

Optimizing Hybrid Energy Harvesting Mechanisms for UAVs

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Abstract

Drones or unmanned aerial vehicles (UAVs) are often limited in range and duration since they can carry limited fuel or small size batteries. While other technologies focusing on batteries, control algorithms, and devices, the immediate improvements could be energy harvesting in which the ambient resources would provide sufficient power for UAVs. This proposed study aims to overcome the limitations in terms of energy and to optimize the energy harvested to prolong the flight time. The proposed mechanism focuses on two resources as radio frequency (RF) and solar energy and optimizes the energy harvesting systems. Two standalone systems are used to extract electricity from surrounding environment sources. RF harvesting energy is supported by a multi-stage of the voltage multiplier. The solar energy is absorbed by solar panels with mounting more the boost converter and using the maximum power point tracking method to achieve better efficiency. The output values of the hybrid energy system will be adjusted by stabilizer and boost the current system to have proper voltage and current with the battery inputs. By adding the supported circuit and methods, the simulation results are suitable to charge electricity for the battery having the capacity 7660 mAh and show promise

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Keywords: Unmanned Aerial Vehicle (UAVs) - Drones, Solar cells, RF energy harvesting, Hybrid energy harvesting, Rechargeable batteries

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1. Introduction

The use of flying platforms such as unmanned aerial vehicles (UAVs), popularly known as drones, is rapidly growing in many different fields, both military, and civil applications. The occurrence of UAVs not only helps humans escape the workplaces with dull, toxic and dangerous tasks but also helps missions achieve higher work efficiency. Recent years have witnessed the tremendous development of research focusing on designing and manufacturing increasingly sophisticated versions of UAVs integrated multi-applications. It is mounted with numerous modern

devices such as cameras for surveillance, sensors for transmitting and collecting data, and weapons used in military combat, etc. [1–3]. There are currently different types of UAVs. They are classified based on various factors in function, size or usage, etc. It is the professional classification that makes it possible for users to use them for the right purpose. Besides, the research and development of UAVs also have a clearer orientation.

Power to supply the battery-operated system of applications such as wireless sensor networks (WSNs) [4, 5], Internet of things (IoTs) [6–9], UAVs [10, 11] has always remained a major constraint. In that vein, the fundamental problem with respect to UAVs is that they eternally have to consume a large portion of their power from the battery source just to resist their gravity. Because of the limited operating time, UAVs are also tough

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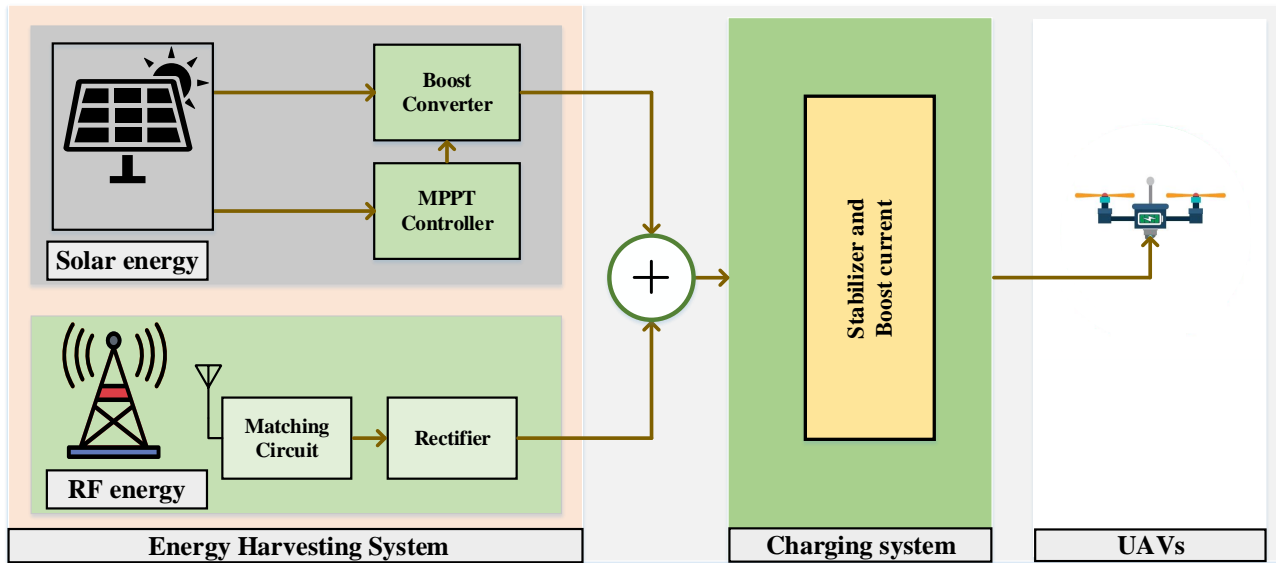


