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Review

Electromagnetic Field Based WPT Technologies for UAVs: A Comprehensive Survey

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Abstract: Wireless power transfer (WPT) techniques are important in a variety of applications in both civilian and military fields. Unmanned aerial vehicles (UAVs) are being used for many practical purposes, such as monitoring or delivering payloads. There is a trade-off between the weight of the UAVs or their batteries and their flying time. Their working time is expected to be as long as possible. In order to support the UAVs to work effectively, WPT techniques are applied with UAVs to charge secondary energy supply sources in order to increase their working time. This paper reviews common techniques of WPT deployed with UAVs to support them while working for different purposes. Numerous approaches have been considered to illustrate techniques to exploit WPT techniques. The charging distances, energy harvesting techniques, electronic device improvements, transmitting issues, etc., are considered to provide an overview of common problems in utilizing and charging UAVs. Moreover, specific problems are addressed to support suitable solutions with either techniques or applications for UAVs.

Keywords: unmanned aerial vehicles (UAVs); wireless charging; wireless power transfer; resonant inductive coupling; capacitive coupling; RF wireless power transfer; RF energy harvesting

1. Introduction

The concept of wireless power transfer (WPT) can be dated back to the early 20th Century when Nikola Tesla obtained a patent for the Tesla coil, a very revolutionary apparatus able to transfer energy through radial electromagnetic waves. This approach of electrical energy transfer obtained great attention from both the research community and industry, leading to the evolution of such a technique for different applications. Basically, the WPT consists of two consecutive steps: (i) convert the amount of power that would be transmitted into an alternative form of energy; (ii) transmit it to the destination devices without the usage of a static structure. Usually, well-known approaches consist of converting the energy into a magnetic field or an electromagnetic field and transmitting it using magnetic induction or electromagnetic radiation, respectively. More in general, as illustrated in Figure 1, WPT techniques can be broadly categorized into two types: near-field and far-field. Near-field techniques are adopted for applications where the distance between the transmitter and receiver is within a few millimeters or centimeters, for example charging handheld devices, radio frequency identification (RFID) tag technology, induction cooking, and wireless charging or continuous WPT in implantable medical devices. In contrast, far-field methods are able to achieve longer distances. They can be used for applications where the distance between the transmitter and receiver is within several kilometers. An example of far-field methods consists of transmitting power from a geostationary satellite to ground devices. Then, due to their long-range capability, the far-field methods have been recently labeled as a promising solution to supply power to mobile electric devices (MEDs) operating in harsh conditions where people cannot access and the use of conductive cables is infeasible [1,2].

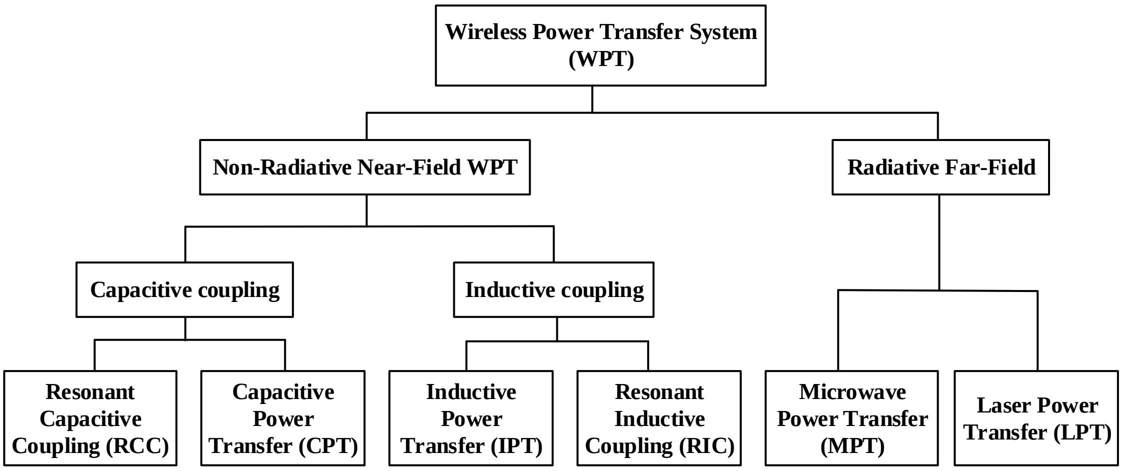

Figure 1. The classification of wireless power transfer (WPT) technology.

On the other hand, unmanned aerial vehicles (UAV), commonly known as drones, are an emerging technology that can help future networks achieve better communication performances than the actual base station based networks [3,4]. In addition, due to their mobility and flexibility, UAVs have represented a key enabling technology for the development of a wide range of very innovative applications such as surveillance and military applications [5–7], search and rescue operations [8–10], remote sensing activities in which UAVs collect the data from sensors and deliver the collected data to ground base stations [11–15], construction and infrastructure inspection [16–19], precision agriculture for crop management and monitoring [12,20–22], and the delivery of goods [23]. Generally, commercial UAVs come with lithium batteries that provide power for approximately 20–40 minutes of flying time [24]. However, in order to perform most of the operations mentioned before, they are equipped with additional devices such as cameras and sensors, which usually are powered by the same embedded battery. As a consequence, the flying autonomy of UAV based systems and hence their operational range are strongly dependent on their battery lifetime. This problem can be addressed by equipping the UAV with a bigger battery unit. However, even if it represents a very simple approach, the battery lifetime problem is not fully addressed since this approach leads to an increase in the size and weight of the drone. As a consequence, more energy will be required to fly. An alternative solution would consist of a scenario where the UAVs return to a predefined base station for battery replacement when their battery level is low. However, in addition to requesting a huge amount of time, it could be impractical due to the cost and complexity of these systems [25–27].

The possibility to adopt WPT technologies for supplying power to UAV systems has been recently recognized as a very attractive approach able to lead toward alternative and efficient charging solutions [28–32]. For example, it can be possible to create several wireless charging stations where the UAV can fly back to recharge its battery through the inductive WPT pads present on that station. Alternatively, since this approach would request the interruption of the activities performed by the UAV, the energy would be provided through electromagnetic radiation, avoiding the need for the UAV to fly back to its base station for charging, avoiding the interruption of its tasks, which in some cases like rescue operations could represent a critical aspect.

As far as the authors are aware, at the time of writing, the most relevant contributions aimed to survey and review WPT technology solutions applied in the context of UAV networks were the ones presented in [33,34]. In particular, the study presented in [33] proposed firstly a classification of the various wireless charging techniques into two main classes: (i) non-electromagnetic field (non-EFM) based and (ii) electromagnetic field (EMF) based. Subsequently, for each class, the most relevant techniques adopted to extend UAVs' flight range and mission duration were reviewed. Moreover, discussions and a practical examination of the most feasible and reliable techniques to charge UAV using power lines were provided. On the other side, after illustrating the main fields where UAV based solutions can be adopted, Boukoberine et al. [34] provided a classification of UAV devices according to their main source of power, i.e., battery-cell based, fuel-cell based, and a hybrid solution. Subsequently, a survey regarding the most relevant power management strategies, aimed to extend as much as possible the lifetime of each type of power source, was provided. Taking the previous reviews into consideration, as well as the increasing interest towards the EMF based solution highlighted in [1], in this paper, we propose a comprehensive survey on the most contemporary EMF based WPT techniques presented in literature and proposed to provide power to UAV based networks. In particular, a classification of these techniques into near-field and far-field technique is firstly provided. Subsequently, in addition to illustrating the general working principle of these EMF-WPT techniques, this survey is organized in order to analyze the most important aspects and key factors that result in being useful for the design and deployment of such WPT systems acting as the power supply for UAV-enabled networks.

For the sake of clarity and completeness, this paper is organized as follows. Section 2 contains an overview of the wireless power transfer technology principle, introducing the reader to the main characteristics of this technology and system design. Subsequently, the near-field and far-field WPT methods are reviewed in Section 3 and Section 4, respectively. Open issues and challenges of WPT techniques for charging UAVs are discussed in Section 5. Finally, conclusions and future directions in this research field are provided in Section 6.

2. Wireless Power Transfer Technology Principle

As mentioned in the previous section, the most diffused principle of the WPT technique consists of a two-step process, which first converts the amount of power into an alternative type of energy, i.e., electric field or magnetic field, which can be transmitted to a receiver exploiting the magnetic induction or the electromagnetic radiation. Then, as illustrated in Figure 2, each WPT technique involves three main parts such as the transmitter, receiver, and coupling devices.

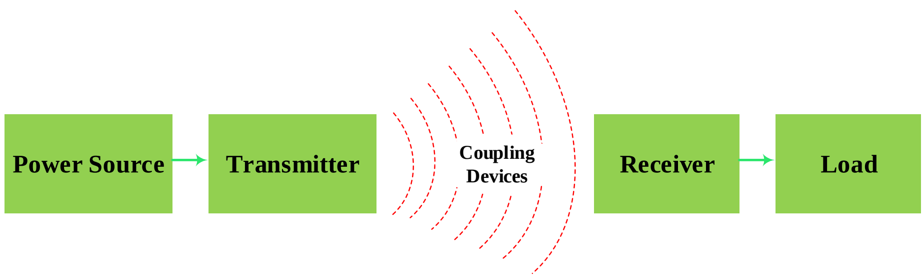

Figure 2. Schematic block diagram of the WPT system.

The transmitter is directly connected to an energy source, which is converted into a time-varying electromagnetic (EM) field and radiated through the coupling device. On the other side, the receiver uses its coupling device to receive the radiated power and convert it back to direct current (DC) or alternate current (AC), which is used by the load. Although this represents a common principle, each wireless transmission method has its own power converting circuit, operating frequency, and coupling devices, which impact the transfer distance capability and transmission efficiency of the WPT method. In particular, based on the relation between the maximum diameter of the radiation pattern and the operating frequencies, WPT techniques are labeled as near-field radiation (NFR) and far-field radiation (FFR) as follows:

$$NFR < \frac{2d^2}{\lambda}, \qquad FFR > \frac{2d^2}{\lambda}; \tag{1}$$

where d is the maximum diameter of the coupling devices and λ is the wavelength of the radiated field, i.e., device operating frequency.

Near-field or non-radiative techniques can be broadly divided into two categories: (i) capacitive coupling and (ii) inductive coupling. In the first case, the power is transmitted by exploiting the coupling principle between two metallic plates traversed by an electric field. In the second case, the power is converted into a magnetic field in order to exploit the magnetic induction between wire coils, which act as coupling devices. These types of techniques are used to transmit power at a very short distance, i.e., a few millimeters or centimeters. On the other side, far-field techniques are used to transmit power within distances up to several kilometers. In order to reach these higher distances, these techniques convert the power into EM waves and exploit the EM radiation as a coupling principle. Based on their operational frequency, even in this case, it is possible to classify these techniques as: (i) micro-power transfer (MPT) and (ii) laser power transfer (LPT) techniques. In the first case, the electromagnetic radiation is performed by generating EM waves in the radio spectrum, i.e., from a few kHz up to 300 GHz, radiated by using antenna systems. In the second case, the power is transmitted within the visible light spectrum, using laser couplers as coupling devices.

