measuring sensors for identifying safety regulation abuse	[198]
	Interference attacks	• Listening for suspicious transmissions	[198]
	Software attacks	• Use of trusted applications and digital signatures	[168], [198], [200]
	Monitoring attacks	• Periodic scanning for untrusted nodes	[198]
	Handling Large data	• Implementing Big data analytics and AI for easy administration	[202]
	Charging conflicts	• Charge Scheduling	[169]-[174]
Novel Coil Structures	Light-Weight, Super Conducting coils	• Use of innovative materials for receiver coil, such as HTS coils	[149], [151], [152]
V2V Charging	Drone to Drone Charging	• Use of concepts from EV to grid and EV to EV charging	[175]
Super-Capacitor based Charging	Instantaneous Charge storing	• Solutions from literature indicate that the technology is still in development phase	[176]
Dynamic UAV charging	Intermittent Charge during long flight hours	• Gathering charge from High-Tension Transmission lines	[177], [178]
AI integrated BMS	Battery health monitoring	• Keeping battery SOC between 20–80 %	[179]-[181]
Multi-Drone Coordination	High Latency, Signal Interference	• Implementation of Big data, traceability	[182], [183]
5G/6G Communication through UAVs	High power requirement Privacy concerns	• Implementation of AI • Implementation of Blockchain	[184], [185]
Drone Landing	Accurate landing onto charging pad	• Using Image Processing techniques	[186]-[188]
Human Exposure to EM waves	Over exposure to EM waves	• Use of EM absorbing materials and development of EM blocking methods	[189]

system that can charge autonomously and is ready to be deployed in remote locations. The transmission side battery is charged through the attached solar panels, thus making the system self-sufficient. Arteaga *et al.* [48] demonstrated a compact drone wireless charging system with a coil's unique arrangement. The receiver coil is placed at the drone's

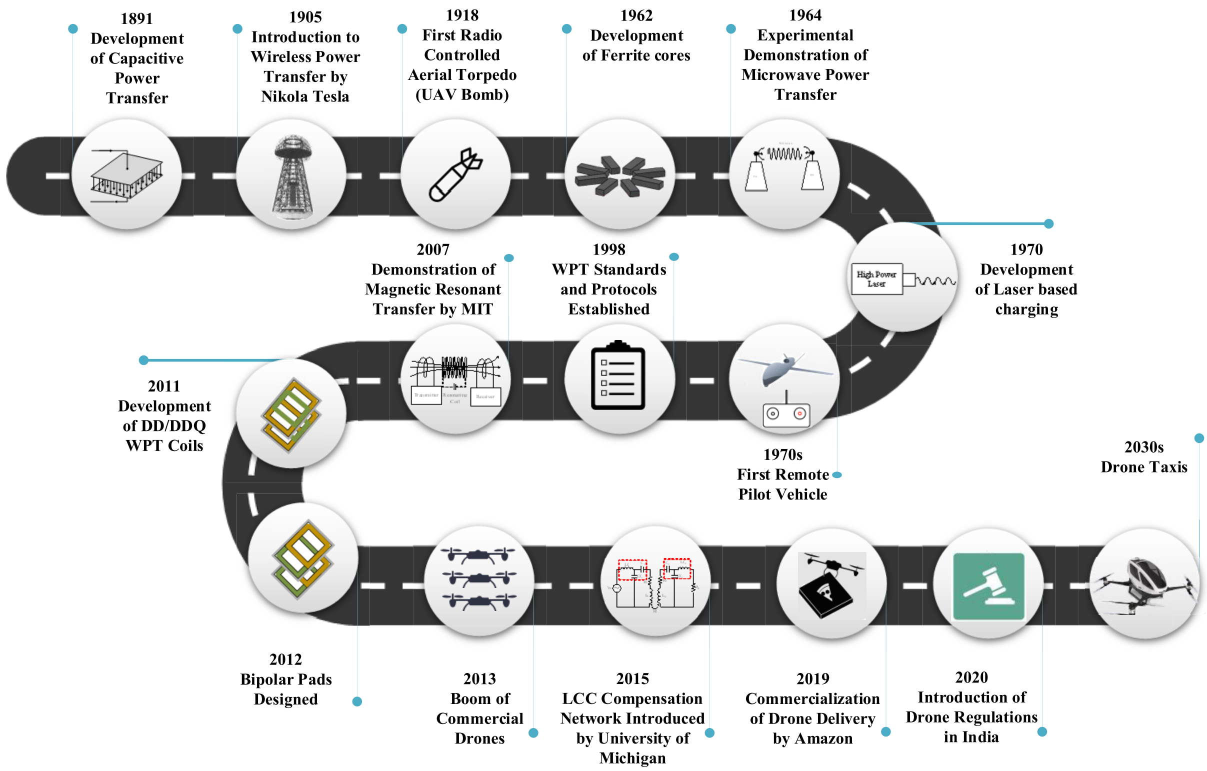


FIGURE 16. Roadmap for the Development of UAV Charging.