Figure 1. The block diagram of model system for UAVs

to perform several different tasks continuously and efficiently. In practice, most of the small UAVs out there are capable of only a 20 to 40 minutes flying time [12]. This is a big obstacle that needs to be meliorated. Therefore, the power provision for mobile devices is an inspiration for a lot of recent research [11–14]. The supplying and supplementing energy can guarantee and even prolong the working time for UAVs through the energy harvesting (EH) circuit system which can simultaneously scavenge energy from readily available in the ambient environment.

EH technology allows equipment and applications that manipulate them for more self-sustaining operating time on their thanks to the surrounding energy supply. The most striking energy here is the solar energy that directly uses photovoltaics (PV) placed in the sunlight to convert from sunlight into electric energy and stored in rechargeable batteries. On the other hand, RF is a suitable choice to replace solar energy because it can still well work in conditions without sunlight. In [15], Shruti B. Jadhav *et al.* used the combination of these energy to create a power supply system for low-power applications. They analyzed and compared the output parameters of the standalone sources and the output parameters of the hybrid system. This shows the significant improvement of the designed system. In addition, Singh *et al.* executed measurements at different frequency ranges at different times to show the output value of each source and the output value of the combined system [16]. The provision energy to UAVs can be implemented by wireless power transfer techniques such as near-field, far-field amalgamated with EH technologies such as solar power, RF energy, wind

power, etc. Obviously based on existing techniques and from natural energy sources, we have proposed an optimal method of hybridizing RF energy from the surrounding environment with solar energy from nature to create a stable source of energy for adding energy to UAVs [12, 17].

In this paper, we propose to optimize the hybrid method between solar-RF energy for UAVs during the flight, shown in Fig. 1. This combination aims to leverage two sources to provide a sustainable operation mechanism in all different weather conditions at all times. The harvesting system performs the function directly scavenging power from sunlight and RF from the ambient environment to provide power for the whole UAV's flight process. In that vein, the flight time and the weight of the UAVs is also an important factor to directly affect the operational process of performing their tasks. Hence in this paper, the energy source will be the hybrid system including solar and RF energy. The EH system has specialized integrated circuits for both RF and solar sources. This helps to optimize the yield of these two energy sources. The charging system makes the voltage stable and steps up the current to charge for the UAV's batteries. The UAV includes the battery system to store power. The voltage and current are designed to meet the M200 V2 and its intelligent battery 6S Li-po having the capacity of this battery 7660 mAh [10].

The remainder of this paper is organized as follows. The background of EH techniques of Solar-RF energy in general analysis and design are mentioned in Section 2. Section 3 provides simulation and results.

Finally, conclusions and suggestions for future work are presented in Section 4.

2. Theoretical Description and Design

This section analyzes knowledge about maximum power point tracking (MPPT) algorithm and the DC-DC boost converter for solar system and RF-EH system.

2.1. Solar Energy

Solar energy (SE) is a renewable source that has many advantages such as environment-friendly, no fuel cost, little maintenance, and durability. In fact, the conversion efficiency of solar cells in solar PV is still low. Therefore, the method of the maximum power point tracking (MPPT) is applied to maximize power extraction for any given environmental conditions for PV solar systems. The operation principle bases on varying irradiation and temperature of the maximum power point of solar panels. We deployed the SE system to supply power for UAVs. The surface area that absorbs sunlight of the PV system is directly proportional to the amount of electricity produced. That also significantly increases their mass to achieve the required capacity for the device. One of the requirements for devices attached to UAVs must be light so they can minimize the power consumption. In order to solve this drawback, the boost converter is used to step up the output voltage of the solar panels that helps to obtain the desired output value. It is relatively easy to implement, less cost and simple structure with high efficiency in the conversion of electrical energy.