According to the previous classifications, one can note how each WPT application is possible to choose the proper technique in order to meet the system requirements and constraints. For this reason, highlighted in the previous section, the possibility to adopt WPT technologies as the power supplier for UAV applications is gaining momentum. Indeed, depending on the specific UAV-enabled application, the battery lifetime would be optimized with several system constraints such as weight, range, maximum altitude, wing loading, and engine type [35]. Then, for each different type of UAV application, it would be possible to use the most suitable WPT charging technology in order to optimize the energy transmission performance at each operational distance [36].

For the sake of completeness, the following subsections will introduce the general working principle of the near-field and far-field WPT techniques.

2.1. Near-Field Wireless Power Transfer Techniques

As mentioned earlier, near-field WPT techniques can be broadly divided into capacitive coupling and inductive coupling WPT techniques. The basic principles of these techniques are briefly discussed within this subsection.

2.1.1. Capacitive Coupling Wireless Power Transfer

In a general capacitive coupling wireless power transfer (CCWPT) system, as illustrated in Figure 3, the transmitter is directly connected to a DC input source. Depending on the operational frequency, using an AC/DC converter and a proper compensating network, the DC input is converted into an AC voltage applied to a set of asymmetric electric dipoles. Equipping the receiver with the same set of asymmetric electric poles, it is able to receive the transmitted power by exploiting the capacitive coupling [37–39].

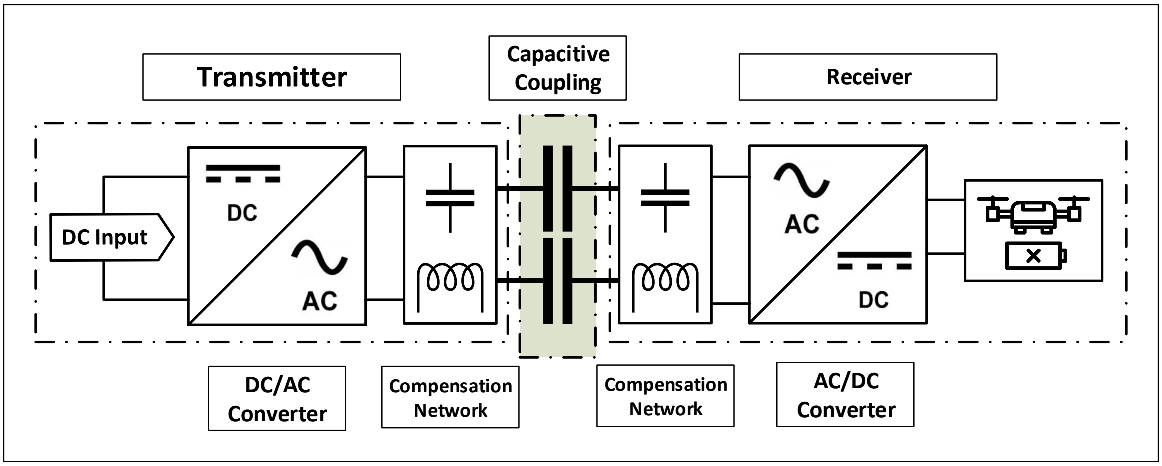

Figure 3. The structure of a typical capacitive coupling wireless power transfer (CCWPT) UAV charging system.

The capacitive coupling represents the main component of this WPT technique. Power can be transferred via electric fields by capacitive coupling between metal electrodes. These fields are non-radiative, i.e., the energy stays within a short distance from the transmitter. If there is no receiving device or absorbing material within the limited range to the couple, no power leaves the transmitter. In addition, it is worth mentioning that the strength of generated electric fields decreases exponentially with distance, so if the distance between the two "antennas" (D_{range}) is much larger than the diameter of the "antennas" (D_{ant}), a very small amount power will be received. In order to point out further characteristics of this WPT approach, as illustrated in Figure 4, a typical CCWPT system can be modeled as a simple linear circuit with an alternating input alternative voltage V_{IN} within an operating frequency ω, the compensating inductor L, and the coupling capacitance C_{cc}.

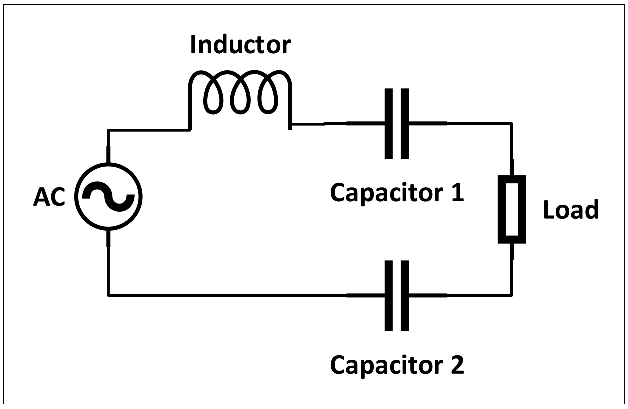

Figure 4. The simplified CCWPT circuit.

According to this electric model, the output voltage applied to a load with resistance R_L is formulated as:

$$V_{OUT} = \frac{V_{IN}\angle 0}{j\omega L + \frac{2}{j\omega C_{cc}} + R_L} R_L \tag{2}$$

Then, even if the perceived voltage results in being constrained by the distance between the power transmitter and receiver, from Equation (2), it can be noted that the output voltage can be increased in other different ways. First is increasing the operating frequency to reduce the impedance of the circuit. Second is that the compensation inductor can also be used to counteract the capacitive impedance. Thirdly, to get the required output voltage, boost up circuits can be used to increase the voltage fed into the coupling device plates [40].

The main advantages of CCWPT technology are low cost, low weight, and low eddy current loss in nearby metals [40]. CCWPT can be used in short distance and low power applications, such as integrated circuits (IC) [41], biomedical devices [42,43], LED lighting [44], USB, and mobile device charging [45,46], especially for UAV wireless charging [47–49]. In addition, it can be also adopted to realize high power level applications such as synchronous machine excitation [50–52] and either static or dynamic electric vehicle charging systems [53–55].

2.1.2. Inductive Coupling Wireless Power Transfer

On the other side, inductive coupling wireless power transfer (ICWPT) is a near-field WPT method based on the magnetic induction principle [56]. This method can be divided into inductive power transfer (IPT) and resonant inductive coupling (RIC).

As illustrated in Figure 5, the AC voltage generated by an IPT transmitter is applied to a wired coil, which generates a corresponding AC magnetic field. At the same time, due to the magnetic induction principle, an AC voltage is generated on the wired coil present on the IPT receiver. Then, the essence of this techniques is the same as a voltage transformer including two coils: a transmitter (primary) coil and a receiver (secondary) coil. However, in this case, the transformer has an air-gap, which results in a very poor magnetic conductive environment. Then, as for the CCWPT, the distance between the coupling devices plays a crucial role. Indeed, for long distances, the IPT technique is highly inefficient and causes energy consumption for the resistors in the primary coil.

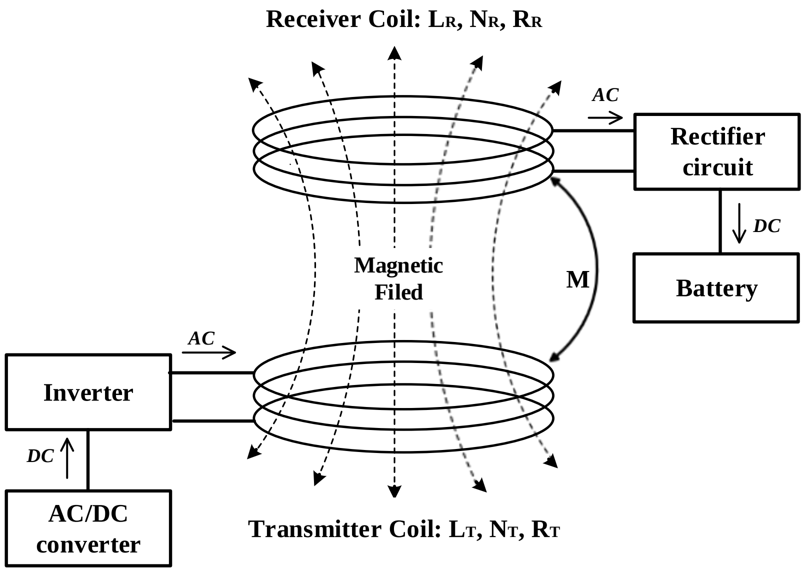

Figure 5. Typical inductive coupling system.

In order to achieve longer distances, the resonance principle is used in the RIC methods. It is worth to mentioning that the first prototype of an RIC system was the one used by Nikola Tesla at the beginning of the 20th Century for conducting his first experiment on wireless power transmission. As illustrated in Figure 6, an RIC system can be viewed as an IPT system with two resonant LC-groups added both in the transmitter and receiver side. Then, changing the values of the LC-resonator, it is possible to work at the desired frequency [57]. In addition, these type of WPT systems support mobile applications and do not need the fitted alignment between charging devices and the WPT system [30].

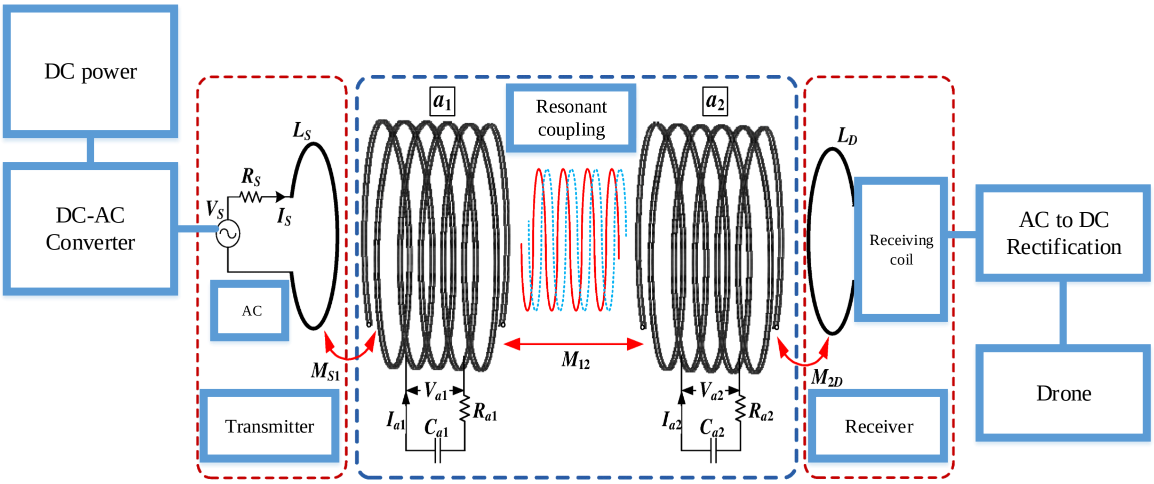

Figure 6. Typical resonant coupling system.