perimeter, thus effectively increasing the size of the receiving coil and with only a single turn to achieve 13 W of power transfer at 60% efficiency. An innovative technique for transferring power from UAV to ground-based receivers is proposed by Xu *et al.* [163] called Energy Beamforming. In this wireless power transfer technique, a UAV is mounted with a wireless energy transmitter and the ground based receivers are equipped with an array of antenna-based receivers to gather the energy being transmitted from the UAV's transmitter. This allows the UAV to hover over an area of interest and gather vital information from the ground-based sensors [164].

GIST OF CHAPTER

The chapter can be summarized as follow:

- Numerous attempts were made for developing a WPT system for drone charging, as shown in Table 11-12.
- From the literature, it is identified that the optimal range of power transmission is in the range of 85 – 300 kHz for voltage up to 24V
- Circular/Rectangular coil structures are preferred for transmitter-receiver coil design
- SP configuration is suitable over SS as it reduces the weight of the coil design
- Future research is directed towards the development of a multi-drone charging circuit using concepts such as frequency splitting and MRC.

IX. PUBLIC EXPOSURE LEVELS OF WPT

The previous data presented in this paper has pointed out that the increase in frequency above 130 kHz has a significant effect on power transmission efficiency, as higher frequencies are necessary for effective WPT. These higher frequencies induce a voltage in the surrounding living/metallic objects, which pose a severe threat of health risk due to EM radiations. Thus, specific standards have been proposed to limit health risks. According to the guidelines laid by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), EMF exposure cannot exceed 1.35×10^{-4} times the operating frequency. In 1998, WPT standards for public safety had been set to 6.25 μT units of magnetic flux density and later in 2010 increased to 27 μT. Electric field-induced to the skin is to be limited to 83 V/m [190]. Table 13 shows the guidelines for operating WPT equipment under certain levels for the safety of public operations. Recent studies have shown few methodologies for limiting EMF exposure, such as EMF noise cancellation from WPT system, passive shielding, independent self EMF cancellation, leakage flux cancellation and magnetic field cancellation using a reactive resonant current loop [191]–[195].

GIST OF CHAPTER

The chapter can be summarized as follow:

- As per the recommendations of INCIRP, EMF exposure should not exceed beyond 1.35 x 10^{-4} times the operating frequency

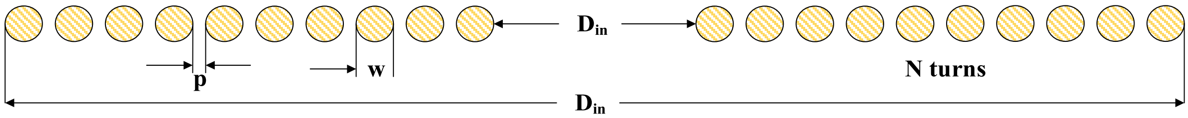


FIGURE 17. Cross-Sectional view of 10 turn planar circular coil.

TABLE 15. UAV weight distribution.

Part	Weight per Piece	Quantity	Total Weight
Motor	158 g	8	1264 g
ESC	35 g	8	280 g
Propeller	13 g	8	104 g
Centre Frame	1330 g	1	1330 g
Arm	119 g	8	952 g
Flight Controller	70 g	1	70 g
Receiver and wires	200 g	1	200 g
Battery	2500 g	1	2500 g
		Total Weight	6700 g

- WPT standards for public safety had been set to 27 μT
- Electric field-induced to the skin must be limited to 83 V/m, as per the recommended guidelines when designing a wireless charging circuit.

