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Wireless Charging Techniques for UAVs: A Review, Reconceptualization, and Extension

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ABSTRACT An important application in the growing field of unmanned aerial vehicles (UAVs) is in monitoring and inspection of high voltage power lines and electrical networks. The UAV-based monitoring method will save energy, simplify access to impassable or remote areas, reduce inspection cost, and automate the inspection process. However, the battery capacity of a medium scale drone limits their travel distance and mission duration. It is crucial to improve the energy feeding system of drones and overcome the battery capacity problem to foster the use of drones for routine monitoring operations. In this study, we focus on presenting wireless techniques available for drone mission duration improvement as well as discuss and practically examine the most feasible and reliable technique to charge UAV using power lines.

INDEX TERMS Unmanned aerial vehicles, wireless charging, wireless energy transfer, inductive power transfer.

I. INTRODUCTION

Over the last decade, UAVs with different capabilities and applications are developed for commercial, recreational and public use. Military application accounts for about 90 percent of the UAV's market; however, it is projected that with growing industrial and recreational interests, the global non-military drone's market is expected to increase its share to at least a half over the next decade [1]. The market size for global non-military drones is estimated at 120 billion USD in 2016 [2], while infrastructural projects alone account for more than 40 billion USD [2]. There is also an increasing interest towards this technology from the industry, especially electrical utilities [3]–[5], and oil and gas operators [6]–[8]. Major service providers and delivery companies are looking into deploying drones for routine delivery operations [9]–[12]. UAVs are also used for scientific monitoring purposes, such as water sampling [13], landslide [14] and volcanic activity monitoring [15], [16] and civil structures health check-up [17]. Some early attempts to design a drone able to manipulate equipment remotely using highly dexterous robotic arms are described in [18]. UAVs are also potentially useful for search and surveillance operations in hazardous or inaccessible areas [19]–[22] as well as for communication and radio access [23]–[25].

Given increasing industrial interest and promising market projections, this paper investigates existing technical barriers that impede the higher rate of expansion of commercial drone's utilization.

Lack of battery capacity is considered as one of the crucial technical challenges in modern UAVs applications [26]. On the one hand, mission duration of a typical small-scale drone which can be used for monitoring operation is limited to the capacity of its energy storage system. On the other hand, from the standpoint of such drone's applications as electrical power line or gas pipelines' inspection and monitoring, the amount of time UAV can be autonomous should be as long as possible. In addition to that, in some cases dispatching a team of engineers to perform the inspection is not feasible or even impossible due to hazardous environment or inaccessibility of the destination, while a UAV provides a viable alternative to accomplish this task. Therefore, there is an open discussion on how to make UAV's mission duration longer and make drones more durable.

There are two options available to increase the flight time. The first one is to increase the battery capacity, which in the conditions of current state-of-the-art battery material technologies is a very limited option. Precisely, the battery might be too large for the drone to fly, or the material of the battery might be too expensive for the deployment to be feasible.

The second option is to charge the battery from an external source of energy intermittently. It can be either wired or wireless approaches. While the wired technique is associated with some complexities such as insufficient mobility of a drone during charging time; wireless options provide sufficiently greater freedom of movement. Also, they can be applied on request, in other words, the drone does not need to return to its base for charging.

The review of existing literature sources on the subject of UAV charging reveals that, apart from a conventional charging type via a cord, there are numerous wireless options to prolong UAVs' mission duration. Gust soaring [27], solar PV arrays installation [28], [29], laser beaming [30], wireless charging [31]–[33] and utilization of fuel cells [34] are some of them to name a few. Also, some of the researchers propose and recommend charging UAV via a transmission line [35], [36]. Some of the solutions have been patented in [37] and [38].

This paper reviews various techniques available in the literature sources on the topic of wireless UAV charging. They can be divided into two subcategories, namely non-electromagnetic field (non-EMF) based and electromagnetic field (EMF) based techniques. As it can be inferred from the name the latter unites the methods which use the electromagnetic field as a source of energy or a means to transport the energy to a UAV. On the other hand, the former groups together all the wireless charging techniques, which exploit any means of power gains except for electromagnetic field. Approaches such as gust soaring, PV arrays installation, laser beaming and battery dumping will be discussed in the following section.

II. NON-EMF BASED TECHNIQUES

In this section, we will introduce the non-EMF based techniques, which can be utilized for prolonging UAV's battery life.

A. GUST SOARING

Gust or dynamic soaring is one of the options to prolong UAVs' mission duration [27], [39]. The basic principle of dynamic soaring lays in gaining the energy from wind and airflow by adjusting the trajectory of an object in a way that captures uplifting airflow [27], [40], [41]. Numerical analysis of the dynamic soaring is presented in [39] and [42].

The role models for this method are albatrosses [27] and it has an interesting feature, which helps albatrosses to cover large distances under very harsh sea weather conditions. It was found that they could soar against the wind without flapping their wings, i.e. without wasting energy [43]–[45]. The schematic description of an albatross in a dynamic soaring manoeuvre is depicted in Fig. 1.

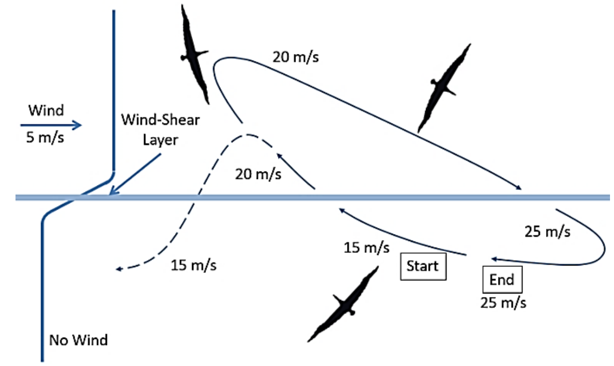

FIGURE 1. The dynamic soaring manoeuvre of a UAV [27].

It can be seen from Fig.1 that this trajectory allows to extract energy from the wind, convert it into potential energy and then back into kinetic energy. An albatross starting from the no-wind area increases its altitude up to the wind-shear layer. There, by adjusting its body and wings position, it can harness the uplifting component of the wind and gain speed as well as altitude. Once the lifting force is not sufficient to further lift it, the albatross aligns its body with the wind direction and descends rapidly. This manoeuvre facilitates gaining speed from the downwind stream and conversion of the potential energy into the kinetic. As a result, when the albatross crosses the shear layer and returns to its starting point it obtains a substantial amount of energy from the wind and increases its speed.

Thus, if a fixed-wing UAV mimics the same approach, it can potentially gain energy from the environment, i.e. from the wind. It is also concluded that the drone can potentially fly much faster than an albatross in the dynamic soaring mode due to its obvious higher strength and endurance. However, deeper and more precise studies devoted to the behaviour of albatrosses in the soaring flights are required to enhance the control model of the UAV's autopilot and create sufficiently precise trajectory enabling substantial gains in energy harvested to replenish battery charge [27].

The main drawback of gust soaring is the fact that a drone is quite dependent on the environmental conditions such as wind and airflow [40], [42]. It cannot maintain position for long, which is required for some of the industrial applications such as surveillance, and border monitoring [46]. Moreover, to employ this energy-harvesting mode, a sophisticated control system should be designed and installed on a drone. Also, it is suitable only for fixed-wing drones, due to the obvious presence of the sufficient wingspan to gain wind energy. This fact limits the applicability of this method for multi-rotor UAVs. It should also be understood, that dynamic soaring energy harvesting mode is intermittent and non-continuous, which should be taken into account while designing the drone for such applications [40]. The movement trajectory of a drone, as well as its kinematics, significantly influences the energy extraction rate [40].

B. PV ARRAYS

Installation of the PV arrays is considered as another technique for prolonging UAVs' mission duration. Normally, PV cells are used to power a drone or recharge its battery when the solar irradiation is available. The battery, in turn, is used for the operation during the night or the times when the solar radiation is insufficient [47]. The topic of designing PV systems for UAV applications has been under intensive consideration by researchers for a long period. Some studies have been published in the area of solar-powered UAV design with particular emphasis on the important design parameters such as cells arrangement and temperature response, tilt angle [48]–[50]. Reinhardt *et al.* [51] indicate that the UAV's battery type and capacity, time of the day and year as well as payload are the most important parameters which affect the mission duration of the PV powered aircraft, while the efficiency of the photovoltaic cells and other electronic components does not play a crucial role. Jashnani *et al.* [28] emphasized that scaling of the UAV is an iterative process and achieving feasible performance, i.e. long flight time, is a trade-off between drone's endurance and its physical dimensions. In order to facilitate design efforts, the authors derived a set of correlations of the drone parameters depending on the payload [28].

The limitation of the PV powered UAVs is their dependency on the solar radiation, which limits their applicability to the daytime use only. Although, as presented in [28] and [52], it is possible to enable a 24-hour operation, one should consider an alternative way to power a UAV in the absence of the sun. Thus, one of the following options can be helpful. It is possible to employ a backup energy supply during night operation such as explained in [34] and [53]. Another approach is increasing the UAV's battery size and subsequently the size of the PV array to account for the absence of the sun during night time. Moreover, a sophisticated path-planning algorithm can be utilised to gain energy from the environment and decrease battery discharge [26], [54]. However, this, in turn, limits the flexibility provided by the deployment of drones in areas requiring strict moving trajectories or level flights [55].

Another important feature of this technique is the fact that it is only applicable to the fixed-wing drones and practically unfeasible for multi-rotor UAVs. Since PV panels require a certain amount of space available at the vehicle to be installed typical multi-rotor drone provides limited opportunities for this technique's implementation.

C. LASER BEAMING

Laser beaming is a way to prolong mission duration, which is frequently used in military surveillance and intelligence missions [30], [56], [57]. The principle of laser beaming is schematically presented in Fig.2.