MPPT Algorithms. As mentioned in the previous section, the MPPT method finds down the highest power point of the PV panel from the sunlight. It is also implemented to control the duty cycle of boost converter to get the most usable power output.

A scheme of the MPPT algorithm is depicted in Fig. 2. The MPPT system measures the values of the output voltage and current (V_o , I_o) of the boost converter and then calculates this power. The duty cycle of the boost converter is going to increase or decrease depending on the old power (P_O) value and the new power (P_N) value. If the P_N value is higher than the P_O value, the P_O value is assigned the P_N value. And if the P_N value is smaller than the P_O value, the P_O will have remained. Following this way, the MPPT algorithm is able to track the maximum point of the PV panels in order to obtain the highest energy. After that, the operating point fluctuates around the maximum power point.

The DC-DC Boost Converter. According to the UAV requirements for the attached devices, the solar panels set up UAVs must be small and light in both size and weight of the PV panel. Therefore the goal is to ensure a compact size but the output is still able to

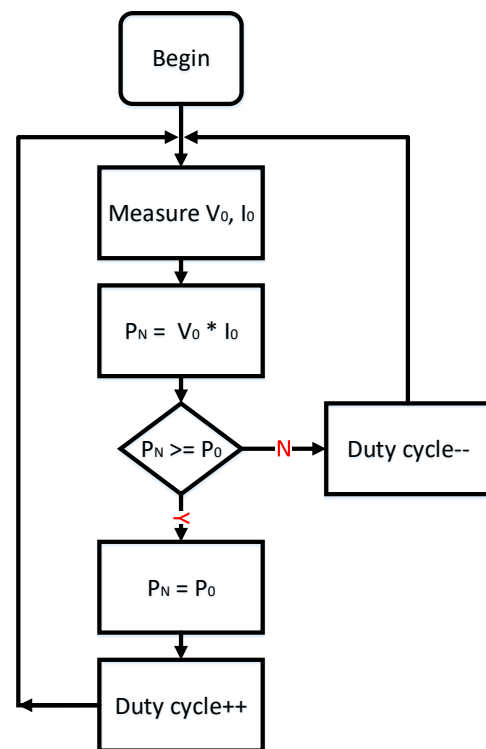


Figure 2. The MPPT algorithms control the duty cycle of the boost converter

meet the power consumption needed. The solution is to integrate a DC-DC booster converter that significantly increases the output voltage and current of the PV panels. The conventional boost converter has often some main components such as one inductor, the diode, the capacitor, and the MOSFET transistor as shown in Fig. 3. The boost converter has two modes equivalent to the opening and closing process of the MOSFET transistor.

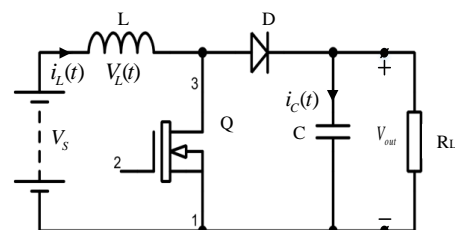


Figure 3. The scheme of the boost converter

The inductor is used to store the current in the closing mode of the MOSFET, while the capacitor is used to store the voltage in the opening mode of the MOSFET. The diode prevents the capacitor's current flowing back to the source. Especially, the ON and OFF time mode of the MOSFET transistor effects significantly

to the output values and the output fluctuation as shown in Eq.2. This paper uses the MPPT algorithm to operate the duty cycle of MOSFET's switch presented in the MPPT algorithm section.