In addition to the supported distances, other important parameters that permit evaluating the quality of an ICWPT system are represented by:

- The resonant frequency is:

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

  where L and C are the inductance and the capacitance of the circuit, respectively.

- The quality factor, which describes the resonance behavior of an underdamped harmonic oscillator (resonator). To a high-quality quality factor corresponds a system with a high harmonic response quality. It is defined as [56]:

$$Q = \frac{\omega L}{R} \tag{4}$$

  where ω is the frequency in rad/s and R is the oscillator resistance.

- The coupling coefficient is defined as:

$$k = \frac{M}{\sqrt{L_T \times L_R}} \tag{5}$$

  where M is mutual inductance and L_T and L_R are the inductance of the transmitting and receiving coils, respectively.

- The figure of merit is a quantity used to characterize the performance of the device, system, or methods relative to the alternatives.

$$f.o.m = k\sqrt{Q_T \times Q_R} \tag{6}$$

  where Q_T and Q_R are the quality factors of the transmitting and receiving coil, respectively.

- The efficiency of the WPT system is determined as [58,59]:

$$\eta = \frac{P_{out}}{P_{in}} \tag{7}$$

  where P_{out} is the output power and P_{in} is the input power.

2.2. Far-Field Wireless Power Transfer Techniques

In the far-field wireless power transfer techniques, also called radiative techniques, power is transmitted by exploiting the electromagnetic radiation (EMR) principle. In contrast to the near-field methods, these types of power transmission techniques are able to transport power for longer distances, i.e., within a transmission range of several kilometers. However, in this type of power transmission, a constant line-of-sight (LoS) between the transmitter and receiver represents a primary requirement. Due to their capability of reaching higher distances, these techniques result in being more indicated for wireless sensor networks (WSNs) and Internet of Things (IoTs) devices' charging, radio-frequency identification (RFID) systems, and wireless powered UAVs.

As stated before, these types of techniques can be categorized into MPT techniques, which operate in the radio propagation spectrum, usually at the microwave frequency, and LPT, which is used to transport energy in the visible spectrum. Typically, MPT power radiation can be more efficient than LPT. Indeed, in contrast to laser radiation, it is less prone to possible atmospheric degradation caused by dust or steam. This permits reaching longer distance. In addition, MPT techniques are less dependent on the LoS requirement, which makes these techniques more flexible. Despite this classification, both techniques can be described using the block diagram illustrated in Figure 7. In this case as well, the power transmission process begins with the RF source, which broadcasts the energy through an antenna, which acts as a coupling device. After propagating through the air, the radiated power is captured by the receiver's matching circuit containing a receiving antenna and rectified into electricity again. Then, the DC output is managed by the DC-DC converter, which provides the energy to the storage device.

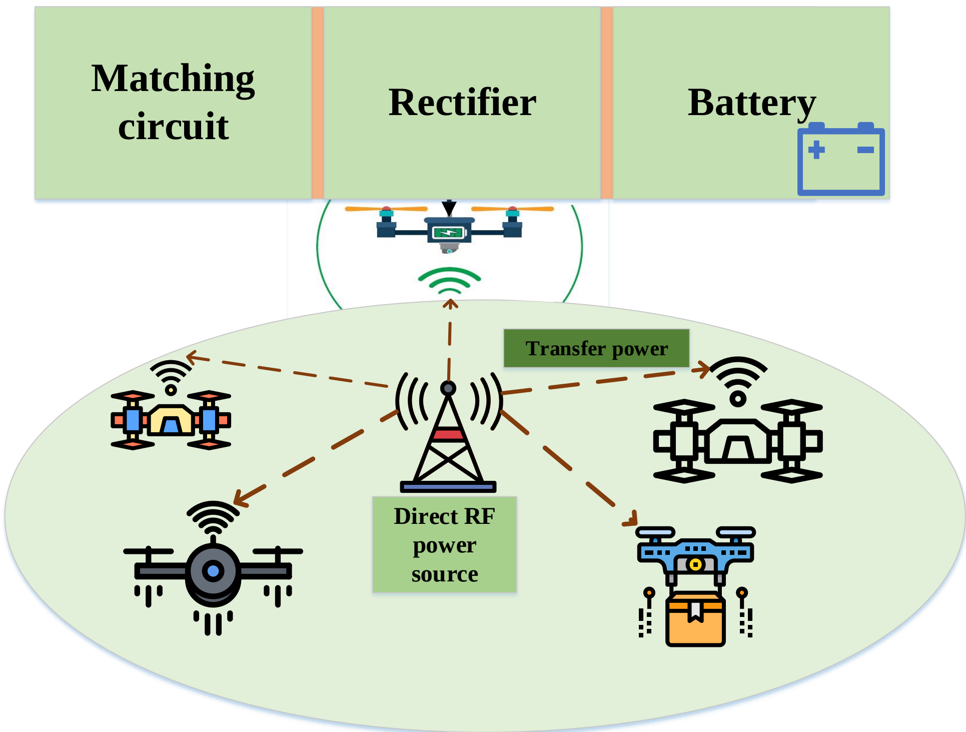

Figure 7. Conceptual block diagram of the far-field WPT system.

3. Near-Field WPT Technologies

This section contains a survey of the most relevant near-field WPT technologies presented in literature. In particular, this section is organized into two subsections, each of them aimed to provide a comprehensive survey on CCWPT and ICWPT technologies, respectively.

3.1. CCWPT Technologies

In this section, weimprove the output voltage for charging UAVs via CCWPT. In addition, wireless charging systems for actual deployment with UAVs are also listed. We classify the proposed methods into three categories: (1) operating frequency; (2) compensation; and (3) boost circuits. Finally, wireless charging systems for actual UAVs deployment are also listed.

3.1.1. Operating Frequency

An alternating voltage generated by the transmitter is applied to the transmitting plate, and the oscillating electric field induces an alternating potential on the receiver plate by electrostatic induction [60], which causes an alternating current to flow in the load circuit. The amount of transferred power increases with the frequency, the square of the voltage, and the capacitance between the plates, which is proportional to the area of the smaller plate and (for short distances) inversely proportional to the separation. If the obtained capacitance is very small, the simple resonant circuit limits the transfer. The quality factor is very high; hence, the operation is unstable [61]. A high-frequency operation and impedance transformation comprise a viable solution to overcome this drawback. Operating frequency selection is necessary to meet wireless regulations in mobile wireless charger applications and standards of the operating frequencies of the industrial, scientific, and medical (ISM) band.

For efficient high-frequency and moderate voltage operation, in [62], Mitchell Kline et al. designed a wireless power transfer (WPT) system using series resonance. Automatic tuning loops were also used to ensure that the circuit operated at the optimal frequency and maximum efficiency over a wide range of coupling capacitance and load conditions. By analysis, they found that the key to high efficiency was series resonant operation using small and moderate Q ferrite core inductors, enabling soft-switching and high frequencies. In addition, the high-frequency operation of capacitive powering can easily be combined with a high-speed data transfer that enables both wireless charging and data synchronization over a single interface. For example, in [63], Asish Koruprolu et al. proposed a system that used a wireless powering scheme for biomedical implants through a two-contact resonant capacitive link where data were transmitted simultaneously in a hybrid amplitude-frequency shift keying (ASK-FSK) technique over the same channel. The data transfer rate was at 170 kbps with a 1 MHz operating resonant frequency, and the power transfer efficiency achieved 70%. Alternatively, in [64], a 100 W WPDTprototype was built. The measured power transfer efficiency, from DC input to DC output, was 90.5%. The transferred data were correctly recovered at the receiver side at a data rate of 119 kbps. The data circuit worked well even though the coupling coefficient was decreased by 60.2%.

A silicon power semiconductor cannot be driven efficiently with a very high frequency such as GHz operation, so Kang in [61], instead of using 13.56 MHz, which is one of the popular ISM operating frequency bands to transfer energy because this frequency is used in other applications, used 6.78 MHz in a capacitive coupling wireless power transfer system. The 6.78 MHz operation could meet wireless regulations without interfering with other devices and transfer energy with a small capacitance in the CCWPT. As shown in Figure 8 the system consisted of a Class D inverter, LC filter, and impedance transformation circuit such as step-up and step-down transformers to increase the coupling capacitance and reduce the Q-factor. Hence, the output power could be obtained in the resonant frequency variation. This system could supply wireless power to mobile chargers or electric devices. As a result, the CCWPT system could supply the power to the 4 W/800 mA output for mobile device chargers and had better efficiency than that of the magnetic resonance WPT with a full load and no load. In order to reduce the switching loss at the transmitted side, Yusop et al. in [65], instead of using the class-D inverter, used the Class E resonant inverter to perform DC-to-AC conversion. In addition, they used a simple frequency tracking unit to tune the operating frequency in response to the change in the coupling gap. Experimentally, with a frequency of 1 MHz and a 0.25 mm coupling gap, the efficiency was 96.3%, and the operating frequency was maintained within 96.3–91% in response to the change in the coupling gap.

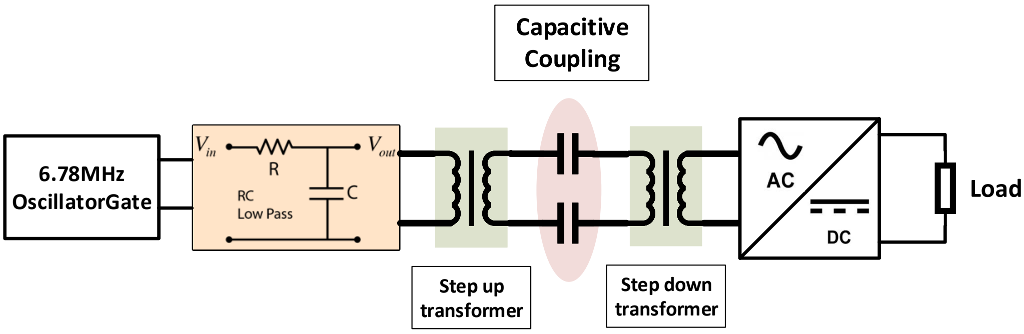

Figure 8. The circuit diagram of 6.78 MHz CCWPT system in [61].