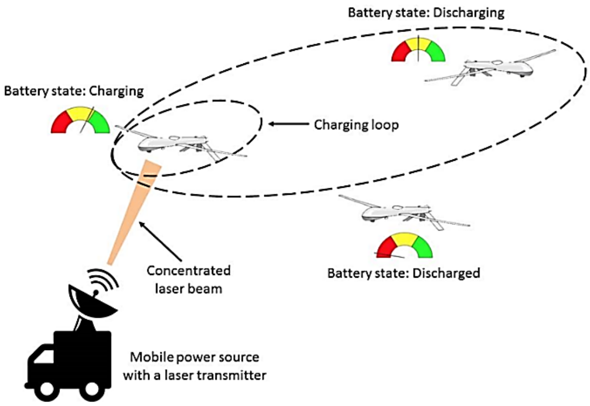

FIGURE 2. **Laser beaming procedure for drone charging.**

The external source of energy feeds the laser, which produces a concentrated and streamlined beam of light at a certain frequency and of a particular wavelength. This is directed to the specifically designed photovoltaic cell, installed on a UAV [58]. This PV cell is utilised to convert the laser beam back into useful energy to recharge the battery of the drone [59]. To enhance the efficiency of the energy transfer a maximum power point tracking device can be installed on a UAV.

The outcomes of the experiment conducted on a quadrotor UAV equipped with a modified solar cell array capable of receiving energy from an infrared laser via a laser beaming technology are presented in [30]. The ultimate result of the experiment conducted at Future of Flight Museum in Everett, WA, was that the given quadcopter with a total mass of 1 kg managed to stay aloft more than 12 hours in a row [30].This technology applies to both fixed wing and multi-rotor UAVs of various scale and is independent of the environmental conditions. However, the largest drawback of this approach is that a source of energy should be mobile and always close to the UAV, which limits the feasibility of its use in some of the long-range applications. Operational safety is another concern. Lasers, in general, are considered a potential hazard to the human health while working with high-intensity lasers are only permitted if protective equipment is on [57]. Also, lasers are restricted in some locations, especially within the urban areas where they can cause severe disturbances to the living environment.

D. BATTERY DUMPING

Another opportunity for prolonging UAV's mission duration is a battery dumping concept. Chang and Yu [60] propose to dump empty battery packs of the UAV to decrease the drone's weight and consequently slightly increase the flight time.

The main idea of battery dumping is to divide the existing battery pack of a drone into sections of either equal or unequal capacity, connect them and detach sections once they are fully discharged. This gives an opportunity to reduce the total weight of a UAV and consequently decrease the amount of energy required to power it. Thus, this strategy helps to increase the mission duration of the aircraft marginally.

The analytical model of the UAV including lithium polymer battery model underlines that the battery weight plays one of the most important roles in determining UAVs' mission duration. The analysis concludes that the battery pack dumping is a promising technique to reduce the energy consumption of a UAV for large battery weight to total UAV weight ratios. Also, it was highlighted that even though there is an increase in endurance, the installation of the battery dumping system onto the drone will increase the weight of the aircraft and consequently decrease the net improvement. The case study examines the aircraft with a battery-to-UAV weight ratio of 30% and a payload of 0.8 kg. Using genetic algorithm optimisation tool, the authors estimate the most appropriate number and size of the battery segments as well as compute the overall increase in mission duration. The results show that the endurance of the UAV extends by 17.6% for the level flight [60]. It was also revealed that the battery pack dumping strategy is very important, i.e. evenly sized battery packs result in lower endurance improvements compared to those divided unevenly.

Some authors also propose to implement automated battery changing stations [61], [62]. Under this technique, a drone lands on a specifically designed platform and with the help of automated manipulators the drone's empty battery is removed from the vehicle, while a new fully charged battery is installed. Once the process is over, the drone can resume its mission. In other words, instead of spending long periods recharging at the station, a much faster (compared to conventional charging) procedure of battery swapping is proposed to be utilized [61]. Also, this automated technique reduces effort spent on changing batteries of UAVs as well as minimising human participation in the process. This technique can be applied to both fixed wing and multi-rotor drones. However, to enable effective battery changing for long-range applications a network of such changing points should be created; otherwise, the drone will have to return to the base for a battery change.

III. EMF-BASED TECHNIQUES: HIGH VOLTAGE POWER LINE UAV CHARGING

High voltage power lines are also considered as one of the options, which can be used to recharge UAV's battery and subsequently prolong mission duration. There are studies on the potential of using the power lines electromagnetic field for device charging [63] and some of them attempt to estimate the amount of energy available for a drone to use around the transmission line using magnetic field intensity [64]. More formally, magnetic field intensity, H, is given as [33]:

$$H = \frac{i}{2\pi r} \tag{1}$$

where i is the current flowing through the transmission line conductor, and r is the radius of the conductor.

Magnetic flux density can be obtained as [33]:

$$B = \mu_r \mu_0 H \tag{2}$$

where μ_r is the relative permeability, and μ_0 is the free space permeability. It is assumed that μ_0 is constant in the air, while μ_r has high values in the order of 1–3 × 10^5.

Magnetic flux will be given as [33]:

$$\phi = BA = \mu HA \tag{3}$$

where A is the cross-sectional area of the conductor, while μ is the result of multiplication of μ_0 and μ_r.

Using the following equation one could estimate the amount of energy which is potentially available around alternating-current-carrying conductor [33], energy density around a wire:

$$\frac{dW_m}{dV} = \frac{\mu_0}{2}H^2 = \mu_0 \frac{i^2}{2(2\pi r)^2} \tag{4}$$

Based on this technique, [33] concluded that the amount of energy available around a power line's current carrying conductor would be sufficient for charging UAVs. However, at the same time, the authors point out that in real conditions the interference of other magnetic fields should be taken into account [64].

In addition to determining the amount of available energy from the power lines, one needs to think of a way to harness this energy and transfer it to the UAV. The most popular approach reported in the literature is wireless charging. Some authors propose to land a UAV onto a power line [35], [36], [38], while others suggest that charging without landing is also feasible [37].

Moore and Tedrake in [35], [36] developed a technique of navigating a fixed-wing UAV in the vicinity of the power line based on its electromagnetic field. The ultimate goal of the study was to enable a drone to sense the EMF of the power line once close to it, then based on the reading of the internal measurement equipment of the UAV tilt its airfoil like an aeroplane in a landing manoeuvre and perch safely on to the conductor. Then a charging procedure can be started. As described in [38] a drone can grab a power line's conductor with a specially designed connector, which at the same time resembles a magnetic core of the power transfer system of the drone. Thus, once the connector is closed and the current carrying conductor is within its envelope, the whole structure represents a typical electromagnet, and the EMF generated by the power line can be transferred via a magnetic core to the conversion unit and then to the battery of the UAV [38]. A similar approach using inductive power transfer, which is a subject for discussion in the further sections, is presented in [37].

Along with abovementioned techniques, dynamic charging of a moving vehicle without landing is an interesting option [65]. This approach implies that a drone is flying over a power line and harness available energy from the EMF of the conductors using one of the wireless charging techniques. Although this technique is very promising and presents an attractive solution for the problem of the drone's battery recharging, maintaining a strong coupling and high efficiency of the power transfer during the movement is a very challenging task. The attempts to accomplish dynamic charging of an Electric Vehicle (EV) for inroad use have been on the research agenda for more than half of a century [66]. However, commercial systems such as Oak Ridge National Laboratory (ORNL) In-Motion Wireless Charging [66] and Korean Institute of Science and Technology (KAIST)

On Line Electric Vehicle (OLEV) [67] were introduced around a decade ago and they are still not widespread.

On the other hand, the reports on dynamic charging of UAVs are very rare and the area is still underdeveloped. The main difference between the dynamic charging of a UAV from the power line's conductors and an EV from the tracks built into the road is the fact that the shape, topology and materials of the latter are specifically designed to provide strong coupling between the transmitter and the receiver during movement, while former are not. This means that the coupling coefficient between the power line and the UAV-side receiving coil will highly likely be out of control and relatively low. In addition, in case of EVs, it is a normal practice to convert the source's AC energy into high frequency AC via an intermediate transformation into DC, in order to gain control of the transmitter's parameters and adjust them as per necessity. On the other hand, the powerline conductor, representing the source in case of UAV charging is an ambient and uncontrolled low (50 or 60Hz) frequency source of EMF. Taking into account the abovementioned facts, it becomes evident that the realization of the proposed technique should predominantly rely on the drone's side equipment as well as available space and payload. Both coupling coefficient adjustment and frequency management should be done on board of the UAV. This challenge has not yet been resolved and therefore dynamic wireless charging of UAVs from the power lines is still an underexplored research area.

Wireless charging techniques' principles and associated aspects will be discussed in the following sections.

IV. WIRELESS POWER TRANSFER

Wireless Power Transfer (WPT) is a process of transmitting electromagnetic energy from the source of energy to receiver without using any connecting cables between them [68]–[71]. The concept is known since the beginning of the twentieth century when Nicola Tesla presented and patented his idea of transmitting energy through the air without using any intermediates [72].

A typical wireless power transfer system consists of an energy emitting device or a transmitter connected to the energy source, a transfer media and a receiving device or receiver, connected to the load. The transmitter converts electrical energy of the source into the "time-varying electromagnetic field", it is then transferred to the receiver via the transfer media, which then converts the electromagnetic field back to the electric current [33]. The most illustrative example of the given phenomenon is a power transformer consisting of two coils, which are not physically connected. In other words, they are separated and belong to different electrical circuits.

WPT systems can be divided into two categories based on the way of transmitting energy, i.e. radiative and non-radiative [69]. Radiative WPT is characterised by low efficiency and large distance of power transfer, while non-radiative WPT is much more effective for small and medium range applications [69]. The non-radiative transfer is represented by the two most common techniques namely inductive coupling and resonant inductive coupling [69].