X. FUTURE TRENDS AND RESEARCH DIRECTIONS

The application of drones are limited only by imagination and has already penetrated the transportation sector. Thus, the need for fast charging a drone's battery will become the top priority even before commercial drone taxis deployment. Contact-based charging of high kW batteries might lead to electrical hazards and severely injure the human operator. Thus, a non-contact based charging technique such as WPT will become the need of the hour for both equipment and human operator safety. The drone and wireless charging technology has abundant scope for providing jobs and would create new skilled employees. Implementation of Machine Learning and IoT into drone technology will make the devices smart, intelligent and efficient. The self-learning algorithms would improve the flight's performance and study the delivery routes for a faster, safer and reliable delivery experience. Future research is directed towards the development of protecting the wireless charging system against attacks such as Jamming attacks [165]–[168], Spoofing attacks [166], [196], Safety attacks [196], [197], Interference attacks [196], Software attacks [166], [196], [198] and Monitoring attack [196]. Furthermore, research is directed towards the development of energy-saving systems [199], handling large UAV protocol data [200], avoiding charging conflicts [169]–[174], design of novel coil structures [149], [151], [152], drone to drone (V2V) charging [175], Supercapacitor based fast charging [176], dynamic charging of UAV during long flight hours [177], [178], Efficient battery management of UAV for optimized performance [179]–[181], development of coordination algorithms [182], [183], using UAVs for 5G/6G communication [184], [185], accurate drone landing algorithms using image processing techniques [186]–[188] and studying effects of EM waves on the human body [189]. The challenges are further discussed in Table 14.

XI. CONCLUSION

The journey of merging WPT into drones was long (Fig. 16), yet there are limitless development opportunities. With the increase in demand for drone delivery, the need for fast and safe charging methods such as IPT, CPT and MRC will increase. The future of UAV relies on wireless charging, which can handle multiple devices, save time and reduce stress on operators. This paper targets the need for WPT into drones with a systematic study of previous attempts made by prominent research laboratories, universities, and industries. The paper highlights the import role played by drones in world wars and how the technology settled into civil applications. Furthermore, the categories and internal architecture of the UAVs is briefly discussed.

The article also covered the technical aspects of wireless drone charging by elaborating the current drone charging methods and how wireless charging can improve the performance of autonomous operations. The article

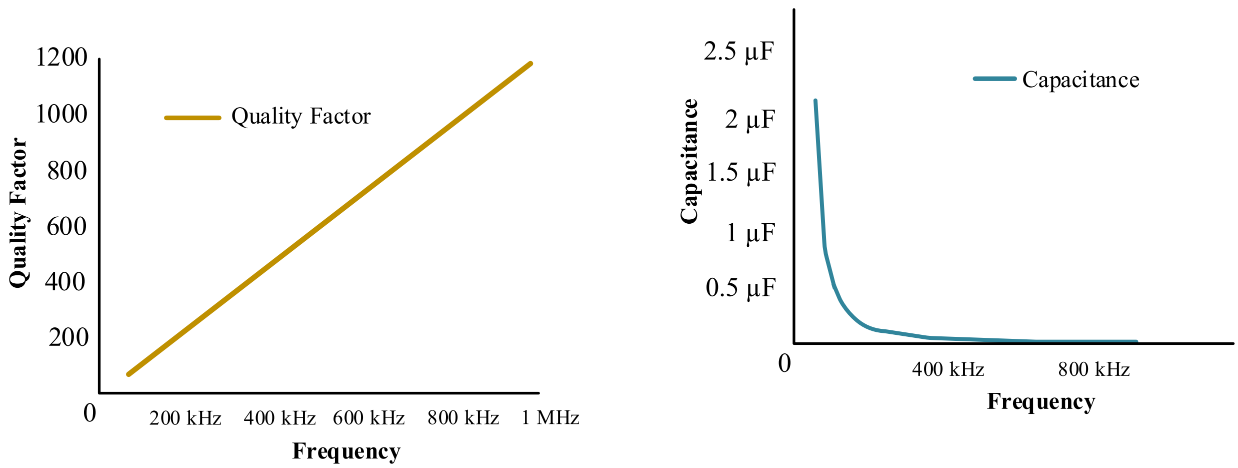


FIGURE 18. Change in quality factor and capacitance with the increase in frequency.

comprehensively reviewed the developments made in the field of wireless charging and summarized the key aspects to be considered when developing a wireless charging circuit for drones. Finally, the article presents open research challenges and possible solutions to tackle them.