In the Eq.1 depicted the relationship between the ON and OFF modes of the MOSFET's switch. While D_{on} is the ON percentage time of the MOSFET transistor and D_{off} is the off duty cycle [18].

$$D_{off} = 1 - D_{on} \quad (1)$$

In the Eq.2 shown the direct affect of the ON and OFF switch of the MOSFET transistor to the output voltage. While V_s is the source voltage and V_o is the output voltage of the boost converter [18].

$$V_o = \frac{V_s}{D_{off}} \quad (2)$$

By using the boost converter, the output values are able to step up to higher levels. However, the system still needs to the trade-off consideration between the high values and the fluctuating of the outputs.

2.2. RF Energy

In recent years, commercial telecommunication networks have been developing strongly on the globe, leading to the existence of numerous radio frequencies (RF) in the surrounding environment, especially the areas where assistance communication devices are installed. In this paper, our proposed system takes advantage of this perpetual energy to provide power for the UAVs. The basic principle of this system is to select a proper frequency band to scavenge energy, then convert them into usable DC electricity. The system is built with three main parts such as the antenna, the matching circuit, and the rectifier circuit (voltage multiplier), shown in Fig. 4.

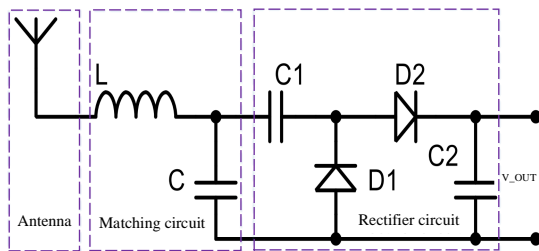


Figure 4. The scheme of the RF energy harvesting

The antennas of the RF harvesting system capture the ambient radio frequencies in the environment. The densities of the radio frequencies are the main factor direct-affecting the harvesting energy. Nowadays, the high RF densities are cell phones (900 MHz), WiFi signals (5 GHz and others), local area networks (2.4 GHz-5.8 GHz), radar (5 MHz-130GHz), satellite stations (1-40 GHz), and TV broadcast (500 MHz-700 MHz). The

amount of harvesting energy at antennas is shown in Eq. 3.

The harvesting power at the receiving antenna [19].

$$P = P_t * G_t * G_r * L_c \left(\frac{\lambda}{4\pi d} \right)^2 \quad (3)$$

While P is the receiving power at the antenna, P_t is the transmitting power, G_t G_r are the gains of the transmitting and receiving antenna, λ is the wavelength, L_c and d are the loss factor and the distance between transmitter and the antenna.

The matching circuit also has another name that's an impedance matching. The matching circuit, including the coil and capacitor to obtain the power, is placed between the antenna and the rectifier circuit to match from the antenna impedance to the rectifier circuit. Therefore, the performance of the system achieves the maximum power and improve transferring efficiency. However, the harvested energy obtained by the RF energy harvesting technology through the antennas is still low power and might be not high enough to supply for the devices.

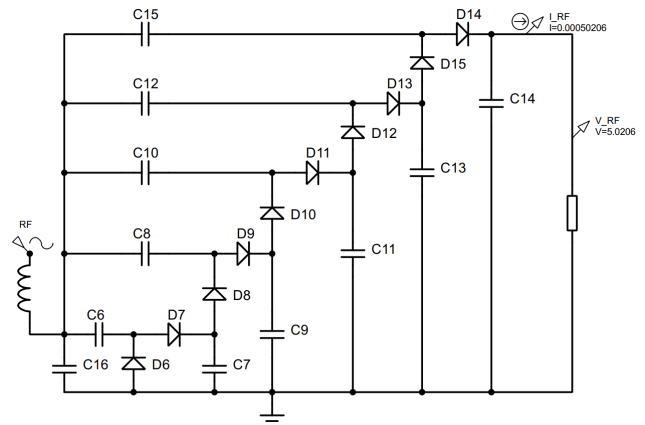


Figure 5. The 5-stages of the voltage multiplier

The voltage multiplier (VM) is utilized to amplify the power and also convert the AC harvesting voltage of the antenna to the DC voltage. Depending on the input and desired output voltage, the VM is used with different stages while each stage consists of two diodes and two capacitors. The number of the stages is directly proportional to the output voltage of the VM and the delay time to approach the target. This drawback is the trade-off between the number of the stages leading of increasing the diodes and the dissipate the power at each stage which is caused by diodes [20, 21]. Hence, we choose 5-stages VM relying on our desired voltage and the delay time in this paper, designed as shown in Fig. 5.