A. INDUCTIVE POWER TRANSFER

Inductive Power Transfer (IPT) is a very popular approach for short-range WPT applications; typically, the distance between the transmitter and receiver in such cases does not exceed several centimetres [69], [73]–[75]. It is often used in wireless charging stations for low power appliances such as cell phones, toothbrushes, medical implants etc. [76]

IPT's efficiency can be as high as 90 percent at very high power ratings. However, the distance plays a significant role in power transfer using this method [75]. The transmission efficiency is inversely proportional to the cube of the distance between the transmitter and receiver [77]. Thus, transmission distance for effective IPT does not exceed several centimetres [69]. Vertical and horizontal alignment between receiver and transmitter coils greatly affects the performance of the wireless transmission system [31], [69], [78], [79]. The further the distance between the coils, the smaller is the efficiency of the transfer. It should be emphasized that horizontal position has a greater value to the transfer efficiency compared to the vertical alignment [78], [80]. Also, as summarised in [81] angular misalignments of the coils play a significant role, for example [79], [82], if small lateral misalignments are considered, angular position mainly determines the performance, while at large lateral disposition angular mismatch can be neglected. Further, the coupling factor between the stationary source and moving receiver is relatively small, i.e. much less than a percent, compared to the robust applications of IPT such as power transformers (up to 98 percent) or electrical motors (up to 92 percent) [83], [84].

A general relation representing the voltage created at the moving receiver from a current carrying conductor of the source [83], [85], [86]:

$$V \propto \omega M I_{source} \tag{5}$$

where M is the mutual inductance between the source and the receiver; ω is the operating frequency of the source current, I_{source}. Thus, taking into account the fact that the mutual inductance is very small, from (5) one can infer that to increase the voltage at the receiver; it is necessary to either increase the current of the source or its frequency [84]. The typical frequency of operation for this technique varies from tens of Hz up to several MHz [69]. Moreover, it should be noted that the source current should be "as sinusoidal as possible" [83].

It is also important to highlight that apart from the electrical parameters of the wireless system, physical characteristics, such as coil's design and system's topology are also crucial for the IPT [85], [87]. Also, magnetic shielding is required for the surrounding objects, since the IPT's coupling is very vulnerable to the presence of metallic objects [77].

Waffenshmidt and Staring conducted a set of experiments comparing IPT and resonant coupled WPT. Fig. 3 represents

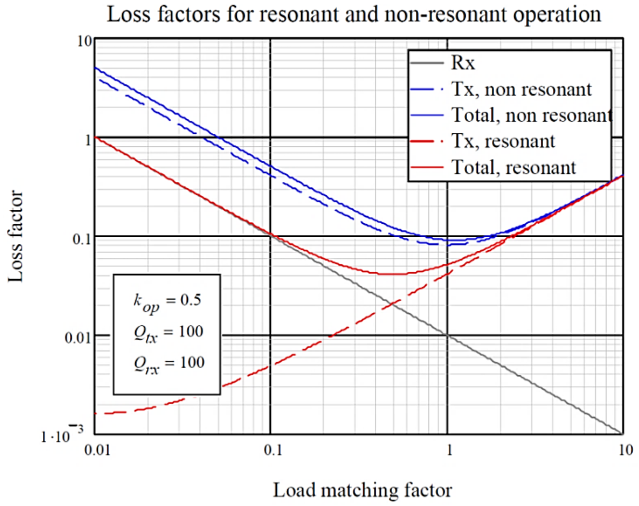

FIGURE 3. **Comparison of the resonant and non-resonant operation of a WPT system for a good coupling factor k = 0.5 and a moderate quality factor of the coils, Q = 10 [86].**

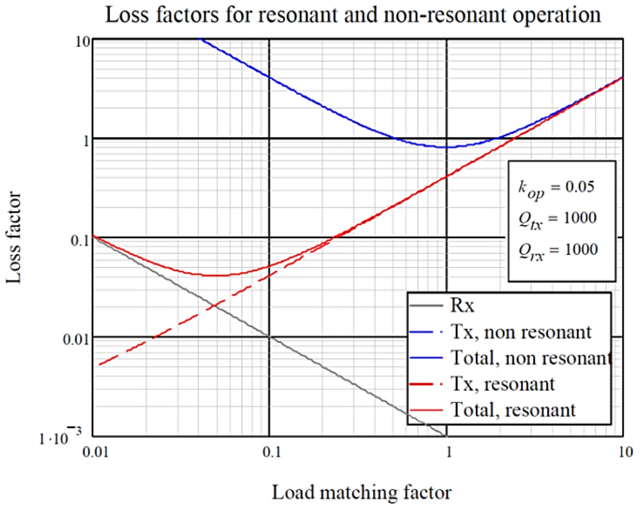

FIGURE 4. **Comparison of the resonant and non-resonant operation of a WPT system for a poor coupling factor k = 0.05 and a high-quality factor of the coils, Q = 1000 [86].**

the results of the experiments summarised as a graph. Here, loss factor is the non-dimensional ratio of the actual losses at either the transmitting (*Tx*) or receiving (*Rx*) coils to the output power, while the non-dimensional load matching factor shows how large the load resistance is in comparison to the receiver's characteristic impedance [88]. The aim is to have the loss factor as low as possible, to enable most of the useful energy transferred from the source to the load. As it can be seen from the Fig. 3, resonant operation is much more efficient than simple IPT since the losses in the system are equal (loss factor is 1) or do not exceed the output power for load matching factor less than or equal to one. On the other hand, the IPT technique, for the same range of load matching factors, demonstrates that the losses during the transfer are significantly higher than for the resonant scenario. Precisely, when the load is 100 times smaller than the characteristic impedance of the IPT wireless link the losses in the system will be 10 times larger than the output power. On the contrary, resonant operation of the same wireless link under the same load and characteristic impedance will result in losses equal to the output power. However, the difference is not that drastic when the coupling factor is relatively high, i.e. $k = 0.5$. Fig. 4 illustrates a case when the coupling factor is ten times less, while the quality of the coils, Q, is ten times larger to account for the loss in the coupling. Quality of the coil can, at this stage, be thought of as a ratio of the coil's inductance to the coils resistance. Large inductance and low resistance characterize high quality coils and vice versa.

As it can be seen from Fig. 4, when the quality factor of the coil increases the losses for the resonant approach become smaller comparing to the output power.

However, the loss in the coupling factor significantly influences the IPT technique's performance. In other words, with the decrease in coupling factor the losses in the system drastically increase and the lowest loss factor which can be achieved is slightly less than one. This conclusion underpins the principles of IPT's operation, which relies heavily on the coupling between the coils and when it is not enough the losses in the system increase dramatically while the efficiency plunges. Hence, comparing Fig. 3 and 4, one can notice that resonant approach is more advantageous type of WPT for various combinations of coupling conditions and quality of the coils. However, what is more, important is the notion that the IPT is strongly dependent on the coupling rate between the *Tx* and *Rx* coils [88], [89]. Waffenshmidt and Staring conclude and confirm a commonly accepted belief that IPT is appropriate and effective for the applications when transmitter and receiver are close to each other [88].

In case of employing IPT for UAV charging, the main point of attention should be the charging range, i.e. the distance between the power source and the drone. It should be as small as possible since the efficiency drops significantly with the distance. Also, lateral movements of the drone under this approach should be minimised because the drop in transfer efficiency is much more drastic when the coils are dispositioned in the horizontal plane rather than situated vertically far away from each other. Lateral, angular and vertical movements of the drone, receiving coil as well as the power line conductor will significantly influence the efficiency of WPT.

Therefore, these parameters need to be precisely controlled and maintained. Such requirements may pose additional pressure on the UAV's control systems; require installing additional as well as improving existing control equipment and strategies. Thus, taking into account the abovementioned information, one can conclude that the most promising applications of IPT lay in, but are not limited to the field of UAV charging stations where the vertical and horizontal distances between the power source and the receiver are stable and under control. However, considering the case of deploying drones for the routine power line inspection, such wireless charging stations will have to be installed over the entire length of the power line to enable reliable and efficient power restoration.

B. RESONANT COUPLED WPT

The other technique namely Resonant Coupled WPT (RC WPT) is insensitive to misalignments of coils and is capable of transferring larger power over greater distances [69], [90]. This method has been introduced and explained by a group of researchers from MIT [91]. It is mainly based on the notion that two magnetically coupled coils in a resonant mode, meaning that their magnetic field oscillates at the same frequency, can exchange energy without significant losses [69], [91]. The typical operating frequency for this technique is reported to be in a range from 10 kHz to 200 MHz [69], [92]. The process can happen via loosely or strongly coupled fields. The difference in quality factors of coils, also referred to as Q-factors, determines the type of coupling [65], [69]. Das Braman *et al.* [69] indicate five main parameters that are affecting the coil design in resonant coupling mode: they are namely power rating of the system, coil geometry, Q-factor, frequency of the system and coupling parameters.

When a coil connected to a capacitor is supplied with energy, the energy will be transformed from the magnetic field of the inductor into the electrical field of the capacitor and back at a certain operating frequency until all the energy is dissipated due to the losses, i.e. inductive and resistive. The rate of dissipation is dependent on the internal parameters of the coil, precisely, Q-factor. However, if the coil is connected to another inductor operating at the same frequency, the latter can draw the energy from the former, instead of that energy being dissipated [69]. To understand the notion of the Q-factor, the internal structure of the coil depicted in Fig. 5 can be considered.

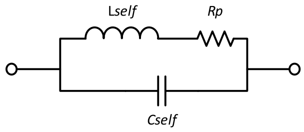

FIGURE 5. **Schematic representation of the induction coil [67].**

Equation (6) presents an analytical way of estimating coil's Q-factor, Q [69]:

$$Q = \frac{\omega_0}{2\Gamma} = \frac{1}{R_p}\sqrt{\frac{L_{self}}{C_{self}}} = \frac{\omega_0 L_{self}}{R_p} \tag{6}$$

where R_p, L_{self}, C_{self} are the parasitic resistance, self-inductance and self-capacitance of the coil, respectively; ω_0 is the operating frequency of the coil; and Γ is the intrinsic loss rate of the coil.