Similar to the operation frequency in [61], Kang in [66] proposed a method to reduce the impedance of the coupling capacitor for sufficient received output voltage in the capacitive coupling WPT (CCWPT). He used glass dielectric layers to make the impedance of the capacitive coupling smaller and easier to transfer power. The LLC resonant circuit was used to reduce the switching loss in the power conversion circuit, so turn-on loss of the power MOSFET in a transmitter and a turn-off loss of the rectifier in a receiver could be reduced. The result showed that with the operating frequency at 6.78-MHz and inductance L_p, which was used for high output power, and reduced switching loss of 491 nH, the thickness of the glass dielectric layer was 2-mm, and the area of the electrode was 196 cm^2 with 695 pF capacitance. Their proposed CCWPT had less power consumption and higher output power than the simple resonant converters. For an example of using different types of dielectric material, the author in [67] designed a contactless battery charging system for soccer-playing robots. Although the system efficiency was still low, it could be improved by using better dielectric materials and more efficient power converters in future developments.

For adapting to different operating frequencies that may be generated from the transmitted side, Chong-Yi Liou et al. in [68] presented a wireless charging system that incorporated a near-field electric field, including a docking station resonator and a multi-frequency resonator. The transmission dock resonator consisted of a flat strip and a ring-shaped metal plate to power multiple folding bands such as a three-dimensional resonator in the GHz band. They further improved the single-band uni-polar resonator into a multi-band resonator and demonstrated the wireless charging application of the handset. Their device was more suitable for a multi-band wireless charging system than previous single-band studies. Similarly, Minnaert et al. in [69] proposed a method to determine closed-form expressions for a CCWPT system with one transmitter and two receivers. They determined the optimal condition for both maximum power transfer and maximum power delivered. The optimal loads and analytical expressions for efficiency and power were derived. Hence, they found that the optimal load conductance for the maximum power configuration was always larger than for the maximum efficiency configuration.

3.1.2. The Compensation

To transfer the power wirelessly, a loosely coupled transformer that involves a large separation between the primary and the secondary winding is essential. If the separation increases, the leakage inductance, proximity effect, and winding resistances also increase. In addition, the magnetizing flux will significantly decrease, resulting in a much lower magnetizing inductance and mutual inductance [70]. To be able to operate well at a frequency below their self-resonant frequencies, compensation capacitors are needed to form the resonant tanks in both the primary and secondary sides. The following reviewed methods used compensation capacitors in both single sides and double sides.

By combining both capacitive and inductive coupling WPT method, Lu et al. in [71] combined the advantage of both capacitive and inductive coupling WPT methods, which were the electric and magnetic field. The advantage of IPT is efficient power transferring at high frequency through a large air-gap distance. Some authors such as [72,73] achieved DC-DC efficiency higher than 95% across 150 mm air-gaps distance. However, when the frequency of operation increases, the eddy current can cause significant temperature rise and be potentially dangerous. In addition, the IPT system usually requires ferrite plates to improve the inductive coupling, which increases the system cost. The CPT system has two advantages: (1) the electric field does not generate an eddy current, so there is no concern about the temperature rising, and (2) the CPT system uses metal plates, which can significantly reduce the system cost and weight when they are removed. By combining the advantages of the two approaches, Lu et al. designed a system in which the coupler contained four metal structures, two each at the primary and secondary side; see Figure 9. Each structure consisted of long strips of metal sheet to increase its self-inductance. In addition, an external LCL compensation network was proposed to resonate with the coupler. As a result, the system achieved 73.6% efficiency with 150 W from the DC source to the DC load across an air-gap distance of 18 mm and a 1.0 MHz frequency of operation. The paper described a system that could transfer power using both the magnetic and electric field simultaneously. Similarly, Fei Lu et al. in [74] combined both inductive and capacitive coupling methods with an LC-compensated topology for charging electric vehicles. The idea was that both the inductive and capacitive coupling resonated together using the compensation components to transfer power. The output power of the system was the sum of IPT and CPT systems. With the inductive coupler size of 300 mm × 300 mm, the capacitive coupler size of 610 mm × 610 mm, and the air-gaps equal to 150 mm, the prototype achieved 2.84 kW of power with an input power of 3.0 kW. With this idea, we could improve the wireless charging efficiency for UAVs and also increase the air-gap between UAVs and charging plates.

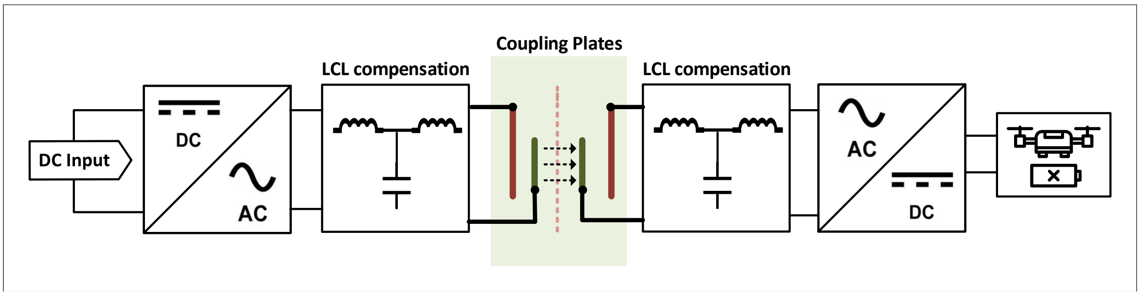

Figure 9. Double-sided LCL compensated circuit topology.

In [75], the author proposed a double-sided LC compensated capacitive power transfer (CPT) system, which was the dual of the conventional series-series (SS)-compensated inductive power transfer (IPT) system. At both the primary and secondary sides, an external inductor was connected in series with the coupler, and an external capacitor was connected in parallel with the coupler. The external capacitor was much larger than the equivalent capacitance of the coupler to reduce the resonant frequency. The capacitive coupler coefficient, which resulted in a loosely-coupled CPT system, was very small. As a result, the system could work in a constant current mode, which was similar to the series-series (SS)-compensated IPT system. A 150 W CPT prototype was designed and constructed to validate the proposed structure. The system's maximum output power was about 100 W with an air-gap of 180 mm. In [76], Zhang et al. designed a double-sided LC compensated capacitive power transfer system and also focused on improving plate structures, the circuit model, and double-side LCL compensation topology. For the plates' structure, the four plates were arranged vertically instead of horizontally and were of different sizes (see Figure 9) to save space in the electric vehicle charging application. The LCL compensation topology was used to resonate with the coupler and provide high voltage on the plates to transfer high power. The method achieved an efficiency of 85.87% at 1.88 kW output power with a 150 mm air-gap distance.

Concerning a high-power and high-efficiency CPT system, Siqi Li et al. in [77] designed a circuit similar to a four-coil configuration of a magnetic field resonance wireless power transfer system for capacitive power transfer. Not only was the unity power factor for the power source achieved, but also a high power factor and low reactive power for the capacitive coupling stage were achieved. One of the important factors that affected the CCWPT system was the phase difference between the voltages on each side of the coupling capacitor. In this paper, they mainly focused on evaluating the compensation network and the reactive power on the coupling capacitor C_S. As a result, their system could control the voltage on each side of the coupling capacitor and also reduce the reactive power. Thus, by increasing the transfer of the active power in contrast with the reactive power, the system could transfer energy more effectively.

In [78], a resonant compensation method for improving the performance of the capacitively coupled power transfer system by using an additional inductor and capacitor was proposed. Figure 10 illustrates the proposed system, which consisted of a Class E inverter and an LCL resonant tank. In addition, the Class E inverter was combined with a computer based iteration algorithm to determine the parameters of the proposed compensation circuit, which gave high power transfer capacity and power efficiency. The proposed method helped reduce the current through the coupling plate, which improved the power transfer capability of the CCWPT system with the reduced voltage across the coupling plates and better filtering of switching harmonics to the load.

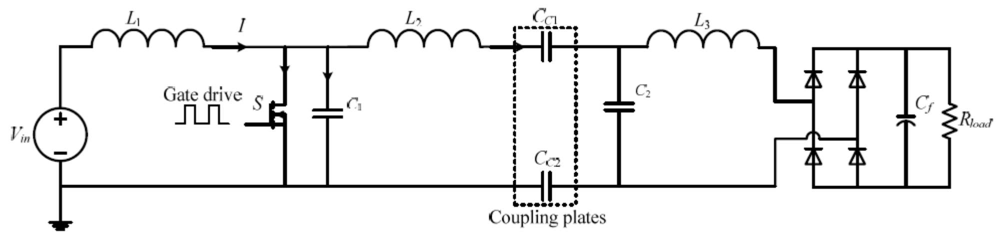

Figure 10. A CCWPT system based on a Class E inverter with LCL load.

In this paper, Kumar et al. [79] introduced a method to enhance power transfer density in large air-gap applications. They reduced the fringing fields in the area where the field must be limited for safety reasons by using multiple phase-shifted capacitive plates. The result showed that a 6.78 MHz, eight plate-pair system reduced fringing fields by a factor of five relative to a two plate-pair system while retaining the same power transfer density. Therefore, proportionally higher power transfer density could be achieved without violating the safety limits.

In [47], Raciti et al. demonstrated a design for a power system for recharging a drone's onboard battery regardless of the misalignment between the UAVs and the pad of the recharge station installed on a building roof. To do that, they proposed a current tuning mechanism that compensated for this variability in a single inverter multi-pad charging station.

3.1.3. Boost up Circuits

For the application of charging electric devices such as laptops, pads, UAVs, etc., where both inductive and capacitive wireless power transfer (IPT and CPT) are realizable, the author in [80] proposed a design to charge with a hybrid wireless power transfer (HWPT) system that combined both IPT and CPT. They analyzed the gain characteristics of CPT, IPT, and HWPT first, then they presented the design guideline. As a result, a 40 W input voltage, 6.78 MHz prototype using a GaN device was designed and implemented to evaluate the feasibility. The output voltage of the HWPT fluctuated from 20 V to 28 V, while conventional CPT fluctuated from 4 V to 22 V. Thus, the proposed system was much less sensitive to pressure change, and at the same time, relatively higher system efficiency was achieved. With the same purpose, Mostafa et al. in [81] proposed a DC-DC buck converter on the secondary side of the CPT system to reduce the voltage and electric field across the interface, the Q-factor, and thus, the system sensitivity. By mathematical analysis and simulation, they found that by reducing the duty cycle of the buck converter at a constant output power, the voltage across the plates could be significantly reduced, and the circuits became less sensitive to the variations in parameters. For delivering 10 W of power, the maximum voltage stress across one pair of the coupling plates was reduced from 211 V in the conventional system without using a DC-DC converter, to 65 V and 44 V at duty cycles of 30% and 20%, respectively. The system achieved an end-to-end power efficiency of 80% at an output power of 10 W and a duty cycle of 30%.