The output voltage [22] for an N-stage with the ideal voltage multiplier is expressed in the Eq 4:

$$V_o = 4NV_{in} \quad (4)$$

Where V_o is the output voltage of the voltage multiplier, N is the number stages, and V_{in} is the input voltage of the voltage multiplier.

Obviously, RF-EH technology is being considered as a promising charging solution. It has the plentiful RF energy source harvested from the ambient environment. Moreover, the structure is simply designed, light-weight and small in size. By using the voltage multiplier (VM), the output values are able to step up to higher levels. However, the system needs to trade-off between the high values and the fluctuating outputs.

2.3. Charging System

The charging system is an important part of the proposed system. It provides the electric energy received from the hybrid solar-RF EH system for UAVs. The charging system consists of the stable voltage and boost current system as shown in Fig. 6.

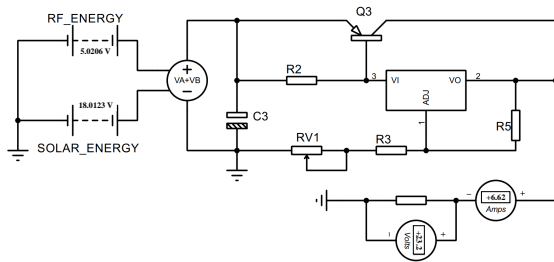


Figure 6. The stabilizer voltage and boost current system

Two energy sources is used to support for together in all weather conditions. This is helpful for always scavenging stable and plentiful energy input. Therefore, the output voltage value of the hybrid system is high enough to meet power for the devices. However, this is not optimal because of the unstable output. Moreover, the output current of this system is not satisfying to quickly charge for the UAVs batteries. To improve these issues, the output power of the hybrid system is fed through the charging system to stable the voltage and enhance the current. The high output current is able to quickly charge for the batteries or reduces the charging time. In this paper, we assume the power is supplied to the real UAVs/drone M200 V2 and its intelligent battery 6S Li-po having the capacity of this battery 7660 mAh [10]. Especially, the charging voltage of this battery is 22.8 V which is suitable with the output voltage of our charging system detailed in the simulation and result section. The result of the output voltage is suitable for charging the battery 22.2 V detailed in the below part.

3. Simulation Results and Discussions

In this section, this study simulates the stand-alone solar and RF energy harvesting, thereby we show some issues of the stand-alone energy harvesting system. To tackle these issues, the power supplying system will be hybrid solar-RF energy. With the purpose to meet power for the UAVs M200 V2's battery, the output values of the energy hybrid must be adjusted by the charging system.

3.1. Harvesting Solar Energy

The solar energy is the main supplying power for the UAVs. We utilize the solar panel which is able to harvest 5 volt from the sunlight. As mentioned in the theoretical analysis and design section to achieve high power, the solar system needs to use the MPPT algorithm and the DC-DC boost converter.

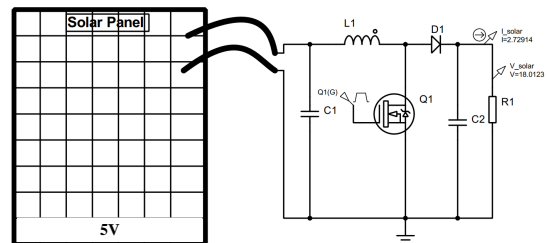


Figure 7. The scheme of the stand-alone harvesting solar energy

In the Fig. 7, the output current of the solar system is 2.73 A and the voltage is 18.01 V. The output voltage of the boost converter is much higher than 5 V, but the result is fluctuating and especially, this value is not proper with the charging voltage of the battery 6S Li-po.