Values of inductance and capacitance used in (6) can be estimated as given in (7) and (8), respectively, if the cross-sectional area of the coil, a is much less than its radius, r_c [69]:

$$L_{self} \cong \mu_0 r_c \left[\ln\left(\frac{8r_c}{a}\right) - 1.75\right] \tag{7}$$

$$C_{self} = \frac{1}{\omega_0^2 L_{self}} \tag{8}$$

The parasitic resistance of the coil's wires should be low to enable high Q-factors, which in turn leads to higher transmission efficiency [69], [91]. This condition is effective for both transmitting and receiving coils. Considering the case of a typical high voltage transmission power line's conductor, which may be perceived as an energy transmitter for UAV charging, this requirement is fulfilled since the main design aim for it is to decrease the resistance to a minimum and subsequently reduce the losses. On the other hand, its inductance is also relatively small. Moreover, since the majority of the commercial power lines in the World operate at 50 or 60 Hz conditions, the frequency term cannot significantly improve the performance of the conductor in terms of quality. All the factors mentioned above, in turn, decrease the power line's quality factor in comparison with regular transmitters, which are characterized by large inductances and operated at higher frequencies.

The value of the parasitic resistance, R_p, can be calculated as follows:

$$R_p = \frac{2l\rho}{\pi r_w \delta} \tag{9}$$

where l is the length of the conductor, ρ is the conductive material resistivity, and r_w is the radius of the wire.

The skin depth δ is given as [69]:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0\mu_r}} \tag{10}$$

where μ_0 is the magnetic permeability of free space, and μ_r is the magnetic permeability of the wire material.

It should be highlighted that this WPT approach is insensitive to the surrounding non-metallic or non-magnetic objects, which makes it very promising for daily applications [69], [93]. It is also relatively safe for people and does not require any specific shielding [94]. Another advantage of the resonant WPT approach is that it can potentially transfer power to multiple receivers tuned at the resonant frequency and, by analogy, such receivers can grab energy from multiple sources [69], [95], [96]. There are two theories which explain the processes occurring during the resonant coupled WPT, namely Reflected Load Theory (RLT) predominantly employed by the engineers and Coupled Mode Theory (CMT) frequently used by the physicists [97].

Wei *et al.* [98] conducted an overview of these theories. The authors compare their mathematical models explaining the processes occurring during the resonant coupled WPT. It has been concluded that the underlying mechanisms of power transfer are robustly represented by both of the theories. This fact is proven by the convergence of the results in steady-state resonance mode, i.e. when both coils are already operating at resonance frequency [98].

Kiani and Ghovanloo [99] and Hui *et al.* [100] also aimed to evaluate CMT and RLT. The study presents the mathematical modelling of resonant coupled WPT link for steady-state and transient cases using CMT and RLT. It theoretically proves that both theories provide the same results for the steady-state resonant mode. However, for the transient mode, i.e. when the coils are operating at frequencies very close to resonance, the results of CMT converge with those of RLT if the following conditions are satisfied: the quality factor of the transmitting coils used in CMT are significantly large, and the coupling coefficient between them is small enough. In other words, for the results of CMT and RLT to converge the coils should be placed far enough apart. This fact limits the applicability of the CMT in transient analysis. In addition to the theoretical proof, the paper provides results of the simulations made in MATLAB and LT-SPICE verifying the accuracy of the derived mathematical models. Furthermore, the theoretical estimations are checked against the experimental values obtained from the laboratory experiment. The results show that the theoretical estimations both for CMT and RLT have shown high accuracy in the steady-state resonant transfer mode [99].

V. RC WPT EXPLAINED VIA RLT

The given section focuses on exploring resonant coupled WPT using reflected load theory. A thorough analysis has been presented by Kiani and Ghovanloo [99]. Fig. 6 represents two inductively connected coils which transfer power using resonant WPT.

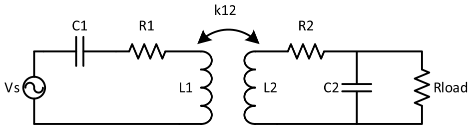

FIGURE 6. Two-coil WPT system.

The resonant condition can be parametrically represented as follows:

$$\omega = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{11}$$

where ω is the resonant frequency of the two LC circuits.

Resonant frequency is one of the crucial parameters determining the overall performance of the wireless power transfer. Generally, as it can be seen from (6) the increase in frequency leads to the rise in quality factors of the coils. This in turn increases the overall performance of a wireless link, including transfer efficiency. Moreover, considering (11) it can be observed that a given resonant frequency is inversely proportional to as well as is determined by a combination of coil's self-inductance and parasitic capacitance. Higher operating frequency implies lower inductance and capacitance values required to be used to achieve resonance. In practical terms, this means that smaller and lighter sizes of the hardware can be employed. This is particularly beneficial for the drones' applications. Since the payload of the drone is limited, the size of the inductor and the resonating capacitor installed on it needs to be minimized. Therefore, the choice of the resonant frequency tends to higher frequencies since the size and the weight of the UAV-side components in that case will be lower.

Moreover, maintaining a stable resonant mode is of immense importance for the efficiency of the WPT. However, even small fluctuations in the combinations of inductance and capacitance may cause sever deviations of the resulting resonant frequency. Therefore, the electronic components should be of a high quality as well as should have very precise parameters. In practice, most of the electronic devices have a certain tolerance, ranging typically from plus to minus 10 percent of the nominal value. Such tolerances are too loose for the frequency tuning applications and stricter tolerances are needed [101]. Alternatively, a variable capacitance and a tuning inductance may be installed to adjust the resonant frequency.

However, taking into account the fact that the standard power line's frequencies utilized in the industry are 50 or 60 Hz, the sizes of the receiver's inductances and capacitances will be considerably large.

According to [91], [93], [99], and [100] the transfer efficiency between two inductances in resonant WPT mode depends on the mutual inductance k_{12} and the quality factors of the coils of L_1 and L_2, which are determined using (12) and (13):

$$Q_1 = \omega \frac{L_1}{R_1} \tag{12}$$

$$Q_2 = \omega \frac{L_2}{R_2} \tag{13}$$

The intrinsic resistance of the coil L_2 which is denoted as R_2 can be represented as a parallel load connected to L_2 using the following relation [99]:

$$R_{P2} = Q_2^2 R_2 \tag{14}$$

Thus, having (14) in mind, the circuit in Fig.6 in a resonant mode can be represented using projecting the load connected to L_2 onto the circuit containing a source of energy V_s. Fig. 7 displays the equivalent circuit for the reflected load.

Reflected capacitance, C_{ref} and reflected resistance, R_{ref} from Fig. 7, can be determined using the following relations [99]:

$$R_{ref} = k_{12}^2 \frac{L_1}{L_2} R_{pr} = k_{12}^2 \omega L_1 Q_{2L} \tag{15}$$

$$C_{ref} = \frac{L_2 C_2}{L_1 k_{12}^2} = \frac{1}{\omega^2 L_1 k_{12}^2} \tag{16}$$

where R_{pr} is the product of connecting R_{ref} and R_{P2} in parallel; Q_{2L} is the loaded quality factor of the coil L_2, which can be calculated as follows:

$$Q_{2L} = \frac{R_{pr}}{\omega L_2} \tag{17}$$

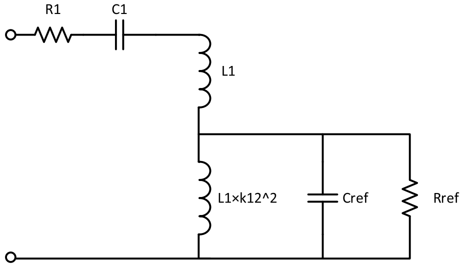

FIGURE 7. **The equivalent circuit for the reflected load case.**

During the resonance the capacitive load C_{ref} and inductive term $k_{12}^2 L_1$ are eliminated leaving only the resistive components, R_1 and R_{ref} connected to the source circuit [99]. Thus, the power provided by V_s is distributed proportionally between them, i.e. some amount is dissipated as heat at R_1 while the rest is the power transferred wirelessly.

The efficiency of the transfer can be estimated as:

$$\eta_{12} = \frac{R_{ref}}{R_1 + R_{ref}} \times \frac{R_{P2}}{R_{P2} + R_{load}} = \frac{k_{12}^2 Q_1 Q_{2L}}{1 + k_{12}^2 Q_1 Q_{2L}} \times \frac{Q_{2L}}{Q_L} \tag{18}$$

where $Q_L = R_{Load}/\omega L_2$ is a load quality factor. Thus, the loaded quality factor of coil L_2 can be obtained as:

$$Q_{2L} = \frac{Q_2 Q_L}{Q_2 + Q_L} \tag{19}$$

Equation (18) underpins the early mentioned idea that high mutual inductance and quality factors of the coils are necessary to maximise the efficiency of the transfer. It also suggests that to maximise the efficiency one can select an optimal load, $Q_{L,OPT}$. This can be proven by differentiating (18) with respect to Q_L [99]:

$$Q_{L,OPT} = \frac{Q_2}{\sqrt{1 + k_{12}^2 Q_1 Q_2}} \tag{20}$$

However, maximising energy efficiency of the WPT system is not always possible and desirable. The following section will introduce two fundamental concepts of the WPT, which determine the characteristics of the system and their applicability.

VI. RESONANT WPT CONCEPTS

To properly design WPT system, it is crucial to be familiar with the two fundamental concepts namely Maximum Power Transfer (MPT) and Maximum Energy Efficiency (MEE). It is also important to understand their advantages and disadvantages because the choice of the principle will determine the efficiency of the system and transmission range.