3.1.4. CCWPT: Deployed Systems

In [49], Deepa Vincent et al. proposed a method of wireless charging for unmanned aerial vehicles (UAVs) in farming. The method helped increase the flying time and range of UAVs, making them more productive. They deployed the CCWPT system for UAVs via a master/slave arrangement where the master drone would act as a transmitter. The receivers or slave UAVs would hover over master UAVs and were recharged wirelessly through capacitive coupling. Thus, the slave UAVs were recharged without landing through the air via a master drone that could reach them from a base station. With different applications, different capacitive charging links suitable at various air-gaps were analyzed. From the analysis of different coupling interfaces, matrix arrangement had a higher mutual capacitance than a row/column structure. The desired mutual capacitance was attained in all configurations only if a high permittivity dielectric was employed between the coupling interfaces.

In [82], the author presented a design for minimizing the component used in the receiver side of the UAVs. They replaced all components that made the size and weight of UAVs increase and controlled at the primary side. Thus, the secondary side circuit could have a light module with minimum components. Their receiver system contained a rectifier, a DC-DC buck converter, and a charging circuit. The system showed the result of the charging process for a Li-ion cell battery with the output power of 8-W, with the power efficiency exceeding 77%. However, the largest loss was in the diode rectifier component followed by the buck converter components and the charging components. For further research, switching losses, and conduction losses, a converter control method will be investigated in order to increase the efficiency.

In [46], Mostafa et al. designed a circuit in which they placed components such as the transformer, matching circuit, and all inductors in the emitting side, and the receiving side contained only small devices using semiconductor elements for the DC-DC converter and charge controlling IC for small size and weight in UAVs. Thus, with less size and weight, the flying time of UAVs could be longer. As the experimental result, this system could deliver 12 W with an efficiency of about 50%, which was enough to charge the three-cell battery of the drones.

3.2. ICWPT Technologies

In this section, we will review the recent methods proposed to improve the efficiency of the WPT system based on the IPT and RIC methods, especially deploying charging for UAVs.

In the subsection, we propose the methods to improve the efficiency of the WPT system for the IPT and RIC methods, especially deploying charging for UAVs.

This part is focused on surveying the inductive coupling method of the WPT system. It consists of two outstanding methods: inductive power transfer (IPT) and resonant inductive coupling (RIC).

3.2.1. Inductive Power Transfer Methods

The idea of the articles in [56,58,83] was to take advantage of IPT for both telemetry and powering purposes and to analyze the relationship between the power transfer efficiency and the specification such as the coupling coefficient, quality factor, and figure of merit. This system obtained an efficiency of 34.2% at k = 0.75 and a frequency range from 100 kHz to 700 kHz. For each value R_L = 70 Ω, C_{series} = 13–14 nF, or $C_{parallel}$ = 6–7 nF, there was a corresponding maximum power transfer efficiency [83]. The authors concluded that the selection of the coupling coefficient at a suitable frequency, the value of the load resistance, and series or parallel capacitance were very important and essential to achieving maximum efficiency.

In the experiment [56], the authors indicated that the coil shapes such as helical, spiral, rectangular, and triangular of the inductor coil affected the wireless power transmission. Based on the relationship between inductive coupling parameters and electrical characteristic, the author in [58] conducted experiments by changing the distance between coupling devices, the values of the transmission signal frequency, the coil diameter, and the ratio of the coil parameter in each experiment to analyze the impact on the power efficiency. The result showed that the transfer energy could reach a higher efficiency of 35.85% at 40 μH, which was a low inductance value.

The transmission distance of the WPT system was extended under the constraint of the coil size and optimized delivered power and performance. Yang et al. in [83] applied the reflection load for quantifying the mutual inductance between coils in a two-coil and four-coil WPT system. The distance was reduced by 50%, while the transmission efficiency was more than 78%. However, this was a trade-off between increasing transmission efficiency and increasing the number and size of the two coils, leading to an increase in the weight of the equipment used.

All of the aforementioned IPT methods improved the parameters related to the EM field in the transmitter and receiver coils. At a short distance, its performance could be very high. In the mid-range, the inductive coupling structure was slightly changed when adding capacitors on both transmitter and receiver coils to become RIC. Similar to the IPT method, the improvement of the parameters such as the coupling coefficient, quality factor, resonant frequency, etc., was necessary for the performance of RIC.

The IPT and RIC method based wireless charging systems have been applied in sensor networks [84], electric vehicles [85], and devices such as UAVs [30,86–91]. Based on the design of the applications, the WPT system could be optimized to suit the product that applied it. In this section, some methods are reviewed to reduce the payload of the UAVs and find suitable positions of the receiver and transmitter on UAVs to transfer power.

3.2.2. Resonant Inductive Coupling

The structures of RIC-WPT are very important in the system. Nevertheless, the conventional structures are still not optimal to obtain high efficiency. According to this, researchers focused on improving the structures and the receiver part of RIC-WPT in order to have higher efficiency.

The structures are improved by having resonant coils in the system. Resonant coils have been added in different ways and with varying intensities, illustrated in Figure 6. In [92], Kurs et al. built a novel model by adding two self-resonant coils to gain a high resonance in [93]. Hence, self-resonant coils can achieve resonance because of the interaction between the distributed inductance and distributed capacitance. According to their optimal method, 40% efficiency could be achieved over distances of 2 m. In [94], Zhang et al. added two more magnetic coupling resonators to the system. By applying magnetic coupling resonators, the transmitter included two inputs and two outputs. The primary side added the drive loop, and the second side was the load loop. Moreover, by using the differential method and optimization for inductors and capacitors, the power transfer efficiency of the system increased to 88.1%. In [95], Ahn et al. designed a novel resonator structure. It also had four coils, but the new structure consisted of two strongly coupled resonators. In [96], these resonators improved the energy exchange between the transmitter and receiver and created high coupling. In [97], Kung et al. designed a structure for near-field resonant wireless power transfer. They presented a dual-band coil module and used only a one-turn coil. This novel design could reportedly reduce the interference caused by the cross-coupling effect. Therefore, they could obtain the desired resonant frequencies, and the power efficiency would be increased. Research has also improved the structures by adding loop antennas, a non-radiative resonant wireless power transfer link, etc. Kim, Hee-Seung et al. in [98] created a structure using 13.56 MHz loop antennas, shown in Figure 11. The loop antennas were simply modeled as the inductance. These had a series capacitors at the resonant frequencies, and a parallel resistor could be added to control the quality factor of the antennas. The wireless power transfer system with two loop antennas improved the input return loss, the coupling coefficient, and the reflected impedance. Therefore, the efficiency was optimized. Bou, Elisenda et al. in [99] experimented with a non-radiative resonant wireless power transfer link to change the load impedance, source impedance, and distance between coils. The authors used load impedance matching techniques to find the highest value of efficiency for each different distance between the transmitter and receiver. Because of the variation of the distance and impedance interaction with each other, they could change one of two parameters; hence, we could find the maximum efficiency for the system. Yang, Ching-Wen et al. in [100] applied the reflected load theory for analyzing the multi-coil system including several resonators. A varying number of resonators would change the resistance, which reflected the transmitting side and influenced the power transmission to the load. This paper's purpose was to find the critical coupling point where power transmission was the highest value. By changing the coupling between coils, the efficiency increased to 71.1% and by shifting the frequency of the source over, 40% with a 2 cm distance. Yan, Rogge et al. in [101] changed the structure of the coil to two coil and four coil.

The RIC WPT system improved the efficiency. They experimented to find the optimal value of parameters such as the distance, the resonance frequency, and the resistance based on the mathematical model and the differential evolution algorithm. Hence, the output power and transmission efficiency of the two- and four-coil WPT system were improved at resonance. The different coil structures would need further investigation.

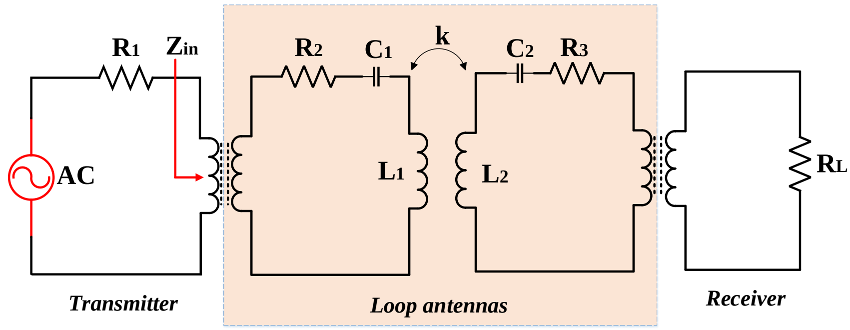

Figure 11. Equivalent circuit of the WPT system with two loop antennas.

The receiving side received and handled the power to extract as much as possible. However, the conventional receiver operated with a low efficiency. Thereby, many researchers have tried to determine how to achieve higher efficiency. Cannon et al. in [102] designed multiple load coils with lumped capacitors at the coil terminals. By applying multiple receivers at the load, the resonant frequency splitting issues occurred when two receivers were in close enough proximity and the Q resonant coupling was high. All of these factors helped to increase the system efficiency. In 2012 [103], Xue et al. presented the optimal resonant load transformation, shown in Figure 12. Printed spiral coils with discrete surface mount components at a 13.56 MHz power carrier improved the factor Q and coupling coefficient k. The power transfer efficiency could be 58% at a 10 mm distance from the external coil. Kato, Masaki et al. in [104] used a DC-DC converter. In order to improve the transmitting efficiency, they focused on the load impedance. The load impedance was controlled by using a DC-DC converter based on the derived equation. The DC-DC converter changed the load impedance by changing the switching duty ratio without changing load resistance. Thus, the efficiency could be enhanced. Honjo et al. in [105] realized the limitation of the receiving coil size and changed the receiving coil structure. The top and the bottom of the core (the collecting magnetic flux area) had similar areas in both structures, but different in the core. They proposed a coil structure that was a thin core that reduced the internal AC resistance. The current of the transmitting coil was set at 1.0 Arms, 800 kHz, and 1.5 Ω load resistance; hence, the result achieved higher output power than the conventional structure. Koyama et al. in [106] used a synchronous rectifier. In reality, the receiving resonator could be affected by either the conduction loss at the diode rectifier, especially for low output voltage applications. These problems were solved by a synchronous rectifier attached to the receiving resonator. The synchronous rectifier reduced much of the voltage drop of the diode. Hence, the conduction loss was optimized, and the merit of the solution would be improved with the diode rectifier. This rectifier is a promising technique for practical application of the RIC-WPT to UAVs.