3.2. Harvesting RF Energy

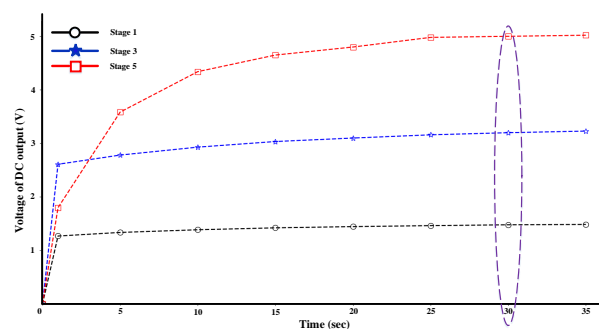


Figure 8. The DC output of different stages

The stage numbers of the VM based on our desired output value and settling time. The settling time is the time to approach the desired value and get stable. Our simulation employs three different cases of the VM to

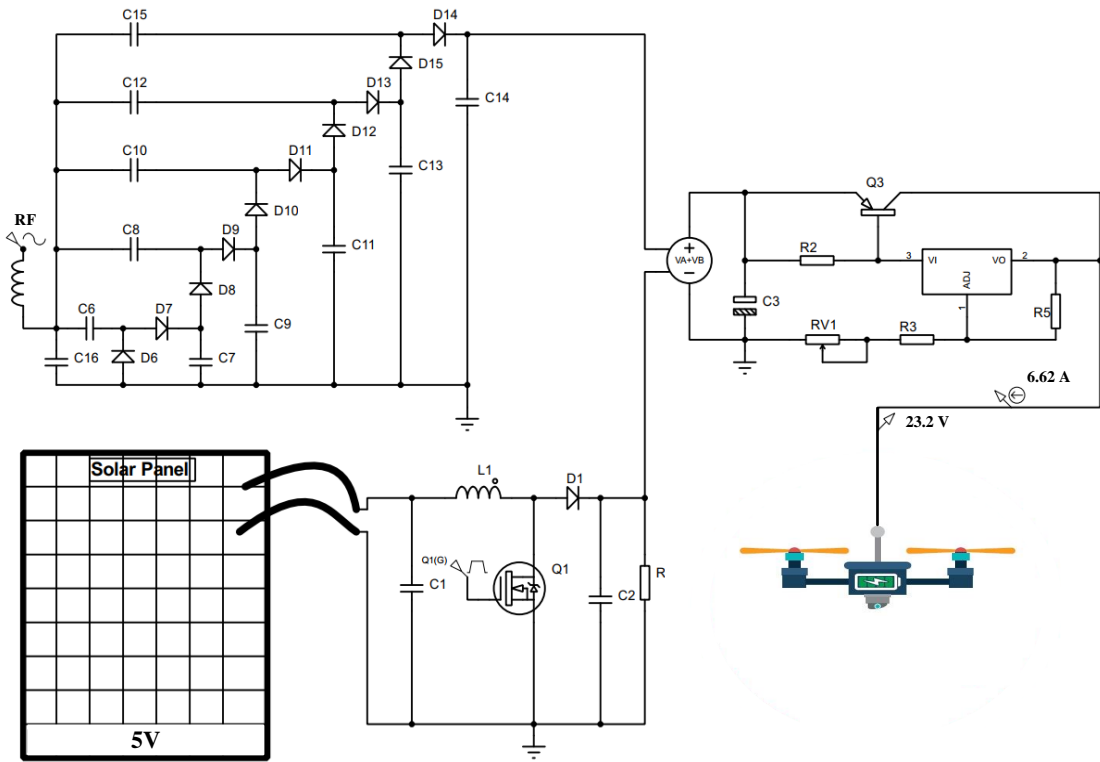


Figure 9. The proposed hybrid solar-RF harvesting energy

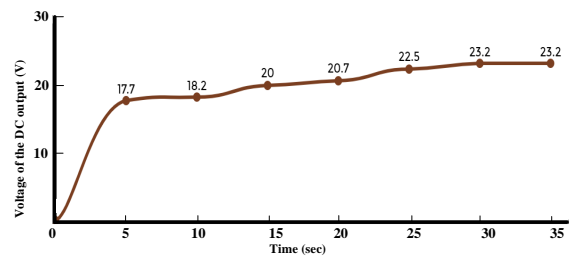
compare the results and then choose the proper stage numbers.