MPT concept specifies the conditions, which allow transferring the largest power possible for the given system over the largest distance. This can be achieved in any WPT system if load and source impedances are equal to each other [69], [100], [102]:

$$\begin{aligned} R_{source} &= R_{load} \\ X_{source} &= X_{load} \end{aligned} \tag{21}$$

In this case, the total energy efficiency of the WPT system can be calculated as follows [69]:

$$\eta_{MPT} = \frac{i^2 R_{load}}{i^2 R_{source} + i^2 R_{load}} = \frac{R_{load}}{R_{source} + R_{load}} = 0.5 \tag{22}$$

From (22) it is evident that if MPT condition specified in (21) is fulfilled, then the efficiency of the WPT, in this case, will not exceed 50 percent, i.e. half of the energy will be dissipated at the power source [69]. This phenomenon has been tested by the researchers at MIT [91]. They employed MPT concept to transfer 80 W over the distance of about 2 m. The outcome of the experiment was as follows. The efficiency of the transfer, i.e. the ratio of the power captured by the receiver over the power sent by the transmitter, has been reported to be around 40 percent. The overall efficiency of the system, in other words, power received by the load divided by the power produced at the source, in turn, has been reported to be less than 15 percent [91]. From this example, it is evident that by employing MPT a significant amount of power can be transferred over a substantially long wireless link. However, the overall efficiency of this transfer will be very poor [102]. It can also be concluded that MPT is applicable in the fields where the efficiency of the WPT is not the main priority, while the power rating and transfer range should be large enough.

On the other hand, MEE concept specifies the conditions, which allow achieving a higher overall energy efficiency of the transfer. Under this approach, the power rating of the system is disregarded. The maximum transferable power is determined by the parameters of the circuit, which provide maximum efficiency of the transfer and can be different from that determined by the MPT. Also, transfer distance is very limited, since MEE is heavily dependent on high coupling coefficients, which in turn correspond to relatively short gaps between transmitting and receiving coils [69].

MEE approach is achieved by means of decreasing losses at the power source, $i^2 R_{source}$. To realize this condition, the impedance of the source should be as low as possible. It is also important to minimise the resistance and impedance of the transmitting and receiving coils [90], [99]. Copper tube or Litz wire utilized as a material for manufacturing of coils can reduce losses in the wires [69]. Moreover, comparing to MPT, this approach allows achieving efficiency levels of more than 50 percent. However, the distance between the transmitter and the receiver is a limiting factor of MEE, since this approach requires high coupling coefficients to be utilised [69]. In other words, the transmission distance should be very small for MEE. To extend the range, one can consider an option to put several intermediate coils, also called magnetic repeaters in between the transmitting and receiving coils [69], [100]. Thus, considering the conditions required for MPT and MEE realization, one can notice that in the first case the impedance of the source should be equal to the impedance of the load, while for the second case the source impedance should be as low as possible. In practice, these two conditions are very hard to be fulfilled simultaneously.

Considering the case of charging a UAV from a power-line conductor inflight, there are several design points which needs to be carefully considered. Firstly, the power line's parameters and output cannot be regulated, and therefore the management of the source impedance is out of control. Therefore, realization of MPT and MEE in this case is a highly challenging task as the only controllable parameters are those possessed by the UAV. It is of course possible to embed additional electronics such as impedance matching or maximum power point tracking cascades, but this action in turn will significantly increase the overall weight of the drone so that it may not be able to take off.

Secondly, from the standpoint of MEE, the distance between the UAV's coil and the power line should be minimized. Therefore, the drone, or to be more specific its receiving coil in a charging maneuver should be positioned as close to and as stable relative to the conductor as possible. In case of IPT it should even be in a range of several millimeters from the line. This will highly likely require improving existing control system of the UAV and add supplementary control mechanism to provide stability and precise positioning of the UAV as well as its receiving coil. Moreover, ground level remote control strategies will require additional improvement in order to position the drone with a millimeter tolerance when it is kilometres away.

Therefore, it is of immense importance to be aware of the benefits provided by those approaches and apply them in the most advantageous way for a specific application.

VII. FREQUENCY SPLITTING

Consider a four coil resonant WPT system shown in Fig.8 under the MPT approach. Such topology is characterized by a higher transfer (source to load) range than analogous two coil system due to the additional distance provided by the drive and load loops. It is advantageous to be utilized for the wireless charging stations, which may be installed on a power line's towers. The concept of such stations has been described and thoroughly discussed in [101], where the energy is transferred from the power line's conductor to the load via numerous transmitting coils embedded into the high voltage insulation string. Similar approach can be used to establish a charging infrastructure for UAVs employed in power line monitoring operations. Although, the system is relatively robust compared to inflight battery charging, the cost of the infrastructure and limited mobility of the drone during charging are two open questions and major points of interest under this approach. Moreover, such systems have not yet been commercially realized and tested. Thus, they present an interesting opportunity for further research.

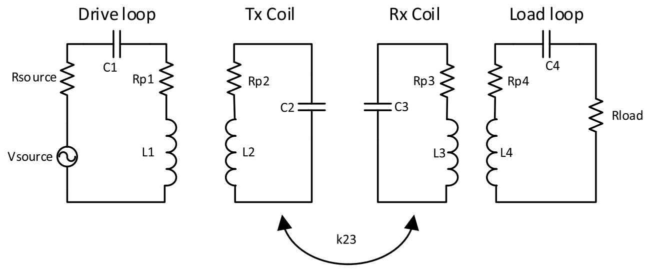

FIGURE 8. Four coil resonant WPT system [102].

While increasing the coupling k_{23} an interesting phenomenon called frequency splitting can be observed [103], [104].

According to a study by Sample *et al.* [105], WPT systems can operate at three different coupling levels, namely under coupled, over coupled and critically coupled modes. The under coupled mode is characterised by low coupling coefficient between the transmitting and receiving coils and overall low power transfer rating of the system. The critical coupling happens when the two coils are tuned at the resonant frequency. It can also be thought of as a distance between the coils at which maximum efficiency can be realised [105]. The coupling at this distance can also be named as critical, $k_{critical}$. If the distance between the coils continues to decrease, it will lead to the increase in coupling coefficient k_{23}. If $k_{23} > k_{critical}$, then the circuit will be operating in the over coupled region, where a frequency splitting phenomenon can be observed. This phenomenon manifests itself as the case when two resonant frequencies instead of one can be possible for a given system operating in the over coupled mode. Moreover, both of them can be used for WPT. Fig. 9 represents the frequency splitting phenomenon using plotting the relation of the scattering parameter S_{12} with respect to the frequency and coupling coefficient:

$$S_{12} = 2\frac{V_{Load}}{V_{Source}}\sqrt{\frac{R_{source}}{R_{Load}}} \tag{23}$$

The scattering parameter is directly related to the transfer function of the WPT [105], [106].

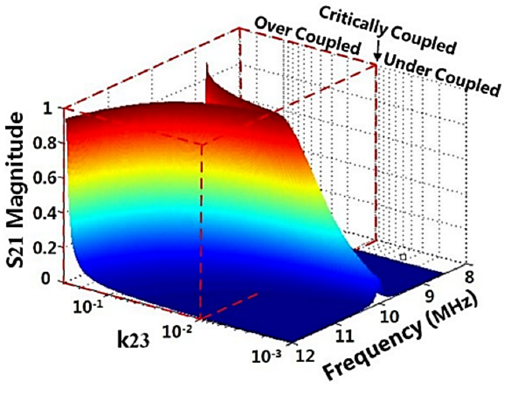

FIGURE 9. Representation of the frequency splitting phenomenon in the over coupled region [102].

The lower frequency mode is characterised by in-phase currents in the transmitting and receiving coils, while for the higher frequency the currents are out of phase [105]–[108].

As [98] and [109] have discussed, frequency splitting is not a disadvantage of the topology, but a consequence of over-coupling and aiming for higher power transfer capabilities of the WPT system. However, it may cause some problems in terms of maintaining a resonant coupled regime. In other words, when a system is tuned at a certain resonant frequency, it should not operate at the over coupled region because if the coupling is too large, the frequency splitting will alter the resonance frequency.

Consequently, some means of adjusting coupling rate or distance between transmitter and receiver, or operating frequency will be required to compensate for this phenomenon. A thorough review of compensating measures is given in [105]. Considering the influence of frequency splitting on the UAV, it is evident that to compensate for this phenomenon some strict control algorithms guiding the operating conditions of the drone during resonant WPT should be employed. Also, some means of frequency adjustment can be implemented. However, this option can potentially increase the hardware weight of the UAV, subsequently increasing the overall mass of the vehicle and reducing the flight time and distance, which is not desirable.

Thus, having considered the information presented above, it is possible to conclude that resonant WPT technique can potentially transfer a significant amount of power over relatively large distances without a considerable reduction in efficiency. Also, it enables a stable coupling between the transmitter and receiver as long as they are synchronised at the same resonant frequency. These features of the technology make it particularly interesting for the UAV charging applications, including dynamic charging of a moving drone.

Examples of WPT applications in the field of drone charging reported by the literature will be presented in the following section.

VIII. WIRELESS CHARGING OF UAVs

The scenario which is of primary interest of this article implies that a utility drone during the monitoring mission can potentially use the power line conductors as a source of energy to recharge its own batteries and prolong its mission duration. However, this approach has rarely been considered and reported in the literature on the subject. In fact, the topic of UAV charging has not yet been thoroughly discussed and has potential for intensive exploration.

This section presents a brief overview of the approaches and techniques reported in the scientific community on the subject of UAV charging using both wireless power transfer technologies, i.e. IPT and resonant WPT, with a particular emphasis on the charging from power line's conductors.

The potential application of Wireless Energy Transfer (WET) for charging moving quadrotor UAV from the power line conductors has been discussed in [33]. The authors conclude that the amount of power which can potentially be extracted from the transmission lines should be enough to restore the UAV's battery.

Practical implementation of this approach has been published in [64] as a continuation of the previously published work of the authors. It presents the idea of using strongly coupled resonance principle for WPT due to its high transmission efficiency and larger transfer distance. The source of the power is the transmission line's conductor connected wirelessly to a transmitter's side of the UAV recharge station. The drone equipped with a receiving coil is assumed to land on the receiving unit mentioned above and restore its battery via RC WPT technique. The study also demonstrates experimental results received from a tabletop power line model. The setup consisted of a 10 A current carrying wire connected to a 240V AC source of 50 Hz and a 250-turn solenoid of 59 mm in diameter and 107 mm in length of an overall inductance of 1.41–1.39 mH. The voltage induced by the line was 10 V, which led authors to a conclusion that the amount of power available from a real power line will be large enough to recharge a typical drone's battery of 5200 mAh.