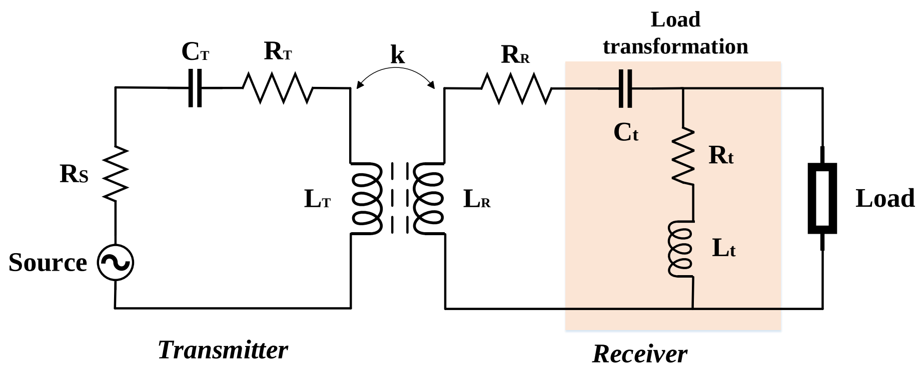

Figure 12. The resonant inductive coupling (RIC) with optimal load transformation.

3.2.3. Other Improvements

There are many possible ways to improve the efficiency of the RIC-WPT system such as material quality, voltage drop, operating frequency, and some special cases. In [107], Fu et al. proposed the proper impedance matching techniques and minimized the power reflection due to impedance mismatch. The system added a novel cascaded boost-buck DC-DC converter to improve impedance matching for rectifier and coils and isolate the dynamic load. Hence, the efficiency increased to 70% for various loads with an operating frequency of 13.56 MHz and a power level of 40 W. In 2014, Li et al. in [108] showed that the efficiency decreased when coupling or load varied. Thus, the authors concentrated on these conditions. A maximum efficiency point tracking (MEPT) control scheme was applied to improve efficiency by regulating the output voltage. The new method indicated the necessity of closed-loop control for the system and needed some conditions: fixed operating frequency and maintenance of the input voltage and the load resistance. Hence, the efficiency achieved the highest point.

Rodriguez et al. in [109] indicated that the material quality of the coil and the mutual coupling were affected by the efficiency of these systems. The proposed meta-material enhanced the efficiency by 10% compared with the original and a working distance of 8.8 cm, which extended by 95% the original system range at a low operating frequency of 5.574 MHz. Moon et al. in [110] improved the voltage drop of the conventionally supplied power by operating the circuit in the power receiver. In order to increase the power efficiency of the receiver, this paper proposed a power supply switching circuit using the DC-DC converter for the system after a conventional low-dropout (LDO) linear regulator supplied power for initialization. By using the DC-DC converter, the transmitted power was controlled. In addition, the matching network of the shunt-series mixed-resonant structures used in the resonant WPT system was important to improve power efficiency. Consequently, the efficiency was improved by adding a DC-DC converter and optimizing the matching network.

The change of the parameters in [90] supported improving the performance of the system as $R = 0.265$ m, $C = 0.1$ µF for the resonant coils, $f_{resonate} \approx 189$ kHz and Q ≈ 192 (dimensionless). A 2 Ω load was applied for the 5 V supply, and the system had 12.5 W. A PD controller was used for adjusting and optimizing the power transfer from UAVs. The author designed more ground sensors to communicate about the information position between the transmitter and receiver coils or between the aerial power transfer and static power transfer. They also developed a control algorithm that could optimize the received power even while the aerial power transfer prevented it from maintaining the optimal position for power transmission. The transmitter was light and efficient enough for the UAVs to carry and operate. For static power transfer, 35% was the highest efficiency from these tests. The aerial power transfer could transfer power of nearly 5 W continuously from the UAVs to the ground sensor.

In 2007, Aldhaher et al. in [48] performed an experiment to allow flying UAVs to be charged in mid-air. The WPT system operated in the MHz region without the need for ferrite. To do that, it was integrated into soft-switching resonant inverter and rectifier topologies that helped the system operate efficiently at an operating frequency of tens of MHz and a power level of hundreds of watts. The mid-air WPT system was designed $f = 13.56$ MHz to supply power for UAVs over a distance of 12 cm. The system included the DC/AC inverter using a load-independent Class EF inverter, a transmitting coil, UAVs, a receiving coil, a rectifier, and a DC/DC converter using a Class-D rectifier.

In [111–113], Yang et al. designed coupling structures to analyze the parameters. They focused on improving the horizontal tolerance and performance for UAVs' charging with an asymmetric wireless charging system. This method improved the magnetic field uniformity and intensity; thereby, the system was more conducive to power transfer and increased self-inductance values. From this optimization, the efficiency of the power transfer was 57.94 % with 64.87 W for UAVs.

Concerning the system configurations, one of several reduction methods is ferrite materials, acting as a partial magnetic core for coupled coils. Some ferrite blocks are located in the surrounding of the primary coil to improve the coupling factor, whereas the secondary coil has no ferrite blocks to reduce the onboard weight [86,89]. In [114], Campi proposed the optimization of the WPT system by establishing the geometric and power requirement constraints. The receiving coil had a rectangular shape, as shown in Figure 13, for easy adaptation to the landing support. The maximum time needed to fully charge the battery was about one hour; therefore; they uses a Litz wire cable to minimize AC inductive losses. The maximum efficiency was η_{max} = 93% at N_1 = 10, N_2 = 2, based on series-parallel compensation topology. The achieved efficiency of the system was η > 85% at any point in the charging area of size C_L = 50 cm and C_W = 50 cm and was covered by a 3 × 2 loop array with O_w = 60 mm and O_L = 70 mm [114].

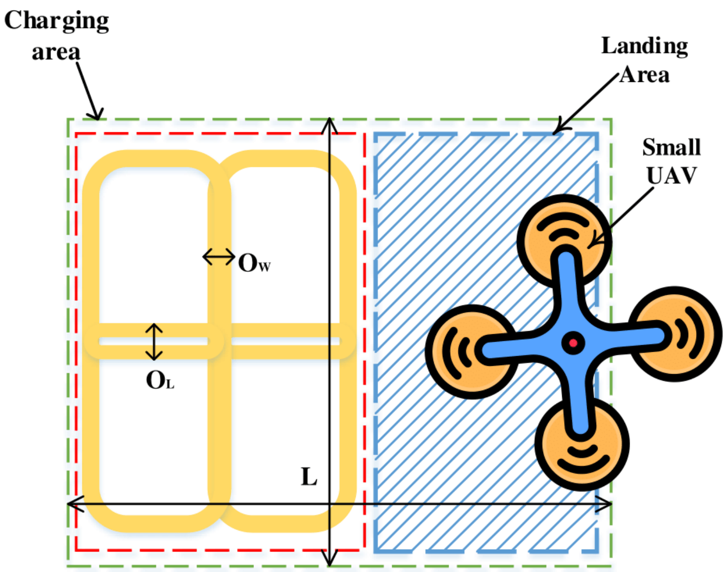

Figure 13. The WPT charging configuration for UAVs.

The DJI F550 drone was used to deploy and evaluate the magnetic field levels emitted by the WPT coil current [86,87]. Using a mobile positioning system for the transmitting coil ensured a correct tolerance to misalignment conditions. As illustrated in Figure 13, the transmitting coil was placed on a motorized two-axis system, whereas the receiving coil was placed on the landing skid of the landing gear to reduce the air gap between the coils to a few millimeters and to increase the value of the coupling factor k. UAVs started scanning the landing area from the center of the area to find the optimal point. The input impedance was calculated by moving the mechanical position system in some specific points selected by an optimized procedure to reduce the scanning time. The process ended when the measured input impedance was at least 95% of the maximum Z_{max}, leading to a minimum efficiency of η = 90% for the WPT system when using this scan method [87].

Most recently in 2019, a method was described for varying the relative position between the transmitting and receiving coils by using a position sensor for measuring the magnetic field. The position of the receiver as located based on the measurement, and based on the test results of the sensor matrix, a decision was made as to which coils among the transmission matrix were to be controlled as charging coils. The author upgraded the sensor system to find the optimal position for delivering charging power to the drones. The author [91] solved the problem to improve the performance of the WPT system and to reduce EMR by a novel parallel transmission coil matrix structure. In the future, we could focus on the optimization of the matrix's structure and simplification of the sensor module.

4. Far-Field WPT Technologies

This section contains a survey of the most relevant far-field WPT technologies presented in literature. In particular, since as mentioned earlier, MPT techniques result in being more flexible than laser beaming, this section results in being mainly focused on the former technologies, aiming to group them according to the approaches proposed to improve (i) the antenna system, (ii) the matching network, (iii) the rectifier, and (iv) the deployed system for UAV charging. Finally, for completeness, a brief review about contemporary LPT systems is provided.

4.1. Microwave Power Transfer

Power transmission via radio waves can be delivered directly to the target, allowing longer distance power beaming, with shorter wavelengths of EM waves of high power, typically in the microwave range. The receiver system in Figure 7 involves energy harvesting including four main components: the antenna, matching circuit, rectifier, and energy storage.

4.1.1. Antenna Design

The antenna is the device in the radio frequency energy harvesting (RF-EH) circuit that captures RF signals. Antenna efficiency is a key factor relating to the operating frequency and helping to ensure the successful operation of the RF-EH system. The main goals of antenna technology are high receive antenna gain and small antenna size, which leads to a trade-off between antenna size and performance. RF antennas can harvest energy from a variety of sources such as mobile phones (900–950 MHz), local area networks (2.4–5.8 GHz), Wi-Fi signals, and broadcast ultra-high-frequency (UHF) TV signals. The amount of harvested energy can be dramatically increased by correctly arranging antennas with the matching circuit or operating antennas at properly selected frequencies.