APPENDIX

A. UAV FLIGHT TIME ANALYSIS

The following notations are considered before the analysis initiates:

AAD	Average Ampere Drawn
P	Power required to lift 1 kg
V	Battery Voltage
D	Maximum Discharge in Percentage (80%)
T	Flight Time
BC	Battery Capacity
W	Total Drone Weight

The following are the specifications of UAV:

Number of motors	8
Battery Specification	22 Ah, 6S
Full charge voltage	25.2 V
Motor Specification	400 kV, 2.5 kg thrust.
Payload	2.5 kg
Total Drone weight	6.7 kg + 2.5 kg = 9.2 kg
Drone's discharge at peak performance	1500 W
Power required tolift 1 kg	190 W

$$AAD = WX\frac{P}{V}$$
$$AAD = 9.2X\frac{190}{25.2} = 69.36\,A \tag{1}$$
$$T = BCX\frac{D}{AAD}$$
$$T = 22X\frac{0.8}{69.39} = 0.253H = 15.2\ minutes \tag{2}$$

TABLE 16. Selection Criteria of k_1.

Factor (k_1)	Number of Bunch
1.02	1
1.04	2
1.06	3

Thus, the drone can perform at peak discharge for approximately 15 minutes with a payload of 2.5 kg.

In-Flight charge time = 6 minutes for 80% charge.

Advantages of Wireless Drone Charging System:

- Installation of an in-field charging pad does not require separate land. Thus, the land cost is saved.
- The battery life of the drone is increased due to the narrow SoC band.
- Short missions do not fully discharge the battery. Thus, battery health is sustained.
- WPT is reliable in the aspects of electrical shocks, sparks generation, and current handling.
- Maintenance of the system is reduced as there is no wear and tear of the charging plug.

B. DETERMINING COIL PARAMETERS

Considering the following notations:

N	Number of turns in the coil
D_{in}	Inner diameter of the coil
D_{out}	Outer coil diameter of the coil
w	Width of the coil conductor
p	Distance between two turns of the coil

Calculating self-inductance of the circular coil using Modified Harold A. Wheeler's formula:

$$L = \frac{N^2(D_{out} - N(w+p))^2}{16D_{out} + 28N(w+p)} \times \frac{39.37}{10^6} Henry \tag{3}$$