Wang and Ma [110] also present a concept of wireless drone charging using a specifically designed charging station located on a power line. However, they propose to use a self-sustaining PV powered charging station based on the RC WPT principles. The article describes the whole charging process and design procedure for various system's elements. They present a principal layout of the wireless power transfer system and conclude that a stable power transfer of 130 W over a distance of 50 mm can be achieved. The article proposes that the implementation of a network of such charging stations will significantly improve the drones' applicability and enhance their deployment.

Even though the concept has potential for implementation it still implies creating an infrastructure of charging pads for the UAVs along the entire length of the power line to be monitored. The authors, however, do not consider the costs of the infrastructural developments, electromagnetic shielding challenges and safety of such systems' operation.

Alternative wireless charging techniques for UAVs reported in the literature predominantly rely on the external sources of energy and transmitters operating at frequencies much higher than 50 or 60 Hz. Dunbar *et al.* in [32] reported on a wireless charging system's architecture for a micro-UAV utilizing 5.9 GHz frequency to transfer 10 W and charge the installed battery wirelessly via an integrated rectifier antennas (rectenna). The overall performance of the system is managed by a micro-controller which is capable of maximum power point tracking [32]. Wang and Ma [110] employed the frequency of approximately 38 kHz for their wireless charging station. The study [111] proposed to operate at 12 MHz in order to boost the quality factors of the coils and achieve high transfer efficiency. Despite the fact that the operational frequencies utilized for UAV charging vary significantly in a range from kHz to GHz, the trend of increasing them as much as possible in order to enhance efficiency of the transfer can be observed.

The UAVs are also used in a reversed way, i.e. drones can charge other devices using the principles of WPT [17], [77]. Griffin and Detweiler [77] report on the procedure to design a device which can be installed on a quadrotor UAV to transfer power from the battery to the remotely positioned sensors. The authors managed to transfer on average 4.43 W from the drone to the ground gadgets [77], [112]. It was also identified that small movements of quadrotor, even those in steady state position, can significantly affect the power output of the resonant WPT system [77]. This fact highlights the need for precise control mechanisms to be installed on UAVs in order to accurately locate and stably maintain the position between the transmitter and the receiver.

Thus, the existing research efforts over the past decade have been intensively directed towards the challenges associated with UAV charging. However, due to a better control over the power output parameters and ease of stable positioning, most of them tend to the development of the wireless charging stations and/or adaptors, ignoring the opportunities provided by the electromagnetic fields of power lines in the free space. The following section attempts to assess the opportunities provided by the power lines by means of testing the WPT in the laboratory conditions.

IX. PRELIMINARY TEST OF THE PROPOSED CONCEPT

Having reviewed techniques commonly employed to prolong UAVs' mission duration, it was decided to test a hypothesis that a drone can potentially harness energy from the electromagnetic field of a high voltage power line using either IPT or RC WPT. For the laboratory experiment, the IPT technique has been chosen due to its simplicity of implementation and well-studied principles of operation described in Section IV.

A. HIGH VOLTAGE POWER LINE EMULATION

To reconstruct a high voltage power line in the laboratory environment, the setup shown in Fig. 10 is used.

It consists of an AC power source which is connected to a resistive load bank via a distribution transformer. The connection from the secondary side of the transformer to the load is accomplished using three insulated cables rated at 12 A. They are all connected to a single phase, which makes them suitable to carry a net current of 36 A.

The setup is capable of producing up to 30 A of net current in the conductors. According to (5), the voltage induced into the receiver is proportional to the source's current, the effect of mutual coupling and supply frequency is not considered.

To harness the energy produced by the current carrying conductors and available via the electromagnetic field, a set of three coils has been manufactured. The first coil, Coil 1, is 85 mm in diameter, a multi-layered 50-turn coil made of 1-mm-thick enamelled copper wire. The second coil, Coil 2 and the third coil, Coil 3, are 85 mm in diameter, made of 0.6-mm-thick insulated aluminium wire and have 25 and 50 turns, respectively. They are all placed in the close vicinity of the current carrying conductors, and their output voltages are measured with respect to the distance from the cables and the current flowing in the power line's prototype.

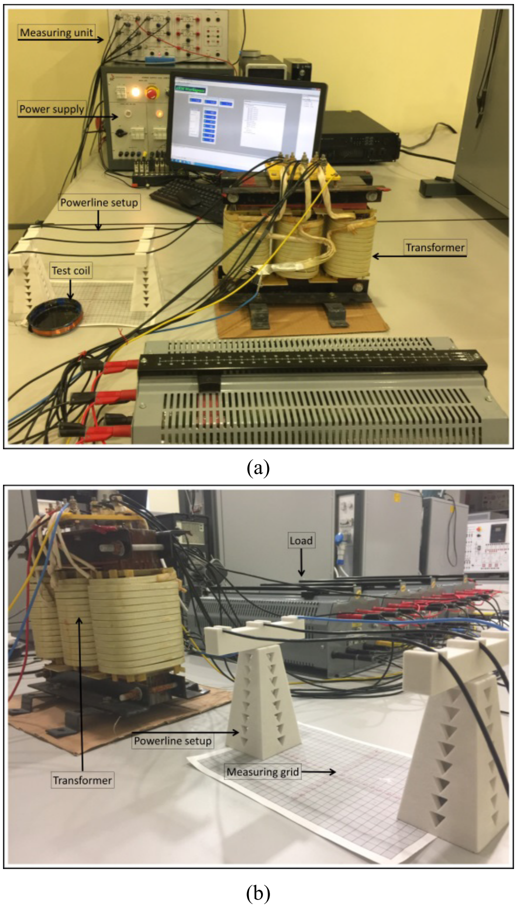

FIGURE 10. **Power line emulation setup, (a) side view, (b) close view.**

B. EXPERIMENTS

The first experiment conducted aims to identify what is the magnitude of the voltage which can be induced by the powerline's electromagnetic field into a simple coil placed nearby. According to Gupta *et al.* [63], the voltage induced into a coil with N number of turns and cross-sectional area, A_c placed at a distance, d from the conductor carrying current, I can be estimated as follows:

$$V = \frac{d\phi}{dt} = \frac{\mu N A_c I \omega_0 \cos(\omega_0 t)}{2\pi d} \tag{24}$$

Considering (24), one can notice that the induced voltage is directly related to the number of coil's turns, the coil's cross-sectional area which is subjected to the field, the current flowing in the conductor as well as its frequency. On the other hand, the voltage is inversely proportional to the distance of the coil from the conductor. It should also be highlighted that since the operating frequency of the power line is predominantly 50 or 60 Hz the term ω_0 will be treated as a constant and its influence on the voltage under these experimental conditions will not be investigated. During the first experiment Coil 1 is placed into the electromagnetic field of the conductors carrying some 30 A net current. Fig. 11 depicts the results of the experiment.

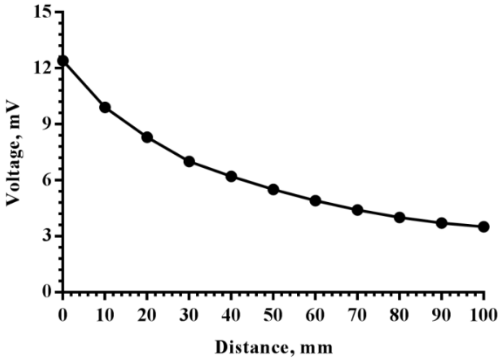

FIGURE 11. **Voltage signal received at Coil 1 with respect to the distance from the current carrying conductor.**

The voltage received by the coil is in a range from 3.2 mV up to 13.8 mV, and as predicted by (24) it is inversely proportional to the distance from the conductor. This, in turn, means that to receive the maximum voltage level, one needs to place the receiver as close to the source as possible.

The second experiment investigates the influence of the number of coil's turns on the voltage level obtained. To do so, Coils 2 and 3 are placed close to the current carrying conductor. Fig. 12 presents the results.

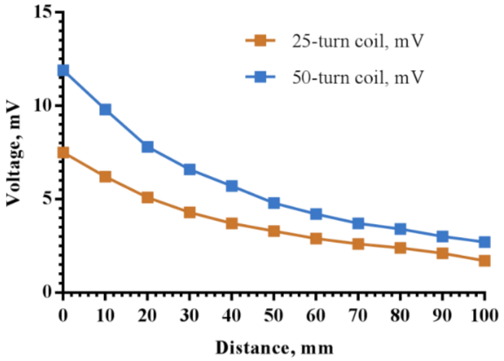

FIGURE 12. **A voltage signal received at Coil 2 and 3 with respect to the distance from the current carrying conductor.**

As it can be seen, the voltage levels induced into Coil 2 at the respective distances from the conductor are much less than those received by Coil 3. It also needs to be pointed out that the voltage level of Coil 2 at a distance 100 mm is not exactly zero, but is slightly less than 2 mV, which is the sensitivity threshold of the multimeter employed.

The third experiment aims to demonstrate the influence of the current flowing in the power line on the voltage level received by a coil placed in its electromagnetic field. Coil 1 is used for this test. Fig. 13 plots a family of voltage curves for different values of current flowing in the conductor.

It is evident that with the increase in current the voltage level induced into Coil 1 is increased at various distances. This fact underpins the proposed technique of wireless charging of UAVs from the power line conductors. Precisely, the current rating of the real power lines is much higher than that demonstrated in the experiment, and consequently, the voltage received by the coil will be much greater than that achieved in the first experiment.