An ultra-sensitive far-field energy harvester based on antenna-and-rectifier co-design was presented in [115]. This work improved a 915 MHz square loop antenna and a custom rectifier that featured a rectification efficiency of approximately 80%. The experimental results showed that the energy harvester operated at a maximum distance of 20 meters at 4-W Tx EIRP. The work in [116] listed parameters such as power density and the output power of energy sources that could be harvested in nature such as solar and thermal. The work in [116] also offered conversion efficiency from RF energy to DC with different RF sources. With a power density of 100 mW/m^2, the efficiency was 30%. The author's antenna was designated to support maximum received power in the 915 MHz and 2.4 GHz bands. The work in [117] described the design of a high-efficiency energy harvesting circuit with an integrated antenna. The circuit, comprised of series resonance and boost rectifier circuits, converted radio frequency power into boosted direct current (DC) voltage. The output voltage was 5.67 V when the input voltage was 100 mV at 900 MHz. The efficiency was 60% for a load equal to 20 kW when the input power was −4.85 dBm. The work in [118] discussed the antenna array design for optimizing RF energy harvesting. However, a trade-off existed between antenna size and performance. A highly efficient multistage rectifier of the antenna array was suggested for RF energy harvesting applications, and the design of a matched multi-band microstrip antenna was presented for this purpose. In [119], a sensitive triple-band rectifier was proposed where the rectifier provided a maximum conversion efficiency of 80%, 46%, and 42% at 940 MHz, 1.95 GHz, and 2.44 GHz, respectively.

In Figure 14, the combination of the antenna and the rectifier is called the rectenna. A rectanna may be used to convert the microwave energy (EM waves) back into electricity to the load. Their RF-to-DC conversion efficiencies were approximately 80% at low/medium power densities [120].

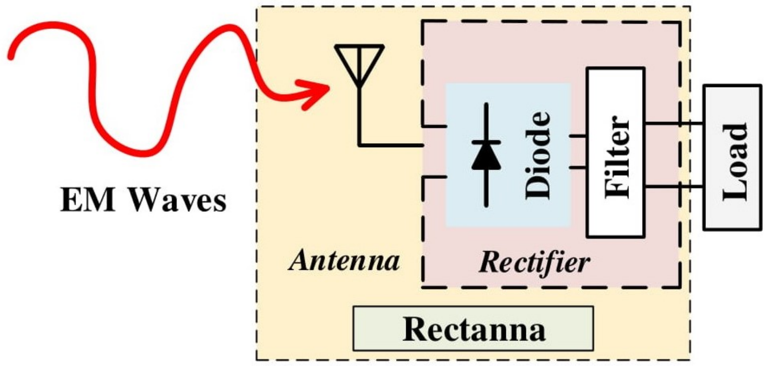

Figure 14. Schematic of the Rectenna.

4.1.2. Matching Network

The main function of a matching network is to maximize the input voltage of the rectifier and to diminish the transmission loss from the antenna to the rectifier. The maximum power transfer could be achieved when the impedance of the loads and impedance at the antenna output are matched. The aim of [121] was to harvest power from free space. The energy levels that were satisfactory to charge low power electronic circuits were attained from this paper. The Π matching network located in between the antenna and the RF-DC conversion module was designed and implemented to provide a good match from the load to the source. Further, the work in [122] also showed that the harvesting circuit benefited from improved output voltage while using a Π-type matching network with a high Q value. Therefore, this circuit appeared to be more sensitive to the various input frequencies and lumped element values. This paper showed that the circuit with low internal resistance components and high load impedance offered optimal matching efficiency and high voltage gain. The authors suggested that the output voltage was higher under some conditions with a high Q matching network.

4.1.3. Rectifier

The main role of the rectifier is to convert RF energy to DC voltage levels. One of the major challenges of the rectifier design is to generate a suitable voltage from the received RF power. The RF to DC conversion efficiency depends on the diode in the rectifier circuit. Therefore, the diode is one of the main considerations in the design of the rectifier circuit. In general, higher rectifying efficiency can be achieved by using a diode with a lower voltage. In [123], the author introduced a new design for RF energy receivers and then compared to traditional energy sources such as solar and wind power, etc. In order to improve the conversion efficiency from RF energy to DC, the author designed multi-stage rectifiers to increase the output voltage. The paper also indicated how to choose equipment and components for optimal circuit design to enhance the RF energy obtained from −20 dBm to 20 dBm while the previous studies were −20 to 7 dBm. Likewise, in [124], a new harmonic-recycling rectifier that differed from conventional rectifiers using harmonic suppression was proposed. Additional components such as diodes, capacitors, etc., which were utilized to optimize the low-power range, enabled more efficient RF-DC conversion over 80%. The novel system enhanced 18% of the DC output voltage and 11% of the RF-DC conversion efficiency compared with conventional designs. To adapt to 2.1 GHz and 2.45 GHz frequencies, the work in [125] designed a dual-band rectifier that utilized a Schottky diode HSMS-285C as the rectification diode to double the output voltage. Impedance matching of the rectifier was carried out to improve the rectifier performance. The result consisted of the output voltages and conversion efficiencies plotted for both the frequencies from 0 to 10 dBm of input power.

By introducing a new approach for a high-efficiency rectifier circuit design at 2.45 GHz, the work in [126] depicted a rectifier circuit capable of recovering signals at 2.45 GHz with a high RF-DC efficiency conversion. The prototype achieved a maximum conversion efficiency of 70.4% for an RF input power of 0 dBm at 2.45 GHz. The work in [127] summarized the major challenges when designing harvesters such as the distance and the free space path loss between the transmitting station and the harvesting location. The author also designed a new broadband Yagi–Uda antenna that covered the DTV broadcasting frequencies (470–810 MHz). In [128], a complete design method was indicated to calculate precisely the impedance and the output voltage of the rectifier part in a wireless power transmission system. The presented method utilized circuit analysis to compute the impedance of a Schottky diode as a function of frequency. The author in [129] calculated the output voltage with each specific number of stages such as n = 4, $V_{out} = 1.2$ V; n = 5, $V_{out} = 1.67$ V; n = 7, $V_{out} = 5$ V. By experimentation, they reported that the output voltage was proportional to the number of stages and how to double the voltage in the conversion from RF-DC at a given frequency range, especially in the 900 MHz frequency band. On the other hand, the work in [130] demonstrated that the RF-to-DC conversion efficiency depended on the captured power density at the receive antenna. The power efficiency of the voltage multiplier that converted the received RF signals to DC voltage was dependent on the accuracy of the impedance matching between the antenna and the voltage multiplier.

Additional researchers have considered optimizing both the matching circuit and the rectifier to increase DC output power. For example, the work in [131] designed the structure of the rectenna to achieve the highest efficiency at the exact frequency where $P_{in}= -20$ dBm; the efficiency was 90%, 86%, 65%, and 40%, corresponding to frequencies of 900 MHz, 1.8 GHz, 2.4 GHz, and 5.8 GHz, respectively. All results concluded that the efficiency was the highest at 900 MHz.

4.1.4. Deploying the System

In recent years, a focus of research has been the development of wireless power supply for drone aircraft. In [132], a method was proposed for charging the battery of UAVs wirelessly to alleviate the problem of the limited flying time of the micro UAVs. The UAV battery was charged from the edge of the far-field with about 5 W of transfer power. To address the limitations of the RF power source, the laser beam method was proposed. Laser power has become a viable solution to provide convenient and sustainable energy supply to unmanned aerial vehicles (UAVs) [133]. In a laser-powered UAV wireless communication system, the transmitter sends laser beams to charge a fixed-wing UAV in flight.

In order to charge unmanned aerial vehicles (UAVs), the author in [134] designed an RF circuit that enabled continuous charging of mobile devices especially in urban areas where the density of ambient RF sources is high. The paper also presented an overview of progress achieved in the RF energy harvesting field. A modified form of an existing CMOS based on voltage doubler circuit was used to to achieve higher output power than traditional circuits at 0 dBm input power. In fact, due to the ability to transmit over long distances with high energy transmission, microwaves were applied to develop a small prototype airplane called the Stationary High Altitude Relay Platform (SHARP) to relay telecommunication data between points on Earth similar to a communications satellite.

4.2. Laser Power Transfer

In the case of EM radiation from the ambient environment or direct RF power source closer to the visible region of the spectrum (tens of micrometers to tens of nanometers), power can be transmitted by converting electricity into a laser beam that is then pointed at a photovoltaic cell, shown in Figure 15. A comprehensive survey of the existed techniques, based on advances and open issues presented by wireless power transfer (WPT) technologies, was presented in [135]. The authors introduced WPT methods as previous studies and some sources of energy in nature and also mentioned beamforming.

However, the author in [136] proposed the design, but did not mention the detailed information about the system. In [137], the received power value could be significantly increased due to the higher chance of short distance line-of-sight energy transmit links. Simulation results illustrated that their proposed design was superior to other benchmark schemes, and the proposed algorithm was efficient in terms of the convergence.

For many years, the applications of laser beaming for military weapons and aerospace applications have been the most well known. Laser beaming is also applied for the powering of several kinds of sensors in the industrial environment. Scientists from the Chinese Academy of Sciences deployed a new concept of utilizing the dual-wavelength laser in wirelessly charging portable devices or UAVs. The fully-coupled model was also established for the technology of laser power beaming to research and develop its applications.

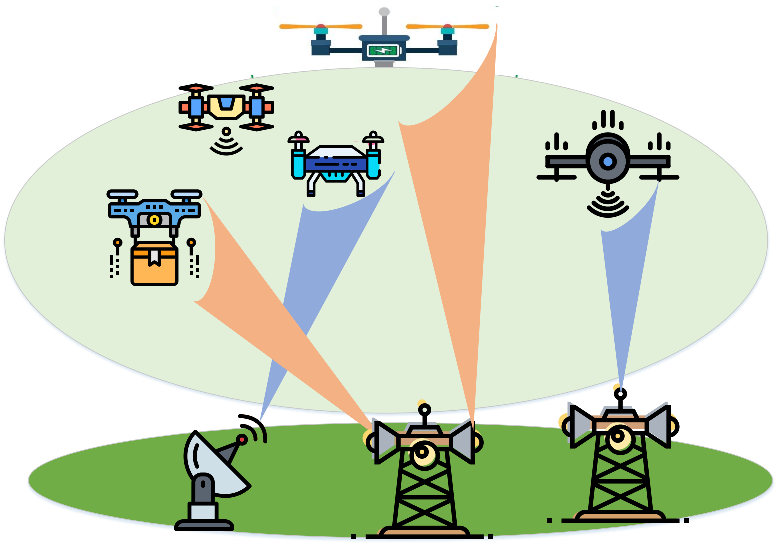

Figure 15. Laser beaming for UAV charging.

5. Opportunities and Challenges of WPT for UAVs

The following subsections discuss the challenges in near-field, as well as far-field WPT, studied in terms of: (1) transfer distance and efficiency; (2) health; and (3) safety and security. As shown in Table 1, the characteristics of each method in both near-field and far-field WPT are listed.

Table 1. Comparison of the main wireless power transfer (WPT) technologies.