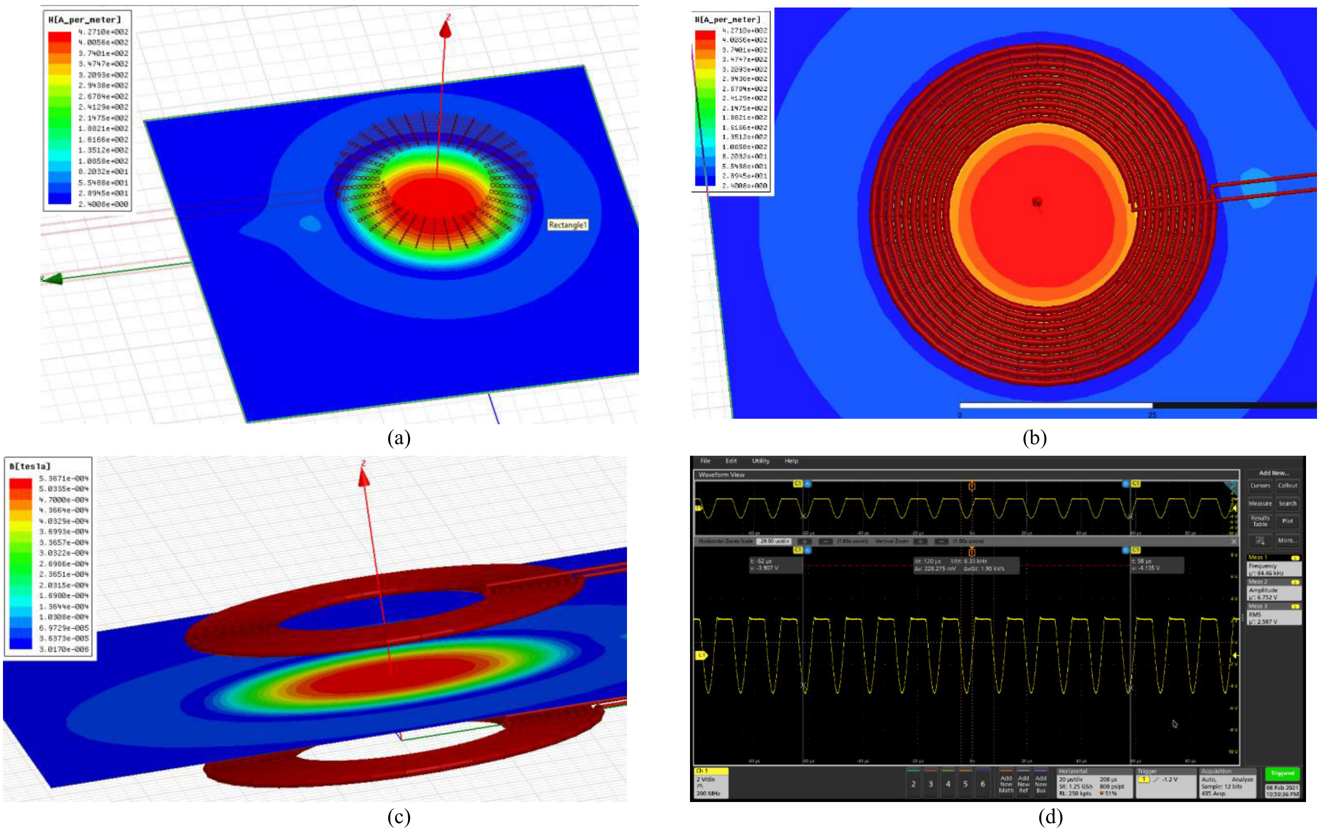


FIGURE 19. ANSYS Maxwell Coil Simulation Results (a) Electric Field intensity on a vacuum sheet placed between the coils (b) Top view of coils (c) Magnetic Field intensity on a vacuum sheet placed between the coils (d) Output waveform of the receiver coil in real-time measurement.

TABLE 17. Experimental and simulated observations.

Distance between Coils (mm)	Simulated Inductance (µH)	Measured Inductance (µH)	*k* Simulated	*k* Measured	Output Voltage (V)
1	4.04	4.876	0.5	0.42	9
7	4.04	4.876	0.46	0.41	8.8
10	4.04	4.877	0.35	0.30	6.5
15	4.04	4.877	0.19	0.20	3.5
20	4.04	4.877	0.12	0.11	1.2

Coil Parameters

D_{in}	21 mm = 0. 021 m
D_{out}	43 mm = 0.043 m
w	1 mm = 0.001 m
p	0.1 mm = 0.0001 mm

From equations (3), $\mathbf{L = 4.04\ \mu H}$.

Calculating Capacitance of the coils at 85 kHz resonant frequency:

$$\omega = \frac{1}{\sqrt{LC}} \tag{4}$$

$$C = \frac{1}{4\pi^2 f^2 L} \tag{5}$$

where $\omega = 2\Pi f$ Thus, from equation (5) Capacitance of the coil is,

$$\mathbf{C = 876\ nF}$$

Calculating Resistance of the transmitter-receiver coil:

$$R = \rho \frac{l}{A} \tag{6}$$

where,

Resistivity of copper (ρ)	1.72×10^8 Ω-m at 20 °C
Length of the conductor (l)	1 m
Area of conductor (A)	$\Pi r^2 m^2$