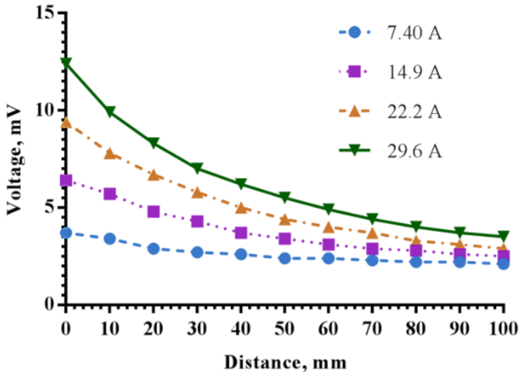

FIGURE 13. **A voltage signal received at Coil 1 with respect to the distance from the conductor and the current flowing in it.**

Thus, one can observe that the correlation described by (24) was successfully verified in practice and the proposed approach to charge drone's batteries wirelessly via the electromagnetic field of the power line conductors is a promising technique which can be studied further.

However, as it can be noticed the voltage level induced into the receiving coil is extremely low ranging from 2 mV to 13 mV depending on the distance from the conductor. Moreover, it is AC voltage, while DC energy storage powers a typical UAV. These two aspects need to be addressed to implement the proposed technique.

One way to overcome the challenge of low induced voltage is to use an amplification circuit. To verify the validity of the approach simple single layer common-emitter NPN-transistor-based amplifier with a gain of approximately 140 has been assembled and connected to the Coil 1. The amplification circuit is powered by two 9 V batteries connected in parallel. The given assembly is then subjected to the electromagnetic field of the conductors carrying 30 A. The results of the experiment demonstrating the amplified and non-amplified voltage levels are depicted in Fig. 14.

From Fig.14 it is evident that the voltage at the coil can be considerably increased utilizing standard electronics circuits and components such as transistors, resistors and capacitors. Also, they are relatively light and will not present a significant burden to the UAV in terms of weight. Consequently, they will not drastically decrease the payload.

Also, it is important to investigate into the power output of the system under the different loading conditions. To accomplish this task, various resistors ranging from 500 Ohm to 1 MOhm are connected to the amplifier's output. Fig. 15 represents the amplified voltage characteristics of the coil under the different loading conditions.

Considering Fig. 15 one can notice that the trend of decreasing voltage with the increase in distance between the unloaded coil and the power line represented in Fig. 11 remains even when a substantial load is connected. However, when the burden connected to the system grows,

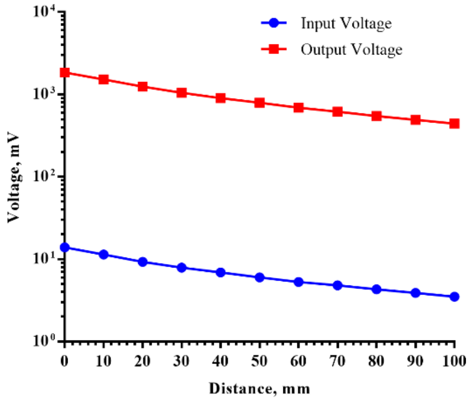

FIGURE 14. Amplified vs. non-amplified induced voltage in the coil.

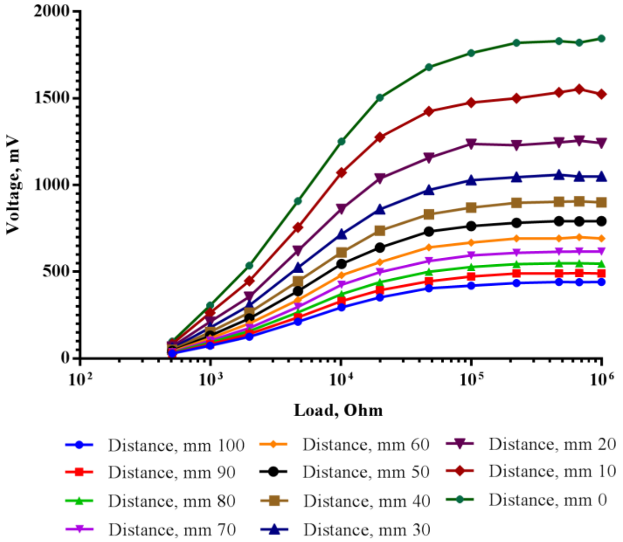

FIGURE 15. Correlation of the amplified voltage to the load applied to the system.

the voltage applied to it exponentially increases and stabilizes at a certain point.

On the other hand, the current flowing through the load follows a hyperbolic pattern and sharply decreases to zero with the increase in load. The correlation of the current flowing through the load is presented in Fig. 16.

It is also important to highlight that the current measured in the given system varies from 0.4 μA to some 190 μA. Since the coil is carrying current in the range of μA, the cross-sectional area of the wire which it is made from can be reduced, while the number of turns can be increased.

Consequently, the voltage induced in the coil will grow, while the weight remains the same. Precisely, Coil 1 used in the experiments has a wire's diameter of 1 mm, which according to [113] corresponds to American Wire Gauge (AWG) size 18 and can carry up to 14 A. This can be considered as overrating the system and therefore, presents an opportunity for coil design optimisation. In other words, the thickness of the Coil 1 wire can be reduced to AWG 26, which can carry roughly 1 A, while having a diameter of some 0.4 mm. According to [113], each coil turn, in this case, will weigh some 0.6 g. Having considered that the total weight of 50-turn Coil 1 is some 100 g, it is possible to manufacture a 150-turn coil using thinner AWG 26 wire, which will weigh approximately 90 g and still be able to carry the currents produced during the WPT process.

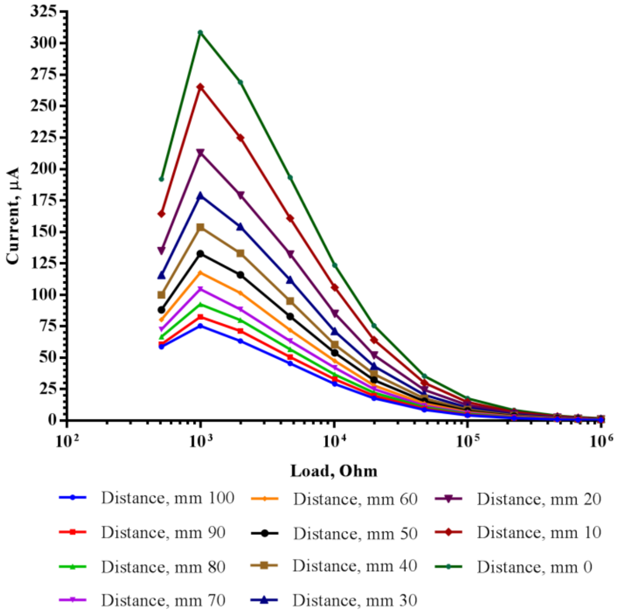

FIGURE 16. Current with respect to the load.

The power supplied to the load is also estimated at the level of micro Watts. The graph representing the power received with respect to the load is provided in Fig. 17.

One can notice that the power increases with the load, reaches its peak at some 5000 Ohm, sharply plunges and goes to zero as the burden goes to infinity.

From the results presented in Figs. 15–17 it can be concluded that the load connected to the coil also plays a significant role in determining the output characteristics of the wireless transfer link along with the distance of the receiver from the current carrying conductors. It is important to note that there is a specific burden value which maximises the power input to the system. Moreover, since the power input is constant, it can be concluded that the efficiency of the power transfer reaches its peak at a certain load, while for other burdens it will be smaller.

Considering, the output power produced by the given system, it is proposed to estimate the amount of energy which can be obtained from the power line's conductor.

From Fig. 17, one can notice that 100 μW can be produced at a distance of 10 mm from the conductor. This amount is produced in the 1 sec period. Consequently, the amount of energy, E produced in an hour by applying power, P will be equal to:

$$E = \int P dt = 100\mu W \times 3600s = 360mWh \tag{25}$$

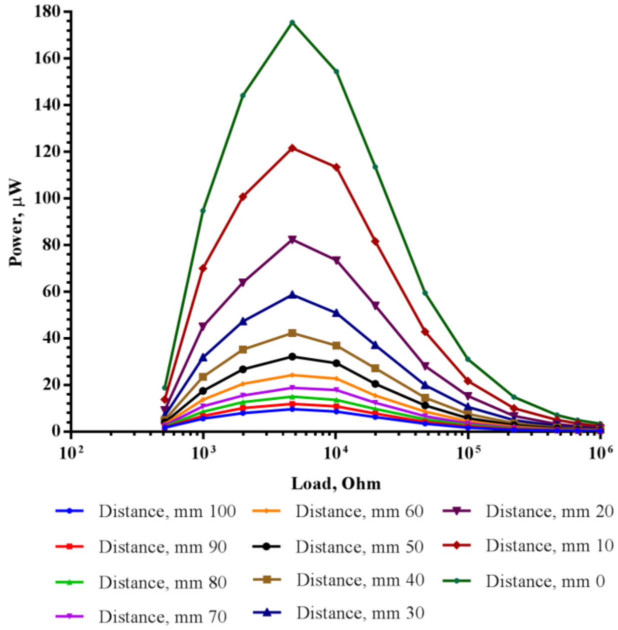

FIGURE 17. Power supplied with respect to the load.

This amount of energy can be supplied to the load by means of using a Coil 1 subjected to the electromagnetic field of the conductors carrying roughly 30 A.

On the other hand, a typical sub-transmission level power-line conductor connected to the transformer rated at 63 kV and 400 MVA carries the current level I_{ST}, which can be estimated as follows:

$$I_{ST} = \frac{400MVA}{\sqrt{3} \times 63kV} \approx 3670A \tag{26}$$

Thus, if the same coil is subjected to the field of the conductor carrying 3670 A, which some 120 times larger than the experimental condition, then, based on (24) and the experimental outputs the energy produced by the coil in one hour will be estimated at 43.2 Wh. A typical drone's battery, on the other hand, contains 2200 mAh at the 11.1 V, which amounts in 24.42 Wh of energy. Thus, one can notice that the energy available from the power line is 80 percent greater than that is required for the battery to be recharged.