	NEAR-FIELD NON-RADIATIVE			FAR-FIELD RADIATIVE	
	Electric Field	Magnetic Field		Electromagnetic Field	
	Capacitive Coupling	**Inductive Power Transfer**	**Resonant Inductive Coupling**	**RF Energy Transfer, Microwaves**	**Laser Beaming**
Range	Short	Short	Mid	Far	Far
Frequency	Hz–MHz	kHz–MHz	kHz–MHz	GHz	>THz
Propagation	Non-radiative	Non-radiative	Non-radiative	Radiative	Radiative
Strength	Very high	Very high	High	Low	High
Multicast	No	No	Yes	Yes	No
Mobility	No	No	Yes	Yes	No
Coupling Device	Metal plate electrodes	Wire coils	Turned wire coils	Parabolic dishes, phased arrays, rectennas	Lasers, photocells, lenses
Safety	Yes	Yes	Yes	Safety constraints may apply	Safety constraints may apply

5.1. Near-Field WPT

The review paper demonstrated the high efficiency of the near-field wireless power transfer techniques (i.e., the capacitive coupling, inductive coupling, and resonant inductive coupling techniques) for wirelessly transferring power, especially to UAVs, while they are automatically recharging their batteries. However, the transfer distance and transfer efficiency of the near-field WPT methods continue to pose a challenge.

In the near-field transfer, the fundamental principle of the coupling between two sides can be capacitive (electrostatic) coupling due to the stray capacitance or can be inductive (electromagnetic) and resonant inductive coupling (RIC) resulting from the mutual inductance. Both inductive and capacitive coupling transfer in a short range, while RIC operates at mid-range distances. Moreover, the resonant frequency range of RIC is larger than the operating frequency in low frequency (LF) bands of the capacitive and inductive coupling methods. Therefore, RIC-WPT is applied more than the other two methods. Its advantages include the ability to transfer energy within several meters; it is unaffected by weather environments; it has high transfer efficiency under an omnidirectional antenna; it is capable of charging several devices concurrently on different power, etc. [30]. RIC-WPT is sensitive to transmitter and receiver coil alignment and large size challenges. In the future, the system will require further research to enhance the design of the resonators to improve the high transfer distance and maximum power transfer during angular or axial misalignment, to reduce system losses when a high oscillation frequency is used, and to increase the dynamic frequency and power control schemes to reduce the effect of electromagnetic waves on the human body to meet international standards.

In this paper, we focused on charging for unmanned aerial vehicles (UAVs). The use of small UAVs for commercial, military, agricultural, etc., purposes is rapidly growing and developing. The charging energy for UAVs can be obtained from the electromagnetic field, so this is an opportunity for applications of the WPT methods to charge the battery of UAVs to increase flight time or extend the range of UAVs. UAV battery size cannot easily be increased because that affects its payload, thereby becoming a limiting factor for flying.

The international standards and safety rules are very important for future applications that require improvement of the configuration of methods to adapt UAVs and other applications. The combination of UAVs and the wireless system network in outdoor surroundings will introduce new trends for research and enable a new design to solve charging problems.

5.2. Far-Field WPT

A basic far-field WPT system consists of three components: (1) energy source-RF (the source used to generate RF signals, DC/AC), (2) RF-RF (energy transmission through the air via RF), and (3) RF-DC (conversion of RF to DC energy to provide load); see Figure 16. The efficiency of the WPT far-field system is determined by the formula [138]:

$$\frac{P_{DC_{out}}}{P_{DC_{in}}} = \frac{P_{RF_{Tx}}}{P_{DC_{in}}} \frac{P_{ANT_{Tx}}}{P_{RF_{Tx}}} \frac{P_{ANT_{Rx}}}{P_{ANT_{Tx}}} \frac{P_{RF_{Rx}}}{P_{ANT_{Rx}}} \frac{P_{DC}}{P_{RF_{Rx}}} \frac{P_{DC_{out}}}{P_{DC}} \tag{8}$$

where $\frac{P_{RF_{Tx}}}{P_{DC_{in}}}$ is the conversion efficiency from DC to RF, $\frac{P_{ANT_{Tx}}}{P_{RF_{Tx}}}$ is the efficiency of the transmitting antenna, $\frac{P_{ANT_{Rx}}}{P_{ANT_{Tx}}}$ is the beam efficiency, and it is mainly dependent on the antenna array design and the multi-path environment. At the receiver stage, the efficiency can also be subdivided into the $\frac{P_{RF_{Rx}}}{P_{ANT_{Rx}}}$ and $\frac{P_{DC}}{P_{RF_{Rx}}}$, which is dominated by the RF-DC converter efficiency and strongly depends on the circuit design and also the waveform used to excite it. Finally, $\frac{P_{DC_{out}}}{P_{DC}}$ efficiency is the DC-DC conversion efficiency from the DC-DC power converter.

The overall efficiency of the far-field WPT system is often low because the energy transfer distance between Tx and Rx is very far, up to several kilometers. Therefore, one of the main challenges of far-field WPT is the issue of improving energy transfer efficiency between Tx and Rx. To overcome this drawback, we can improve each component of the far-field WPT system to increase overall efficiency. For the DC-RF component, the conventional approach, DC to RF, is achieved by using an oscillator followed by a power amplifier or by synthesizing a specific waveform in a baseband FPGA like the system and converting it to analog by using a digital to analog converter. However, the $P_{DC}P_{RF_{Rx}}$ efficiency is low because the power amplifier is normally operated in classes of low efficiency. This can be overcome if the signal to be transmitted is a single sinusoid. We can use several sinusoids combined in a multi-sine transmitter. After the RF signal is generated, the power will be transmitted to the receivers through the air via RF channels. Thus, the transmission and reception efficiencies are crucial parameters within a far-field WPT system. In order to keep the system efficient, the beam efficiency (BE) should be maximized and is given by expression [139]:

$$\eta_{BE} = 1 - e^{-\alpha^2} \quad (9)$$

where $\alpha^2 = \dfrac{A_T A_R}{(\lambda d)^2}$, A_T is the aperture area of the transmitting antenna, A_R the aperture area of the receiving antenna, and λ and d the wavelength and the distance between transmitter and receiver, respectively. Several methods have been proposed to maximize the beam efficiency such as weighting techniques for large antenna arrays including edge tapering techniques [140], micro-strip printed reflect-arrays in which they combine the advantages of conventional phased arrays with their beam steering capabilities and the high gain from reflector antennas [141,142], etc. After the signal is received, it should be converted back to DC, using an RF-DC converter, which is mainly composed of a matching network, a rectifier element, and a DC pass filter. These RF-DC converters are mostly single band and optimized for a single frequency, with high efficiency. Besides, thanks to the development of energy harvesting techniques recently, a broadband RF-DC converter can be considered to obtain power from some possible power sources, thus increasing the power at receivers.

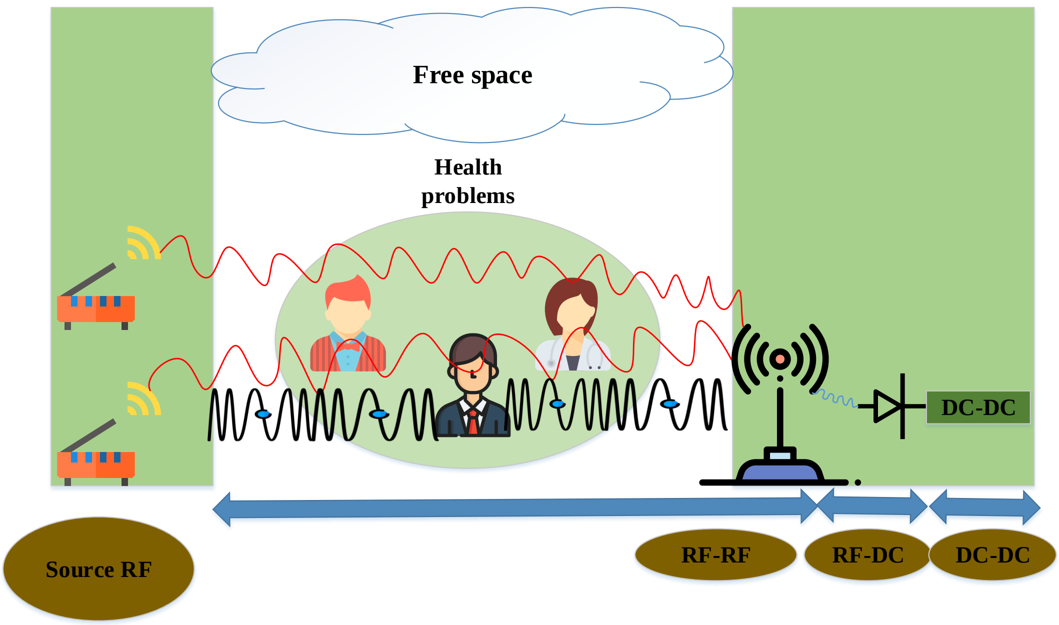

Figure 16. Challenges of wireless power transfer.

To obtain high power transfer and a smaller coil size, the operation frequency of the RF-WPT must be increased to the GHz band [143,144], which poses challenges in human habitats and could potentially be above the level admissible from ICNIRP. A safe-charging wireless power transfer network (WPTN) must guarantee that no humans are exposed to electromagnetic radiation (EMR) that exceeds a safety threshold (a detailed survey of the regulatory framework pertaining to WPT systems). However, ensuring safety where the end-users are allowed to deploy new energy transmitters (ETs) and modify the locations of existing ETs/Ers energy receivers (ERs) at run-time is challenging. On the other hand, for security reasons, ETs should receive requests and feedback from ERs to transfer power to them in an efficient manner. However, malicious ERs may deliberately generate redundancy or requests and incorrect feedback to decrease the overall power transfer efficiency of WPTNs.

6. Conclusions and Further Work

This paper aimed to review the most important EMF based WPT technologies that can be adopted to provide energy in UAV networks. Under these perspectives, RF energy harvesting, capacitive coupling, laser-beam based, inductive, and resonant inductive coupling methods were reviewed, providing all the possible ways to apply WPT techniques to UAV networks, avoiding then the temporary interruption of their performed activities that are usually limited by their own battery life. For each technique, the physical working principle and the corresponding elements of transmitter/receiver circuital scheme were illustrated, showing how the circuital components such as transmitting antenna, compensation circuit, and boost circuit could be properly selected and optimized in order to design and deploy energy efficient WPT systems according to the working distances and the operating frequencies. However, as of the date of writing, the most relevant works on EMF based WPT present in literature assumed that the WPT system provides energy to UAVs one at time. Under these perspectives, future directions, which can contribute to partly filling this area, can be identified in the development of WPT technologies and corresponding charging strategies able to charge multiple UAVs at the same time.

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