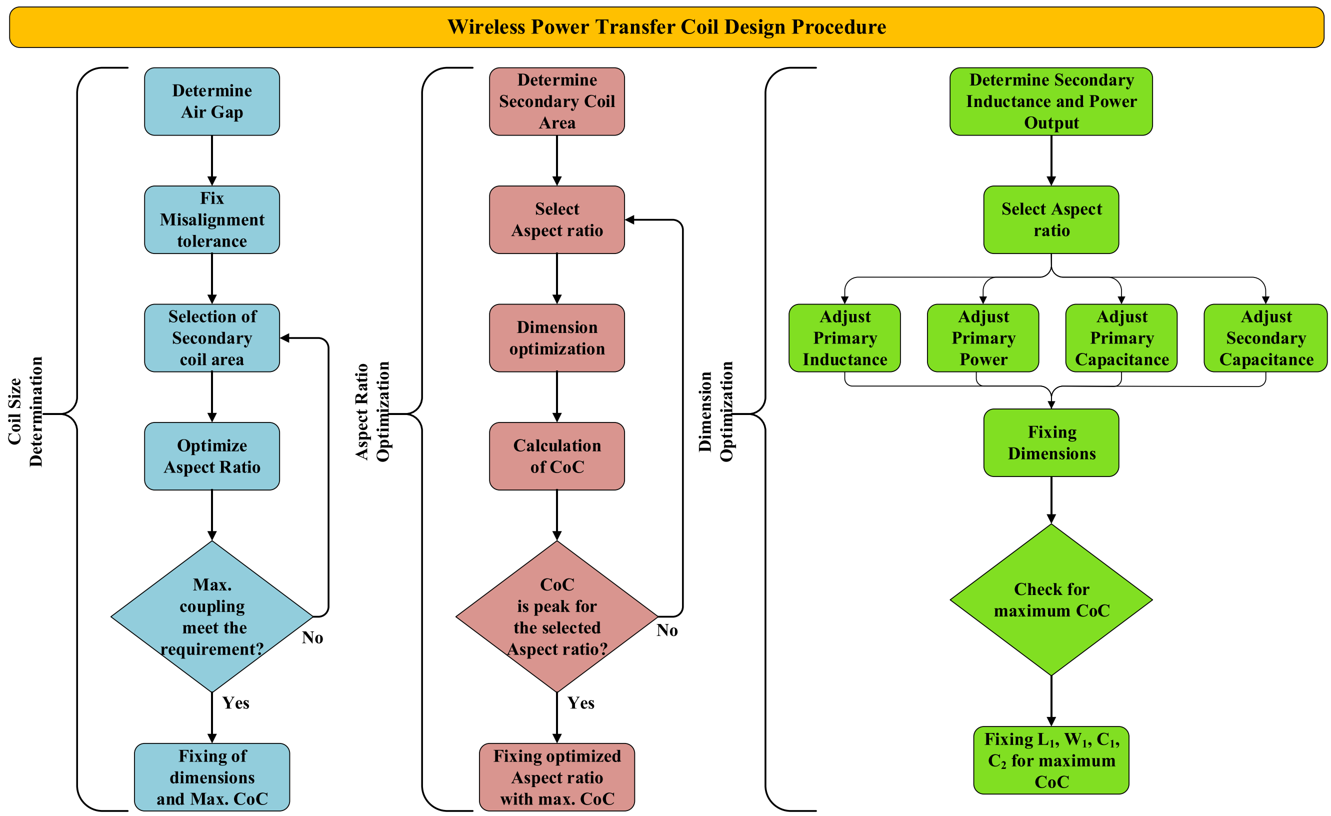


FIGURE 20. Wireless coils design procedure.

Thus, from equation (6), Resistance of 1 m solid copper coil is,

$$\mathbf{R = 21.3\ m\Omega}$$

Calculating Quality Factor of the transmitter-receiver coil:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{7}$$

Thus, the Quality factor of the designed coil is,

$$\mathbf{Q = 101}$$

Improvement of Quality Factor using Litz coil:

For number of wires less than 25,

R_{max} Maximum value of resistance
R_s Maximum value of resistance of single wire

$$R_{max} = \frac{R_s}{\text{Number of Single Wires}} \times k_1 \tag{8}$$

Selection of k1:

For Number of wires greater than 25,

$$R_{max} = \frac{R_s}{\text{Number of Single Wires}} \times k_1 \times k_2 \tag{9}$$

where $k_2 = 1.03$ as the factor for broken wires.

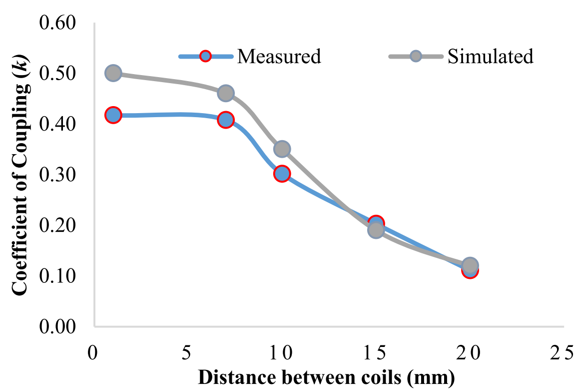


FIGURE 21. Variation in CoC with the Increase in Distance between coils.

C. ANSYS MAXWELL SIMULATION AND VERIFICATION

A simulation of transmitter and receiver coils is performed in ANSYS Maxwell simulation software using the same parameters and the output waveform is measured using Tektronix 4 series Mixed Signal Oscilloscope. The waveform output is shown in Fig. 19 (d), which is receiving 6.74 V peak amplitude and RMS voltage of 2.587 V for a 1 A charging current. To design a WPT transmitter-receiver coil, the design procedure shown in Fig. 20 should be followed. The simulated and the calculated CoC, Self-Inductance values are shown in the Table 17 and the change in CoC with the increase in distance is plotted in Fig. 21. The results indicate a minor deviation from the simulated values with an error well below the acceptable range.

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