However, it should be highlighted that the power source to load efficiency is negligibly low under this approach. Precisely, the supplied power provided by the conductors of the setup carrying 30 A at 42 V is equal to 1260 W, while the receiver coil's output amounts in approximately 300 μA at 13.5 mV. Thus, the overall efficiency of the power transfer tends to 0, which in comparison with the maximum possible efficiency under the IPT reported in other sources is a very poor performance.

The main reason for this is the fact that at such low frequencies the quality factors of both the receiving coil and the transmitting conductor are extremely low.

Considering the Coil 1 from the experiment, the resistance of the coil, R_{coil}, is estimated to be equal to approximately 0.29 Ohm via the following equation:

$$R_{coil} = \rho \frac{l_c}{S_c} \tag{27}$$

where, ρ is resistivity of copper, which is considered to be equal to $1.68 \times 10 - 8$ Ohm × m, l_c is the length of the coil's conductor in meters, S_c is the coil conductor's cross sectional area measured in square meters.

On the other hand, the coil's inductance has been estimated to be equal to some 114 μH using ANSYS Electromagnetics simulation, which was proven to be accurate enough by Rakhymbay *et al.* [114]. Substituting the parameters of inductance, resistance and frequency into (6), it can be possible to estimate the quality factor of the coil. In fact, it amounts in 0.02, which is negligibly small for the application proposed. On the other hand, applying similar approach to estimate the quality factor of a circular power line conductor with a diameter of 3 mm used in the experiment, it was revealed that it is equal to 0.15.

Considering the parameters calculated above, it can be expected that the low coupling coefficient, which ranged from 0.005 to 0.03 as per the Fig. 18 will lead to low efficiency.

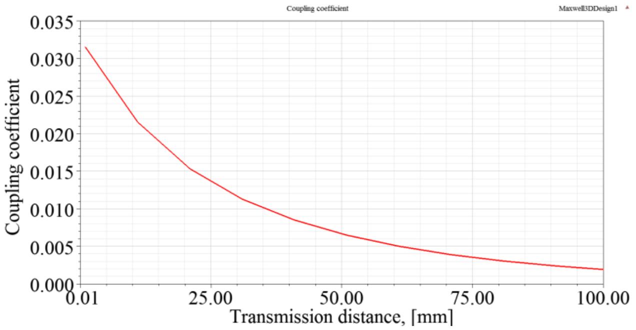

FIGURE 18. Powerline conductor and receiving coil coupling coefficient estimation.

Substituting the values of the load where the system's efficiency reaches its peak, the quality factors for conductor and receiving coil as well as the coupling coefficient shown in Fig. 18 into (18) and (19), it becomes evident that the power transfer efficiency tends to zero, which was proven by the experimental analysis above. This in turn demonstrates relatively good alignment of the mathematical model for the WPT presented in Section V and the practical tests shown in Section VIII.

Improving the performance of wireless links at very low frequencies, especially standard frequencies of 50 and 60 Hz, is one of the major technical challenges associated with the implementation of WPT for charging drones from the electric power lines.

One way to address the challenge is to utilize principles of RC WPT for charging. This puts a set of questions for discussions forward. Firstly, since the optimal operational range for RC WPT technique lay in kHz to MHz region, it is necessary to bring the wireless link's frequency from 50 or 60 Hz up to that level. Another point of attention stemming from the latter statement is whether the frequency conversion process should happen on board the UAV or at the power line's side. In case of onboard conversion, the space and allowable weight of the conversion and WPT equipment are seriously limited by the drone's frame and payload, respectively. On the other hand, installations on the power line towers will raise the questions of electromagnetic interference, shielding as well as the infrastructural costs and maintenance.

Secondly, if operating at the standard frequencies of the power line's EMF, is it possible to achieve reasonable efficiency level of at least 50 percent provided by the MPT approach. In addition, having (11) in mind lower frequencies mean larger resonating equipment, i.e. inductor and capacitor, which in turn pose a pressure on the payload and available useful volume of the UAV.

Thirdly, the issue of magnetic interference and shielding needs to be carefully considered. Although, the body of the drone predominantly consists of non-magnetic materials, other materials surrounding the UAV while chagrining as well as its electronics may interfere and create undesired losses.

The future work on the proposed charging scheme will include further amplification of the induced voltage to the level suitable for charging, rectification of the AC signal received by the coil as well as charging a sample battery using this technique. Also, another important topic is to study the electromagnetic field of the power line conductors to determine the most efficient point for wireless transfer. Moreover, dynamic charging of the UAVs from the power lines is an interesting technique which needs to be investigated. RC WPT is considered as one of the potentially suitable approaches to accomplish this.

However, it has not yet been studied in the context of high voltage power lines. It is also crucial to investigate the receiving coil geometry and its influence on the parameters of the WPT under the described scenario. Multiple coil arrangements are thought to be an opportunity to enhance the energy harvesting rate of the proposed system as well as increase the power output.

X. CONCLUSION

This study reviewed the techniques most frequently employed for extending UAVs flight range and mission duration. Hence, gust soaring method, which is inspired by the behaviour of albatrosses, helps to gain energy from the naturally occurring sources of energy such as wind. Under this technique, a UAV adjusts its trajectory in such a way that employs wind velocity to increase its speed. On the other hand, the drone in this mode of operation becomes too dependent on the intermittent environmental conditions. Therefore, this fact should be considered in the design of the UAV. Also, the drone utilizing this approach, cannot maintain stable position for a sufficiently long period, which can be required for certain applications, since it needs to follow a specific trajectory to harness energy and subsequently move continuously. Moreover, this technique is only advantageous for fixed-wing UAVs, since multi-rotor drones do not have sufficient wingspan to harness energy from the environment.

PV cells installation has been reported to be a relatively mature technique used to enhance UAVs' mission duration. Its application demonstrated some considerable improvements in terms of flight time. However, employment of such approach is mostly suitable for fixed-wing drones, since they have larger wing area for the PV cells installation. Moreover, this technique requires a sufficient level of solar radiation for optimal operation, and in the absence of the sun, one needs to employ an alternative way to power UAV. Also, it was reported that battery size and other physical parameters of the drone play more important role in determining final mission duration of the UAV than PV cells' efficiency.

Laser beaming technique frequently used in military surveillance operations has been identified as a promising option for increasing flight time of drones. It utilises concentrated beams of light directed to a specially designed PV cell, which in turn recharge UAV's battery. One of the biggest disadvantages associated with this technique is that the power source should always be relatively close to the UAV, and therefore should be mobile. Moreover, lasers can potentially be quite dangerous for health, and their application in populated areas can be very challenging.

Another interesting approach for prolonging UAV flight time reviewed in the given study is battery dumping. It implies splitting existing drone's battery in a set of sections to disconnect them from it once empty and dump them to decrease the weight of the vehicle. This, in turn, facilitates a decrease in the power required to move the UAV and consequently prolong the mission duration. It is important, however, to consider the optimal size of each battery section. It was proposed to use optimisation tools such as genetic algorithm. Moreover, it is crucial to account for the installation of a battery dumping apparatus, which might significantly increase UAV's weight and alleviate any energy gains.

Employing battery changing stations were also briefly presented within the framework of the review. This approach is based on the notion that charging of a drone can be very time consuming and therefore swapping a dead battery with a charged one will be faster and will not drastically disturb UAV's mission progress. It was concluded that this technique is advantageous for the large fleet of UAVs, both fixed-wing and multi-rotor, as well as facilitates automation of the process. However, to effectively extend flight range of a UAV a network of changing stations should be created.

Moreover, EMF-based alternatives such as charging UAVs from high voltage power lines was discussed. Based on the literature analysis, the main technique used for charging, in this case, is wireless power transfer. Therefore, techniques such as inductive power transfer and resonant inductive wireless power transfer to harness energy from the electromagnetic field were presented and discussed.

IPT operating at kHz to MHz frequency range was revealed to be applicable for short range applications because its efficiency is significantly dependent on the distance between the transmitter and the receiver. It was also mentioned that lateral misalignment of the coils during the IPT has a more drastic influence on efficiency compared to vertical distance.

RC WPT, on the other hand, is reported to be more beneficial technique than IPT in the mid-range applications since it is not sensitive to lateral misalignments of the coils and is potentially able to transfer power over substantially large distances. It is based on the notion that the transmission coils synchronized at the same resonant frequency can potentially transfer power without significant losses of energy during the process.

In addition to the description of the RC WPT two fundamental concepts of WPT, namely Maximum Power Transfer and Maximum Energy Efficiency approaches were reviewed and discussed. It was revealed that the choice of the approach determines the performance of a WPT system. Thus, if MPT is employed the total energy efficiency of the system will not be more than 50 percent, while the transfer distance can be considerably large. Employing MEE, in turn, will facilitate achieving greater energy efficiency, i.e. larger than 50 percent, while the transmission range will be very short and utilization of intermediate repeaters will be required to extend it. Moreover, the given study has visited the topic of frequency splitting occurring at the over coupled region of RC WPT operation. It manifests itself as the presence of two resonant frequencies at the coupling rates greater than critical. Both of the produced frequencies though can be used for RC WPT.

Concluding the description of the EMF-based techniques, a review of the available literature sources on the topic of wireless charging of UAV using IPT and RC WPT were presented.

Moreover, a preliminary test of a technique which uses power line electromagnetic field as a source for UAV battery recharging was conducted. It revealed that a drone equipped with a simple multilayer coil could potentially receive a voltage signal of some millivolts under the IPT approach. The experiments also proved that the voltage is directly related to the coil number of turns and the current flowing in the conductor, while it is inversely proportional to the distance of the coil from the power line.

Future work on the topic will include studying the mathematical models of the electromagnetic field to identify the most efficient point for drone charging as well as simulating the proposed charging scheme. It will also be interesting to implement the RC WPT technique for wireless charging of UAVs from the power lines as well as consider dynamic charging approach. One of the most important questions for future investigation will be optimization of the UAV coil's design and studying the possibility of connecting multiple coils to a UAV for higher power output and energy harvesting.

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