The given line graph in the Fig. 8 shows that the output voltage of each stage. One stage of the VM has a low output voltage only getting 1.3 V, and three stages have the output voltage value 2 V. Both above cases have the settling time is short which is only 2 seconds. In the last case, five stages are able to generate much higher voltage 5.02 V shown in Fig. 5, and has the settling time 25 seconds. Our purpose uses to charge for battery, so the real-time of the response is not too strict. Based on the theory given above and the measurements on actual simulation, our paper chooses the five stages of the VM to step-up voltage for RF energy source.

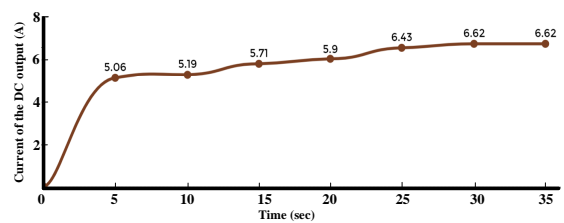
3.3. Hybrid Solar-RF Harvesting Energy

The proposed hybrid solar-RF harvesting energy is the combination of the stand-alone solar and RF energy mentioned above. The harvesting energy flows through the charging system to obtain the stable voltage and boost to higher current, suitable to charge for the UAV's batteries shown in Fig. 9.

The Fig. 10 shows the output values of the solar-RF hybrid harvesting energy system. The output voltage rapidly reaches to the desired value 23.2 V, and the settling time is 30 seconds shown in Fig. 10(a). The importance of this output voltage is suitable to charge



(a) The charging voltage



(b) The charging current

Figure 10. The output values of the hybrid system

for the chosen battery 6S Li-po 22.8 V. The output current showing in Fig. 10(b) is much greater than the above stand-alone energy systems. The response time to approach 6.62 A is very rapidly, only 30 seconds.

Especially, the high current helps directly reduce the charging time for the UAV battery indicated in the Eq.5.

The charging time for the UAV battery [23]

$$T = \frac{C_{bat}}{I} \quad (5)$$

Where T is the charging time to fully charge for the battery in hours, C_{bat} is the capacity of the battery in Ah, and I is the output current of the charging system in Ampere (A).

Table 1. Compare results

Method	Parameter	Solar	RF	Hybrid
[11, 15, 16]	V (V)	15.3	9.77	23.15
	I (A)	0.69	0.48	1.05
	T (h)	11.1	15.9	7.29
Propose	V (V)	18.01	5.02	23.2
	I (A)	2.73	0.0005	6.62
	T (h)	2.8	15320	1.16

In the Tab 1, we compare our proposed method and some regular methods about current (I), voltage (V) and the charging time (T) of the stand-alone solar energy, the stand-alone RF energy, and the hybrid energy system. We focus on analyzing the parameter of the hybrid energy system. The first about the voltage, all methods can generate nearly the same output value which is proper to the input voltage of the battery. The second about the current, our proposed method achieves the value 6.62 A much higher than the value of the other methods 1.05 A. As mentioned above, the current affects significantly and is diversely proportional to the charging time of the battery. The charging time of our method is only 1.16 hours which is faster approximately 7 times than the other methods 7.29 hours. To supply power for the UAV's battery, our method is suitable and effective in both the output power and the charging time.

4. Conclusions and Future Work

In this paper, an energy-efficient combination of solar energy and RF energy is proposed. Two energy harvesting resources are combined to significantly increase the output that support the UAVs to meet the sufficient power requirements corresponding to the power parameters originally needed. In addition, with the usage of the charging system, our system can create a stable voltage as 23.2 V that satisfies all common UAVs battery requirements. The current DC output is significantly increased and achieved at 6.62 A. Therefore, the charging time for batteries is obviously shortened. The performance of the proposed hybrid system has been optimized, evaluated and compared to other systems, such as stand-alone solar and RF harvesting systems.

In order to increase the system performance, the charging processing for the battery to enhance charging efficiency should be considered. The charging processing controls to adjust the charging current and voltage which are depended on the battery percentage in each period could be exploited. Additionally, the MPPT algorithm of the solar system is an important factor affecting directly to the harvesting power. Hence, this MPPT algorithm utilizing fuzzy methods or particle swarm optimization algorithm would be considered to improve the harvesting efficiency.

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